# ACOUSTIC FACADE FOR NOISE POLLUTED LIVING ENVIRONMENTS

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## *ABSTRACT*

*As technology has progressed, urban citizens have been pestered by noise pollution that has contributed to an unhealthy living environment. In many cases, lower-income groups are placed in unhealthy living environments due to the low cost of ground. By clarifying the relation between sound and health, the set of acoustic requirements of organizations can be understood and further be followed to form a base from which an environmentally-friendly solution will derive. As vegetation and natural materials are used more frequently in contemporary architecture, it is of interest to consider these eco-friendly materials as possible acoustic solutions in combination with traditional methods that have been shown to work well in the past. At the end of the day, this research paper is a step in the development towards an acoustic design strategy with an eco-friendly and holistic essence to it.*

***KEYWORDS:*** *acoustic performance, noise pollution, living environment, noise absorption, vegetation, natural material, health, geometric shape, noise barrier*

## I. INTRODUCTION

More than 50% of citizens in European urban areas experience noise pollution during the day, evening and night according to WHO. (Eea.europa, 2021) As civilization has developed itself throughout the years of industrialization, the amount of noise exposure has increased drastically due to the densification of cities. (Brasuell, 2019) The increase in the number of citizens has led to an increase in vehicles, leisure, and public transportation. In other words, the development of civilization has led to different issues and questions of today. Societal concerns are usually multifaceted and require a holistic approach to be solved accordingly. With that being said, architects should position themselves in how the world should function and how contemporary issues should be solved. The issue of noise pollution is one of the global problems that hasn't been addressed appropriately.

It is essential for citizens to live in a healthy environment in order to create a positive perception about their own lives and the realm they find themselves in. The performance of society is widely dependent on the health of its people, which makes it logical to prioritize urban health. Living environments with high noise pollution created by rail or road traffic can be hazardous and require noise barriers for citizens to live in a healthy manner. Yet, there are many citizens that live in noise polluted living environments. Frequently, citizens from lower-income groups are placed in these substandard living environments in the form of social housing because these sites have lower costs due to their contextual issues. According to (RIVM, 2019) citizens from lower-income groups are associated more often with substandard health compared to middle and high-income groups.

Noise pollution is known for causing health issues for society both in a direct and indirect manner. The perception of noise is of great influence on the cause of health issues, while at the same time, a certain level of noise will damage the human hearing organ regardless. Emotional and physical damage can occur when humans are overly exposed to sound. Health and building organizations have collaborated to translate the health requirements of human beings to the building industry by creating sound regulations. These regulations contain parameters that specify each building project according to the reference point of the sound source.

Striving for more sustainable and environmentally-friendly buildings is a steer towards the right direction to achieve a healthy living environment. Consequently, to address the issue of noise pollution in the living environment, architectural interventions have to be designed adequately. By combining the ambition to build in a sustainable and eco-friendly manner with the ambition to solve noise pollution in living environments, the following research question shall be discussed: *"How can geometric shapes, the urban form, and the use of vegetation- and natural materials contribute to the acoustic performance of buildings in noise polluted living environments, and thereby stimulate the health of its users?"*

This research question will be categorized into 3 sub-questions:
*Q1: What are the acoustic requirements to create a residential building that stimulates the health of human beings?*
*Q2: What vegetation- and natural materials can be utilized to function as acoustic skin?*
*Q3: What eco-friendly solutions have been applied on the urban and building scale level that could address the issue of noise polluted living environments?*

The hypothesis of this research question is the assumption that the complexity of sound leads to the requirement of tailored solutions for each reference point of sound exposure, and thus is in need of a holistic approach and design strategy to address nuisance accordingly. Using natural materials and vegetation that solves noise issues, will contribute greatly to this approach as it can be one of the foundations of a healthy living environment.

## II. METHODOLOGY

To answer the research questions, the results will be presented into 3 categories based on the relevant research question. The sequence of questions will offer clarity and understanding for the next question in order.

- In sub-research Q1, health requirements and effects will be discussed based on literature and statistics from WHO. Residential requirements will be explored through regulations from the Dutch Government, and guidelines from the WHO will be discovered to obtain a cohesive understanding of what the requirements of an acoustic skin entail. Q1 will be discussed in part 3.1
- In sub-research Q2, Information about the acoustic potential of vegetation- and natural materials will be researched using relevant literature. Specific criteria for both types of material will be determined to reveal their most relevant qualities next to their acoustic performance. Q2 will be discussed in part 3.2
- In sub-research Q3: To illustrate the state-of-the-art, case studies will be analysed, described and supported through literature. The case studies are categorized in the aspects of urban form, geometrical shape, vegetation- and natural materials. The extent of noise reduction achieved by the application of acoustic solutions will further be described to get an overview of the quality and adequacy of the solution. Q3 will be discussed in part 3.3.

# III. RESULTS

## 3.1 Acoustic requirements for health stimulation

### 3.1.1 Health risk

Noise pollution in the living environment can result in health risks when sound exposure isn't addressed. The difficulty of this problem lies in the dynamic of sound and the complexity of the human body, which contains many factors. The hearing organ of humans-beings is not equally sensitive to sounds of different frequencies. Consequently, A-weighting was introduced, expressed as dB(A) – a spectral sensitivity factor that is used to rate sound pressure levels(SPL) at different frequencies in a way that is comparable to that of the human hearing organ. (Passchier-Vermeer and Passchier, 2000)
The perception of noisiness and the interference with work, sleep, resting and communication are the main effects of noise. At the extreme side of the spectrum, hearing damage and other physical damages to the human hearing organ can occur. Yet, the probability of annoyance evoked by noise is already seen as hazardous according to WHO because "health is a state of complete physical, mental and social well-being, and not merely the absence of disease or infirmity." (Osada, 1988) With this philosophy, the WHO has recommended the exposure of 85 dB(A) for a maximum of 8 hours, with every increase of 3 dB(A) reducing the time of exposure by half. (World Health Organisation, 2017) This lays the fundaments of the sound regulations of the building industry.

### 3.1.2 Effects on health

Hearing loss occurs when the organ of Corti is damaged, which occurs when it is overstimulated by noise. The direct and specific effects of noise are noise-induced hearing loss, perceived nosiness and masking of signal sounds, as these types of noise effects are not induced by stimuli other than noise. (Osada, 1988) Different areas of the cerebral cortex get activated by the reception of noise. The limbic cortex, a direct noise effect causes emotional responses, for instance, irritation and discomfort. Physiological effects, which are indirect noise effects, are represented in cardiovascular, gastrointestinal and metabolic functions of the human body. Indirect noise effects can also be stimulated through the same mechanism by other triggers from the environment, for instance, high or low temperatures, intense light, vibrations and unpleasant odours. (Osada, 1988) The presence of these triggers can be heavily influenced by the design of a living environment when considered accordingly. These effects are illustrated in fig. 5 in the appendix.

### 3.1.3 Factors influencing the effects on health

There are many factors that influence the effects of sound on the health of human beings. The difficulty of this problem lies in the dynamic of sound and the complexity of the human body. The wide spectrum of the parameters makes the measurement of sound specific very contextual and specific. There are noise factors and human factors that heavily correlate with each other that result in a certain effect on the health of a human being. (Osada, 1988) These parameters (see table 3 in the appendix) need to be clear in order to propose an adequate solution to noise exposure.

### 3.1.4 Guidelines by WHO

The WHO published 'Environmental Noise Guidelines for the European region' in 2018. The statistics of this guidebook can function as the foundation for an acoustic design in noise polluted living environments. Noise limits in road traffic, railway and leisure noise will be exemplified. To clarify, all the noise limits that are expanded upon by WHO are related to the effects on the health of human beings. The research was done by WHO to reevaluate their previous guidelines to justify a modification in their recommendations. The guidelines are illustrated in appendix p.3.

### 3.1.5 Residential requirements

To create an acoustic design that solves potential health issues in noise polluted living environments, it is required to determine the recommended noise exposure for residents of housing. People of this day and age are spending 86.9% of their time indoors, with 68,7% being in residence. (Tristan Roberts, 2016) Outdoor noise exposure will influence the liveability and health of the residents, and thus requires limits to safeguard the well-being of the residents. Residents possibly experience traffic noise, construction noise, installation noise, leisure noise, alarm noise and animal noise from the outdoor environment. Traffic noise usually consists of low-frequency sounds (around 700 - 1300 Hz), which can trigger an annoyance response in the psyche of human beings. To address health issues induced by noise, the low-frequency sounds produced by traffic need to be reflected or absorbed appropriately. Regulations from the Dutch 'Bouwbesluit 2012' and NEN 5077 were used to elaborate on the cohesive relation between outdoor noise pollution and the residence area of a building. Moreover, the maximum permitted noise exposure of the outdoor noise sources needs to be clarified in order to determine the acoustic requirement of a noise barrier. The **maximum** noise exposure for road traffic is **65 dB(A)** and railway traffic is **70 dB(A)** in the Netherlands. In addition to that, the **preferred** noise exposure in the Netherlands is **50 dB(A)** for road traffic and **55 dB(A)** for railway traffic. The **maximum** indoor values of noise exposure are between **36 dB(A)** and **41 dB(A)**, depending on the year of construction of the roads. (Wet milieubeheer, 2019) These values are determined to regulate vehicle speed in the living environment and the acoustic performance of the required noise barrier.

For starters, the **minimum** requirement of an external noise barrier in relation to residential areas is **20 dB(A)**. This value is convenient when exceptions need to be made while considering the acoustic skin of a residential building.

The **minimum requirement** of an external noise barrier in relation to residential areas next to the road or railway traffic is the difference between the maximum permitted noise exposure of the sound sources, which is equal to 33 dB(A). This results in a minimum requirement of a **37 dB(A)** noise barrier for residential areas.

The **minimum requirement** of an external noise barrier in relation to bedroom areas is 5 dB(A) higher than the initial minimum requirement of noise exposure related to other residential areas. This results in the minimum requirement of a **42 dB(A)** noise barrier for bedroom areas.

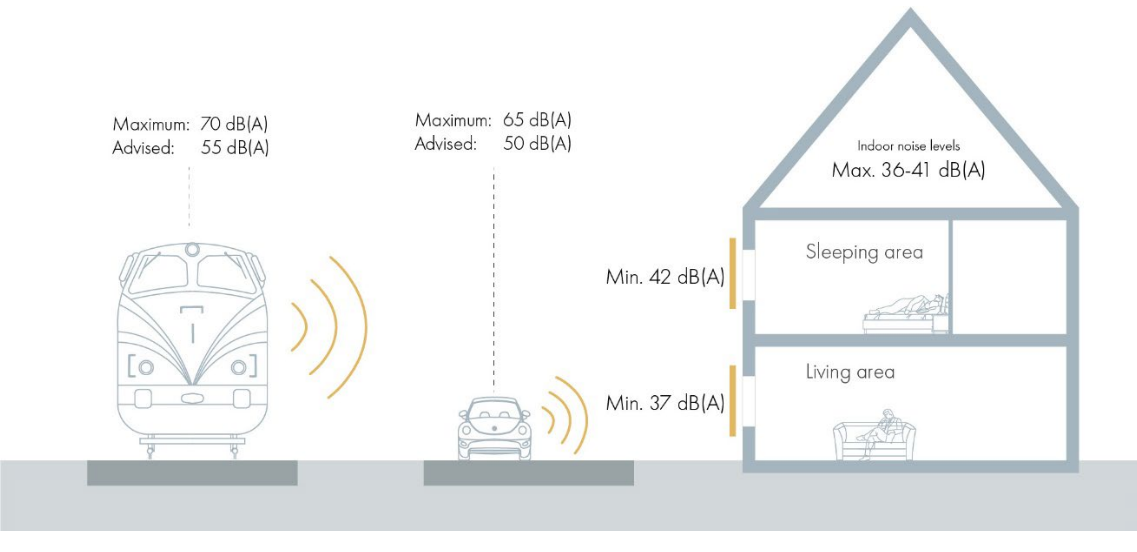


*Fig 1: Residential noise requirements in the Netherlands (own image)*

## 3.2 Acoustic performance of vegetation- and natural materials

### 3.2.1 The acoustic performance of vegetation

Vegetation has been getting more attention in contemporary architecture as it holds many benefits to provide in the building industry. For instance, certain plants can offer an additional amount of oxygen, lower stress levels, function as an air filter and stimulate biophilia. Visual interaction with vegetation can increase human productivity up to 15%. (Andy Williams, 2018) Next to its health benefits, vegetation also stimulates biodiversity, improves thermal comfort and diminishes the urban heat island effect.

Even though vegetation doesn't offer a big contribution as an acoustic barrier by itself, the application of vegetation can improve the acoustic performance of acoustic living wall systems (LWS). LWSs have the capability to function as an acoustic barrier due to their sound absorption values in either soil or hydroponic substrate. (Bakker, 2021) The acoustic performance of plants in the LWS is influenced by their density, leaf area density, leaf orientation and permeability. Certain plants with large leaf area densities can improve the substrate's sound absorption coefficient (SBC) by more than 50%. (Horoshenkov, Khan and Benkreira, 2013) The flexibility of the LWS offers the application of adequate planting depending on the season or wall orientation. The LWS will be elaborated in a more thorough manner through a case study in appendix p.17. In this subchapter, the type of plants that can improve the acoustic performance of the LWS substrate is described in table 1.

In the research of (Bakker, 2021), various plants were measured for their acoustic potential, of which 7 plants received a high score. These 7 plants (see appendix p.4) will further be measured through criteria in table 1. These criteria will reveal their quality and capability to improve the acoustic performance of a LWS throughout the year. Only specific types of plants fit the modularity of the LWS, in which plants should be less compact than 50 cm or be able to take regular pruning. (Gardenersworld, 2019)

Table 1
Vegetation that contributes to the acoustic performance of LWS

| Plant | Sun exposure | Evergreen | Maintenance | Hardiness zones |
|---|---|---|---|---|
| Bergenia | Part shade / Full sun | Yes | Low | 10-11 |
| Hosta | Partial | No | Average | 3-9 |
| Heuchera | Partial | Yes | Low | 4-8 |
| Primula | Part to full shade | Semi | Average | 2-8 |
| Begonia | Part shade / Full sun | Yes | Average | 10-11 |
| Philodendron | Shade | Yes | Low | 9-11 |
| Viola sororia | Part shade – Full sun | No | Average | 3-8 |

*Fig 2: Vegetation that contributes to the acoustic performance of LWS*

### 3.2.2 The acoustic performance of natural materials

As we strive to create a more sustainable living environment, natural materials have been the priority for designers and developers as building materials. To clarify, natural materials are physical matter that is found in nature, with little to no human intervention to make it directly usable. (Designingbuildings, 2021) Natural materials usually have a good sustainability value compared to traditional materials, hence the adjustment in the design interests of the building industry. Energy consumption and CO2 emissions during transport can also be reduced by locally extracting raw materials, which is less likely with man-made materials. Nevertheless, a chemical treatment to address a lack of fire, fungal, pest, and moisture resistance of certain natural materials is required to increase their sustainability value. Logically, this depends on the type of material.

Natural materials are one of the first bricks to lay when designing a sustainable, environmentally-friendly and healthy building. One of the important characteristics of natural materials is their density and porosity, which are favourable for the material's absorption coefficient. As a starting point, an effective absorber will have a sound absorption coefficient greater than 0.75. (Demi, 2018) Materials that are high in density and high in porosity will have a higher absorption coefficient than materials that are high in density and low in porosity or low in density and high in porosity. (Tiuc et al., 2014) Furthermore, density is related to temperature and pressure, which makes it context-related. It is therefore essential to know that the found measures can differ from the set parameters. The acoustic performance of natural materials was researched by (Asdrubali, Schiavoni and Horoshenkov, 2012) and will be described in combination with other relevant attributes as criteria. In appendix p.5 and 6, these natural materials are described and expanded upon.

Table 2
Characteristics of natural materials that can contribute to an acoustic design

| **Material** | **Absorption coefficient at 500 Hz** | **Est. embodied energy (MJ/kg)** | **Thermal conductivity (W/m K)** | **Avg. density (g/cm3)** |
|---|---|---|---|---|
| Hemp | 0.21 (3mm) | 15 | 0,04 | 0.86 |
| Kenaf | 0.63 (6mm) | 15 | 0.044 | 0.37 |
| Cork | 0,78 (60mm) | 7,05 | 0.39 | 0.24 |
| Coco fibres | 0.82 (10mm) | 4,90 | 0.42 | 0,67-1.00 |
| Wood fibres | 0.79 (6mm) | 35 | 0.038 | 0.645 |
| Cardboard | 0.47 (11,5mm) | 30 | 0.5 | 0.69 |
| Sheep wool | 0.33 (4mm) | 13 | 0.044 | 0.031 |
| Straw | 0.63 (10mm) | 15 | 0.052 | 0.54 |
| Jute fibre | 0.64 (50mm) | 0,5 | 0.43 | 0.24 |

*Fig 3: Characteristics of natural materials that can contribute to an acoustic design*

## 3.3 Case studies

The state-of-art of acoustic solutions is explored through the analysis of cases studies. Understanding how built projects can (possibly) solve acoustic issues can widen the spectrum of acoustic solutions to implement in the future, depending on the context. The 5 selected case studies (see appendix p.7-19) have an association with either noise polluted environments or potentially contain an environmentally-friendly material with good acoustic properties. The acoustic solutions applied in the case studies are divided into 3 categories: Urban form, geometric shape, and materials. To compare the case studies, the solutions of the case studies are clarified in a more concise and overarching manner down below. Estimation of noise reduction was made for the case study - Het Funen (see appendix p.21.) in order to see if and how the acoustic requirements were met. Noise calculator and diagram tools were used to support the analysis.

*Urban form*

Resulting of the case studies, the urban form of the buildings arise from their location next to the source of the sound, the railway. These buildings act as habitable noise barriers to protect the underlying buildings and neighborhood from noise pollution, thus creating a harmonious living environment. In order for this to function well, the amount of openings in the noise-affected façade needs to be minimized or fixated. Furthermore, having a quiet and visually attractive neighborhood can positively influence the perception of noise, meaning that the occurrence of annoyance will decrease, and thus will stimulate the health of human beings.

*Geometric shape*

Sound is heavily influenced by the geometric shape of its reflector. A façade with a zigzag shape can scatter the sound differently and more evenly than a flat surface because of the angle of incidence, which is affected by the reference point of the sound source. Geometric shapes in façade elements are also a great way to reflect noise from transmitting indoors, as balconies and galleries can function well as noise barriers, especially when the source of noise comes from the ground level. Plasticity in geometric shapes will also cause sound to interact differently with the façade and to be distributed in a more desired fashion. Moreover, the angled ceiling of the gallery or balcony can help reflect the sound away from the façade opening. These phenomena also occur with slanted roofs, which can help protect vulnerable spaces like courtyards from sound exposure that travels over the building roofs.

*Materials*

Materials have different acoustic properties and qualities from one another that can address different types of sound frequency.

The traditional materials, concrete and glass, are building materials that offer great qualities in the building industry. Their density is what makes them valuable in their acoustic value, as dense materials are great at reflecting sound. These materials are usually less environmentally friendly.

In contrary, natural materials are essentially porous, which makes them less good at reflecting sound, but very good at absorbing sound. These natural materials are environmentally-friendly because of their low embodied energy or renewability. Cork is one of the many natural and environmentally friendly materials and has great sound-absorbing values. The thickness of the noise absorbing materials depend on the frequency of the sound. (See appendix fig.7)

Plants don’t function well on their own to address acoustic issues directly, but living wall systems(LWS) contain a substrate that can have high sound absorption values, for instance mineral wool. Plants can contribute to the absorption values of porous substrates in LWS’ by up to 50%, depending on the type of plant.

Noise polluted environments usually contain low-frequency sounds, which are harder to absorb than high-frequency sounds. With that being said, the quality of absorption only goes as far as its suitable level of sound frequency, as the material wouldn’t be efficient when addressing a frequency that isn’t suitable.

## IV. CONCLUSION

After examining how sound and health are related to each other, a set of issues were identified that can be solved through architectural design. As both sound and health are essentially complex and multifaceted, multiple perspectives and a clear strategy are required to address noise polluted environments. To answer the research question *"How can geometric shapes, the urban form, and the use of vegetation- and natural materials contribute to the acoustic performance of buildings in noise polluted living environments, and thereby stimulate the health of its users?"*, an understanding of which factors of sound and health play a role and what characteristics of materials are relevant to this issue, is of importance. Sub-questions were answered to dissect the research question into manageable and clear parts.

The perception of noisiness and the interference with work, sleep, resting and communication are the main effects of noise. The level of interference or damage is related to the many factors, of which sound and health consist of. The perception of noise can either decrease or increase the effects of the same level of decibel. Yet, physical damage to the organ of Corti will occur regardless at a certain level of decibel. The sound exposure recommendation by WHO accommodates this body of knowledge to regulate the amount of noise pollution in society, leading to the determination of allowing 85 dB(A) for a maximum of 8 hours as the norm for human beings. These norms are further integrated into the residential building requirements that are composed by governments. Traffic noise contains low-frequency sounds and evokes more annoyance in human beings than high-frequency sounds. To create a more healthy living environment, these low-frequency sounds need to be addressed. In the Netherlands, the minimum requirements of external noise barriers depend on the maximum traffic noise exposure that is allowed, and this calculation will determine what the acoustic performance of the building façade has to be. In most cases, an acoustic performance of at least 32 dB(A) is required.

The potential acoustic value of vegetation- and natural materials were analysed and described in this paper. Firstly, the contribution of vegetation is rather disappointing when it comes to a direct influence, but plants with the characteristics of high leaf density, permeability, density and leaf orientation can stimulate the absorption value of the substrates of living wall systems by up to 50%. The acoustic quality of plants are thus expressed through these phenomena, and the analysis has resulted in a selection of plants that could all be suitable to an acoustic design depending on the context and orientation. Secondly, natural materials possess good sound absorption qualities when they have a high density and open pores. A good absorption coefficient is deemed at 0.75, but the most natural materials only reach that level at 500 Hz with additional thickness, which is important to address traffic noise. These natural materials have different levels of embodied energy that could act as a factor when designing an acoustic façade.

The case studies reveal how noise polluted environments can be solved and how vegetational and natural materials can be applied. Noise polluted environments are solved on the urban scale by creating a habitable noise barrier that protects the underlying neighborhood. The living and sleeping areas in the floor plan of the noise polluted building can be orientated away from the sound source. On building façade scale, angled geometric shapes in combination with plasticity towards the sound source and noise reflecting and absorbing materials contribute greatly to a pleasant indoor soundscape. Lastly, on the material scale, very dense materials like concrete and glass are used to reflect noise away from indoors. This is useful for low-frequency sounds because they are more difficult to absorb due to the amount of energy they contain. However, the absorption of sound can create a more pleasant soundscape through the use of natural materials and the help of specific vegetation on living wall systems.

In conclusion, this paper is intended to be part of a development towards a holistic design strategy that utilizes the potential of an eco-friendly acoustic design. To further develop this, an analysis of the context has to be done in combination with sound measurements. More specific research can result in a better determination of what type of acoustic solution is required for each project. The acoustic solutions in this research could be supported with noise reduction measurements to get a better view of how effective the solutions are.

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## REFERECES

### ILLUSTRATIONS

# Appendix


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**Date:**
17-01-2022

# Tables, graphics and illustrations

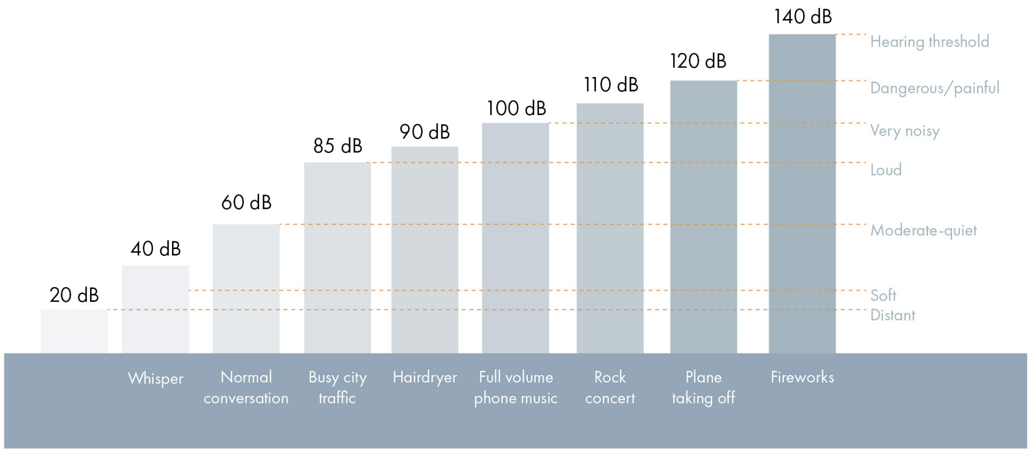



*Fig 4. Hearing threshold (Sadler, 2020)*

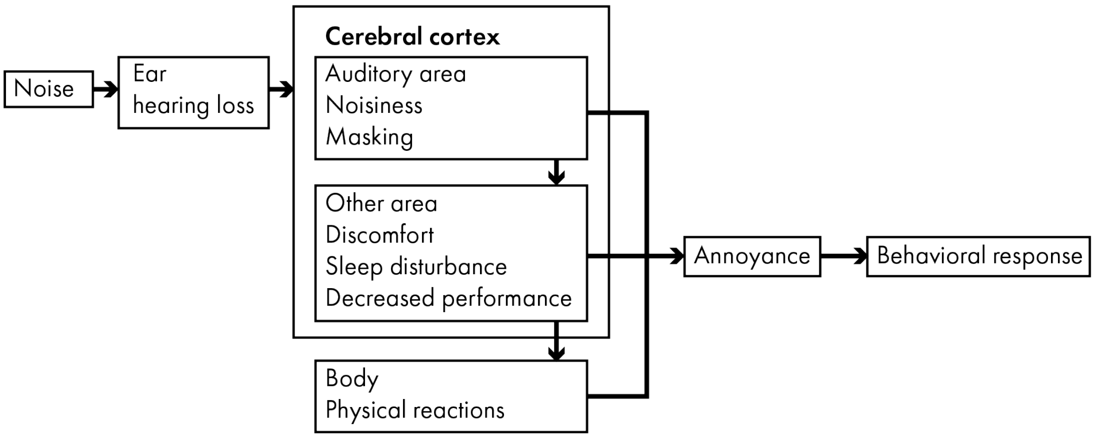



*Fig 5. Hearing threshold (Osada, 1988)*

Table 3
Relevant factors in health effects of noise (Osada, 1988)

| Noise factors | | Human factors | | Health effects |
|---|---|---|---|---|
| Noise level | | Sex | | Direct effects |
| Frequency spectrum | | Age | | Sensation |
| Flunctation of level | | Health state | | Masking |
| Impulsiveness | | Occupation | | Hearing loss |
| Intermittency | | Personality | | Indirect effects |
| Time of occurrence | x | History of exposure | = | Emotional effects |
| Duration | | Attitude | | Sleep disturbance |
| Direction | | Situation | | Decreased performance |
| Distance from source | | Work, study | | Physiological reaction |
| etc. | | Relaxation | | Integrated effects |
| | | Sleep | | Annoyance |
| | | etc. | | Behavioral reaction |

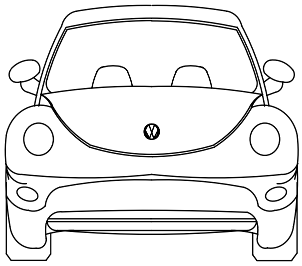
*Fig 6.* Relevant factors in health effects of noise (Osada, 1988)

## Road traffic

For average noise exposure, the GDG strongly recommends reducing noise levels produced by road traffic below **53 dB** Lden, as road traffic noise above this level is associated with adverse health effects.

For night noise exposure, the GDG strongly recommends reducing noise levels produced by road traffic during night time below **45 dB** Lnight, as road traffic noise above this level is associated with adverse effects on sleep.

53 dB day 45 dB night

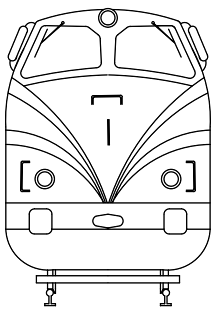


## Railway traffic

For average noise exposure, the GDG strongly recommends reducing noise levels produced by railway traffic below **54 dB** Lden, as railway noise above this level is associated with adverse health effects.

For night noise exposure, the GDG strongly recommends reducing noise levels produced by railway traffic during night time below **44 dB** Lnight, as railway noise above this level is associated with adverse effects on sleep.

54 dB day 44 dB night



## Leisure

For average noise exposure, the GDG conditionally recommends reducing the yearly average from all leisure noise sources combined to **70 dB** LAeq,24h, as leisure noise above this level is associated with adverse health effects. The equal energy principle 19 can be used to derive exposure limits for other time averages, which might be more practical in regulatory processes. associated with adverse effects on sleep.

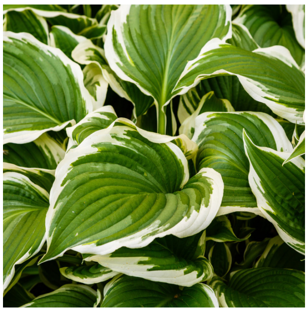
70 dB average

*Source: (World Health Organisation, 2018)*

*Philodendron*

*Viola Sororia*

*Bergenia*



*Hosta*

*Heuchera*

*Primula*

*Begonia*

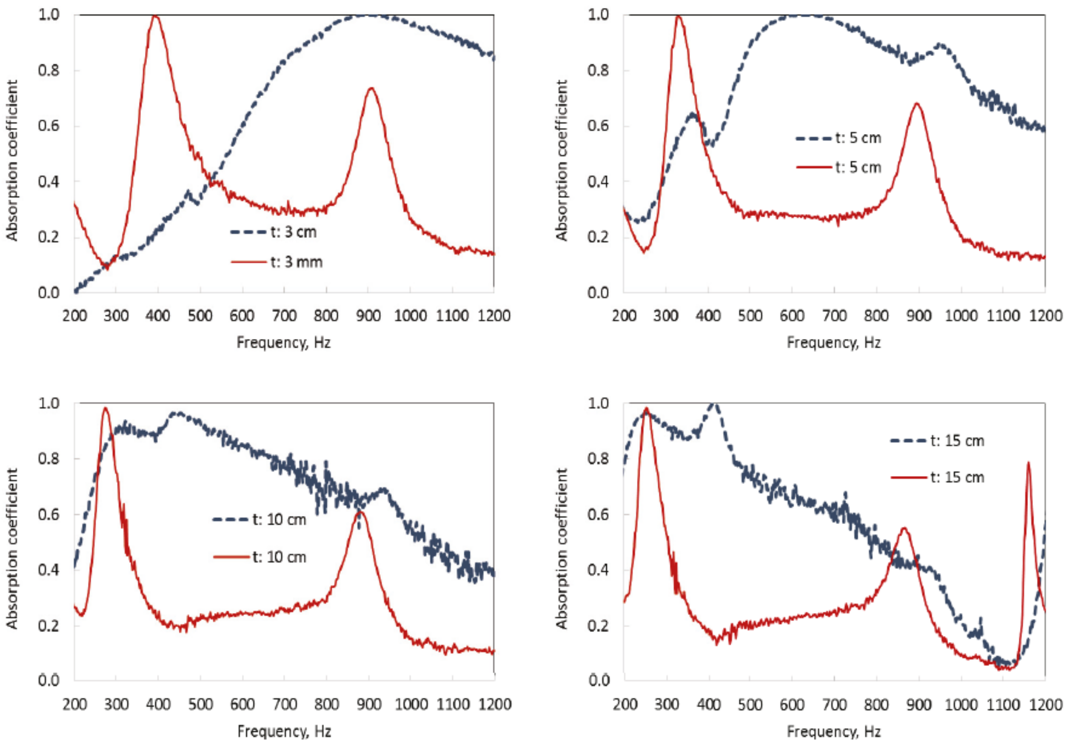



*Fig 7. Dissimilarity in absorption performance of perpetual thickness of cork depending on the frequency of sound (Amelia Trematerra, 2017)*

*Hemp*

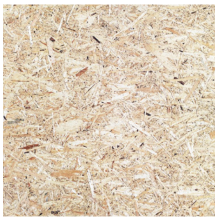
Hemp is a natural plant fiber under the category of bast fibers, which means the fibers comes from the stem of a plant. Hemp is seen as a sustainable fiber with less harmful environmental impact. It is renewable, doesn't require chemical pesticides, requires little water, and can be beneficial to the environment to extract pollutants from the soil. (cfda, n.d.)

*Cork*

Cork is a cellular material that is configurated as a honeycomb design of air-sealed cells. Cork is made of the bark of cork oak. Cork oak trees don't have to be cut down to make cork, which results in an environmentally friendly industry. Next to the fact that cork has good acoustic qualities, it is also a natural fire retardant. (bettersoundproofing, 2019)

*Sheep wool*

Sheep wool is a renewable material as it is a by-product of the livestock farming process. With its low embodied energy and GHG emission, it is considered to have a low environmental impact. It has a similar performance to that of standard insulation, but a big difference is that it isn't a health hazard during application. (Asachi, 2018)


Wood fibers

Wood is a renewable material that stores $CO_2$ during tree growth, which makes it a sustainable and environmentally friendly material. Wood fibre is also a porous or breathable material. That contributes to the absorption qualities and moisture regulation qualities of the material. Unfortunately, wood fibre is usually imported from other countries, which increases its embodied energy value.


Jute

Jute fibres are made from the bark of the Corchorus capsularis. 90% of all jute comes from Bangladesh. It is a very environmentally friendly material due to it being a renewable source, its lack of pesticides and its cost-to-outcome ratio. (recycledmats, 2018) Jute can be used as wall insulation for its thermal and acoustic qualities, while also being user-friendly in terms of hazardousness.


Kenaf

Kenaf fibers are made from the Kenaf plants that belong to Malvaceae family. The use of kenaf fibers is generally in panels that act as an insulator with both thermal and acoustic qualities. This material is environmentally friendly due to it being renewable, improving the qualities of the soil when planted and being 100% recyclable. (homexyou, n.d.)


Cardboard

Cardboard is made from pine tree pulp, like paper. These trees grow quickly, which makes the material renewable and also recyclable. But due to the additives, fillers, coatings, etc. to become usable, which makes it less recyclable. The material also is highly energy-intensive compared to the other described natural materials. However, the material can be of use due to its insulation qualities. (Latka, 2017)


Straw bale

Straw bale is a sustainable material that is renewable. The use of the materials dates back to 1700, as its great acoustic and thermal insulation qualities were already recognized. The material was also used during those early periods because it was user-friendly for novice builders. (Johnson, 2017)


Coco fibers

Coco fiber, or Coir, is a by-product of the production of coconuts and is known for its insulating qualities. A big portion of the coir producers come from East Asia. It being a by-product means it is an environmentally friendly material that is renewable or dependent on the production of coconuts. The fibers act as an insulating material for the coconut kernel, these qualities translate into the insulation quality in contains as a building material. (Kürsten, 2015)

# Case studies

The design solutions of noise polluted areas are analyzed through case studies. The listed projects are categorized in three different typologies of acoustic design. The projects are either located next to a noise polluted area or contain the potential to address noise polluted areas.

**U - Urban Form**
**G - Geometric shape**
**M - Materialization**

**Projects:**

*Het Funen - Amsterdam | Netherlands | U M G

Pauline symfonie - Rijswijk | Netherlands | U M G

272 Spoorwijk - The Hague | Netherlands | U M G

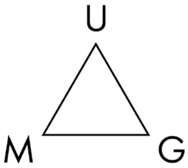
Cork Screw House - Berlin | Germany | M

Radiotherapiegroep - Apeldoorn | Netherlands | M

*The noise reduction of the acoustic interventions of Het Funen will be analyzed and estimated through calculation.

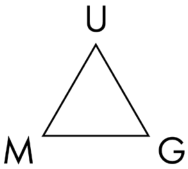
## Case studies - overview

Het Funen
Frits van Dongen, 2011



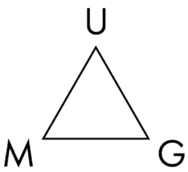

| Positives | Negatives |
| --- | --- |
| + Noise barrier for whole neighborhood<br>+ Lowers noise costs for area<br>+ Low frequency sounds get reflected | - Noise gets reflected, near railway can be very loud<br>- Glass is not environentally friendly<br>- Rooms contain small window openings |

Pauline Symfonie
Van Dop + Mathot architecten, 2011



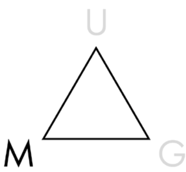

| Positives | Negatives |
| --- | --- |
| + Noise barrier for whole neighborhood<br>+ Low frequency sounds get reflected & absorbed through gallery configuration<br>+ Living & sleeping areas dis-tanced from noise source | - Noise gets reflected, near railway can be very loud<br>- Glass & concrete are not environentally friendly |

272 Spoorwijk
Bureau MASSA, 2011



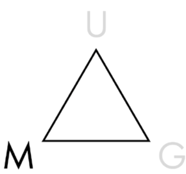

| Positives | Negatives |
| --- | --- |
| + Noise barrier for whole neighborhood<br>+ Low frequency sounds get reflected by dense balconies & facade plasticity<br>+ Remaining noise gets absor-bed by wood panels of loggia | - Living areas are placed near noise source<br>- Noise gets reflected, near railway can be very loud |

Cork Screw House
Rundzwei Architekten, 2018



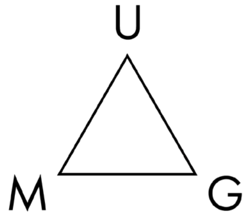

| Positives | Negatives |
| --- | --- |
| + Cork has good absorption qualities<br>+ Cork is a environmental-ly-friendly material | - Cork is has bad noise reflec-ting qualities<br>- Cork might possibly have a tough time absorbing low frequency sounds |

Radiotherapiegroep Apeldoorn
Bureau Berndsen, 2020




| Positives | Negatives |
| --- | --- |
| + Vegetation contributes well to human health, the environ-ment and biodiversity<br>+ Vegetation can stimulate the absorption qualities of living wall systems(LWS), which are great sound absorbers. | - Vegetation doesn't have good acoustic qualities to address noise on its own<br>- Maintenance, orientati-on, and plant selection are important to benefit from the stimulation of absorption |

# Het Funen




### Details

Architect: Frits van Dongen and de Architecten Cie
City: Amsterdam, The Netherlands
Program: Residential housing
Built in: 2011

*Fig 8. Het Funen (Cie, n.d.)*

## Urban form

Het Funen' is a neighborhood located in the East of Amsterdam Centrum. The concept was to create a park next to the railway that consists of housing, with the ambition to give residents the feeling of living in a park. By creating an acoustic barrier orientated towards the railway, the underlying housing in the park will be liberated from noise issues, creating a harmonious atmosphere in the park. In order to give a healthy living environment to the residents that live in the L-shaped building (Sporenboog), a noise-reducing- and reflecting façade with a geometrical shape was designed, parallel to the railway.

*Fig 9. Het Funen top view (Own image)*

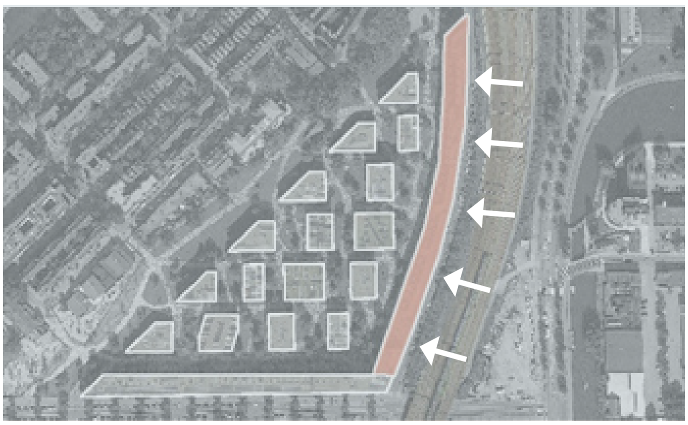


*Fig 10. Het Funen noise barrier (Own image)*

## Geometric shape

The angled zigzag shape of the outer skin from 'Het Funen' is designed to reflect the sound of the railway parallel to the building. One of the methods of solving the noise issue of the environment is using a zigzag surface instead of a flat surface. This method is used frequently in combination with a sound-reflecting material. (Krimm, 2018) To improve the sound distribution of this method, varied dimensions of zigzag surfaces could be integrated into the acoustic façade. In this case, the acoustic façade of 'Het Funen' consists of the duplication of only one module shape. According to (Ragni, Avallone and van der Velden, 2017), a zigzag geometric shape can reduce noise by 6 dB.

*Fig 11. Het Funen facade (Herout, 2020)*

## Materialization

The façade is made from laminated glass for its acoustic qualities. Glass has a high density (2,4-2,8 kg/m3)(engineeringtoolbox, n.d.), and this characteristic of the material makes it a great sound reflector compared to other commonly used building materials. In comparison, concrete has a density of 2,0-2,4 kg/m3 (engineeringtoolbox, n.d.), while concrete is widely known for having mass, and thus great sound-reflecting ability. In this case, the thicker the glass the better the acoustic performance, which is why laminated glass is an adequate material to solve noise issues. laminated glass consists of polyvinyl butyral(PVB) between the two panes of glass. PVB damps the sound waves, reduces the transmission of UV-rays and keeps the window intact during impact. (Leeglass, 2016)Laminated glass has a sound transmission coefficient(STC) of 40, which means it will reduce noise by 40 dB. (MORN, 2019) Furthermore, an alternative to laminated glass is double or triple glazed glass. These systems function with spacing filled with argon or vacuum between the pane of glass. (Guardian Glass, n.d.)In spite of the necessity to have wall openings for daylight, glass is not an environmentally friendly material due to embodied energy it contains and should be considered holistically during the design phase.

*Fig 12. Het Funen facade indoors (vanceva, n.d.)*

*Fig 13. Het Funen facade (Schlijper, 2018)*

# Paulinesymfonie

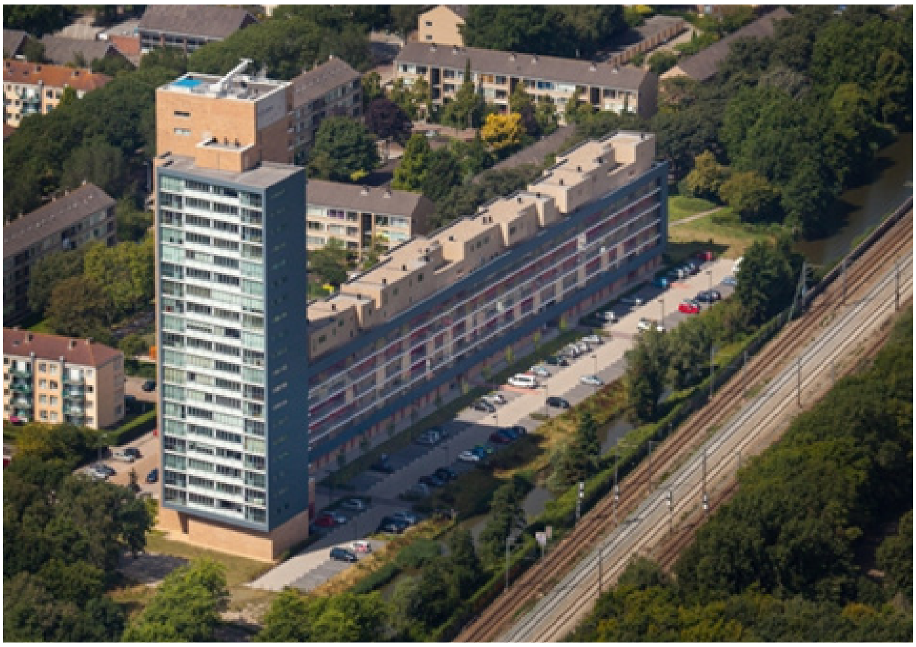
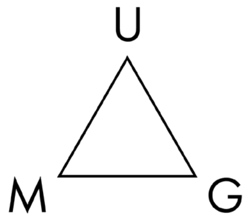


Fig 14. Paulinesymfonie (vdmarchitecten, n.d.)




### Details

Architect: Van Dop + Mathot architecten
City: Rijswijk, The Netherlands
Program: Residential housing
Built in: 2011

## Urban form

Paulinesymfonie consists of two parts. 'Het Lint'(8 floors tall), which is the horizontal part of the building, and 'De Toren'(24 floors tall), which is the vertical part of the building, functioning as a landmark and the beginning of Rijswijk. The building is situated 55 meters from the railway connection between Delft and The Hague, and approx. 100 meters from the A4 highway. Due to a large amount of noise pollution, respectively 75 dB from the railway traffic and 65 dB highway traffic (Bogaerts, 2016), the design of the building is heavily influenced by the context of noise pollution. Besides the building functioning as a noise barrier, resulting in saving costs of solving acoustic issues of the underlying neighborhood, acoustic measures were required in the façade and floorplan of the building for the residents to live in an adequate living environment. (Bogaerts, 2016)

Fig 15. Paulinesymfonie top view (Own image)

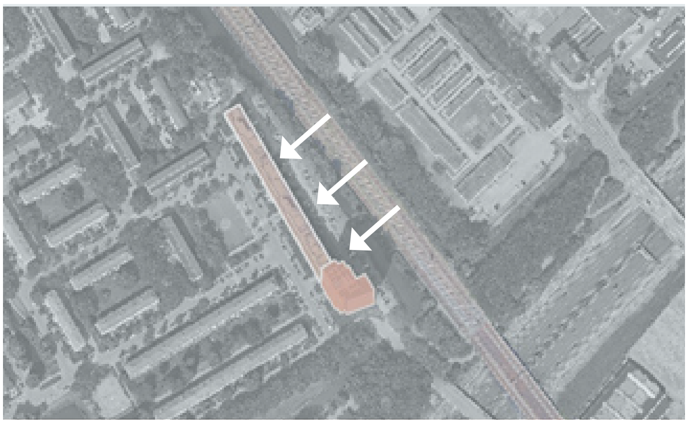


Fig 16. Paulinesymfonie noise barrier (Own image)

The floorplan of 'Het Lint' was influenced by the acoustic measures that were implemented in the noise-affected façade of the building. The kitchen, sanitary spaces, fuse box and entrance hall were placed nearest to the source of noise, and the residential rooms (bed- and living rooms) were placed away from the noise-affected façade. The spaces that are utilized the most throughout the day will be affected the least by a disturbing amount of sound, and thus will lead to a healthier living environment for the residents.

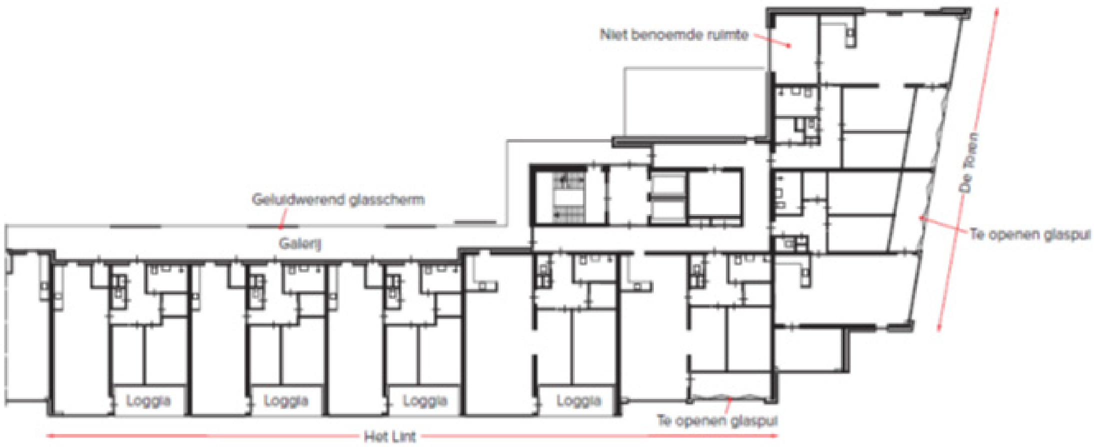



*Fig 17. Paulinesymfonie floor plan (Bogaerts, 2016)*

## Materialization

The gallery is made from concrete, which is a good material for reflecting sound due to its density. Having concrete as sound reflecting material outdoors is more beneficial than using concrete indoors, in terms of acoustics. Outdoor sound is usually traffic and having reflective materials results in the noise returning into traffic. Having reflective materials indoors will lead to echoes if there is a lack of objects that diffuse or absorb sound. This can be perceived as annoying if the residents find themselves in that same space.
Furthermore, the glass panels in front of the entrances were chosen because of the good acoustic qualities of glass. An adequate thickness of the glass was calculated to conform to acoustic requirements for the noise exposure of the environment. Also, the ceilings and walls of the galleries are plated with a sound-absorbing material. These plates help with the interception of sound that isn't reflected by the gallery's geometry. Moreover, the noise polluted side of 'De Toren' was solved differently, all the housing have a loggia that is closed off by openable folding windows of glass. (Bogaerts, 2016)

*Fig 18. Paulinesymfonie facade (VMG, n.d.)*

## Geometric shape

In order to address the noise pollution of the rail- and highway, galleries orientated towards the source of sound were implemented at 'Het Lint'. According to research, geometrically optimized façades with absorbing materials can achieve a great reduction in noise. (Busa, Secchi and Baldini, 2010) Additionally, projection depths of balconies and inclined parapets also contribute to the reduction in noise, depending on the contextual parameters. (Lee et al., 2007) Balconies and galleries can function as noise diffusers, because of their geometry, density and the shortening of distance towards the sound of noise.

The façade of 'Het Lint' is configurated with this exact philosophy. It is essential to minimalize the number of openings in the façade to keep a pleasant indoor climate in terms of sound. The noise-affected façade has non-openable windows but contains entrance doors that are opened regularly. To stay true to the requirements of an effective acoustic façade, glass panels were placed as a ceiling-high parapet of the gallery in front of the entrance doors of the housing.

*Fig 19. Paulinesymfonie gallery (bouwwereld, 2012)*

*Fig 20. Paulinesymfonie facade (smoutbouwmanagement, n.d.)*

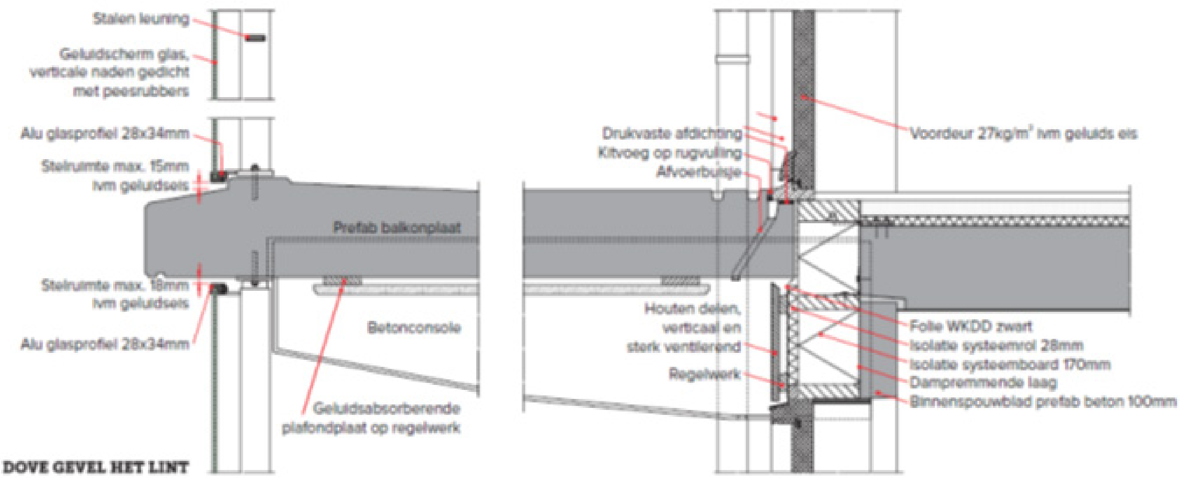
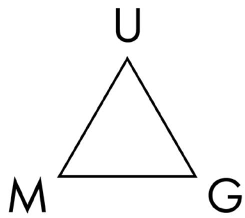



*Fig 21. Paulinesymfonie technical drawing (Bogaerts, 2016)*

# 272 Spoorwijk

Fig 22. 272 Spoorwijk (dearchitect, 2010)




## Details

Architect: Bureau MASSA
City: The Hague, The Netherlands
Program: Residential housing
Built in: 2011

## Urban form

Spoorwijk 272 in The Hague, is a neighborhood that is located next to a railway that produces noise pollution for its environment. This project addresses the noise issues through its urban form by creating urban courtyards. Each courtyard has a side towards the railway that is equipped to function as a noise barrier for the underlying sides and buildings. These courtyards need to be designed accordingly because low-frequency sound (traffic noise) resonates well in courtyards. (Taghipour, Sievers and Eggenschwiler, 2019)
According to (Gidlöf-Gunnarsson and Öhrström, 2010), a 'quiet and visually attractive' courtyard can contribute to the improvement of the wellbeing of humans. It was stated that minimizing the number of openings in the noise-affected side will protect the courtyard from noise. Interestingly, it was further stated that creating an aesthetically pleasing environment with 'high-quality' greenery makes residents less annoyed by the traffic noise, and thus a reduction in the stimulation of health issues. High-quality greenery can attract birds that can contribute to a positively perceived soundscape.

Fig 23. 272 Spoorwijk top view (Own image)

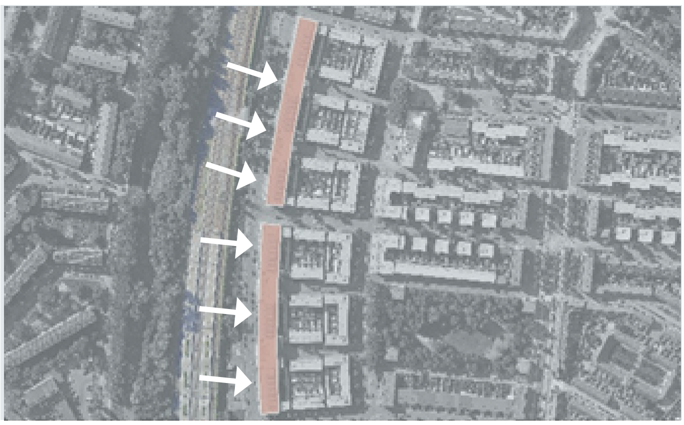


Fig 24. 272 Spoorwijk noise barrier (Own image)

## Geometric shape

The floorplan of the building is oriented towards the railway. The living area is connected with a loggia and balcony so that residents could experience the sun from the west. These façade elements form the geometric shape of the noise-affected façade of the buildings, as the plasticity of the façade addresses the noise produced by the railway parallel to the building. The density of the balconies' parapet helps to reflect the sound towards its source, while the depth of the loggia and balcony amalgamation help to distance the living spaces from the traffic noise.
According to (Van Renterghem et al., 2013), using green roofs with a slanted shape on buildings that act as the noise barrier can heavily influence the soundscape of the courtyards. The traffic sound can be absorbed by the soil of the green roof, while the geometric shape of the roof will offer a different angle of incidence and more surface for soil.

## Materialization

Besides the fact that the living areas of the noise-affected buildings are orientated towards the west, the living area is also orientated towards the noise-producing railway. To address this issue, brick and glass were applied as the dense materials that were used to reflect the noise. The glass windows are fixated and not openable, in order to retain the noise protection capabilities of the façade. Additionally, the entrance doors of the buildings were placed as a side entrance in the niche on the ground level. These niches consist of slats with absorbing material behind them.

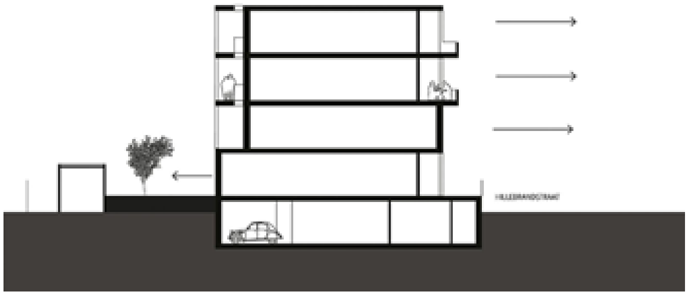


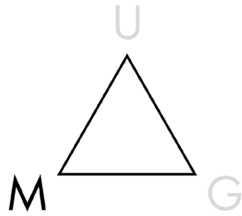
*Fig 25. 272 Spoorwijk section (bureaumassa, n.d.)*

*Fig 26. 272 Spoorwijk facade (bureaumassa, n.d.)*

*Fig 27. 272 Spoorwijk dense balconies (bureaumassa, n.d.)*

# Cork Screw House

Fig 28. Cork Screw House (Archdaily, 2018)




### Details

Architect: Rundzwei Architekten
City: Berlin, Germany
Program: Housing
Built in: 2018

## Materialization

Natural cork was used in this project because of its high insulation values that contribute to the energy efficiency and the sustainability of the building. The client of this project had an interest in living in a building with a good acoustic performance, which led to the discovery of cork as a possible acoustic material. (ArchDaily, 2018) As (bettersoundproofing, 2019) states, cork is a cellular material and is more than 50% air, which makes it a good sound absorber. The noise reduction coefficient(NRC) of cork is 0,7, which means it absorbs 70% and reflects 30% of sound. Cork is a buoyant, impermeable, cellular material. It is made up of a honeycomb design of air-sealed cells made of the bark of the cork oak. According to (Trematerra, Lombardi and D'Alesio, 2017), a 1,5mm thick cork has good absorbing qualities at low and medium-frequencies, which is relevant to addressing traffic noise. Whether the cork panels absorb low or high-frequency sounds, is related to the depth of the air cavity behind the cork panels. A decrease in cavity depth will result in the absorption of high-frequency sounds and an increase will result in absorption of low-frequency sounds. Even though a promising noise reduction of 10 dB can be expected with a cork thickness of 3mm and even 23 dB with 6mm, panels between 1-2 mm thickness is a particle size where the sound-absorbing coefficient is optimal in its acoustic consistency. As a starting point, an effective absorber will have a sound absorption coefficient greater than 0.75. (Demi, 2018) In this case, 1,5 mm cork panels mounted with a back cavity of 15 cm have an absorption coefficient between 0,95 and 1 at a low-frequency of 300 Hz.(Trematerra, Lombardi and D'Alesio, 2017) This reveals that cork panels are an adequate material to absorb traffic noise. That being said, thin cork sheets are susceptible to water damage and puncture damage, which will negatively impact the acoustic performance of the material. Cork Screw House seemingly solved this issue by using 40mm thick cork panels. The thickness of these panels makes the application of the natural cladding more practical and convenient, next to the increased acoustic performance.

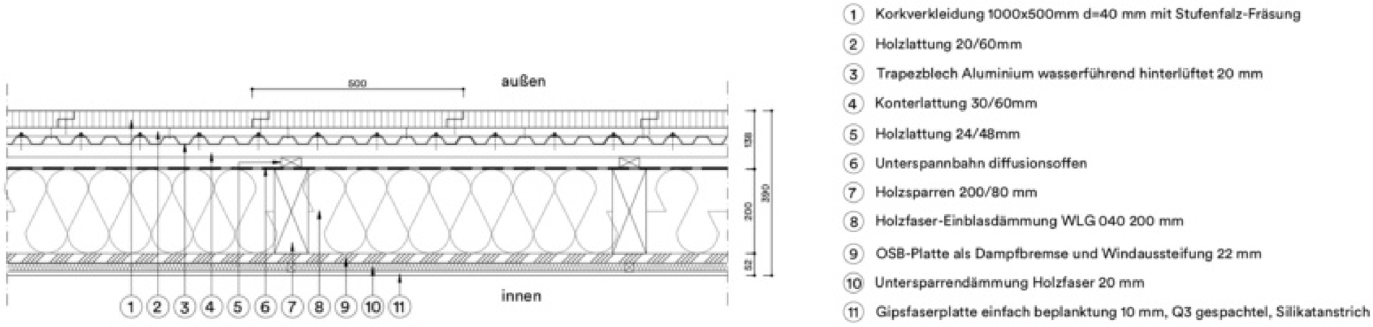



*Fig 29. Cork Screw House - cork wall configuration (Marani, 2019)*

*Fig 30. Possible Gencork cladding shapes to reflect sound (Gencork, n.d.)*

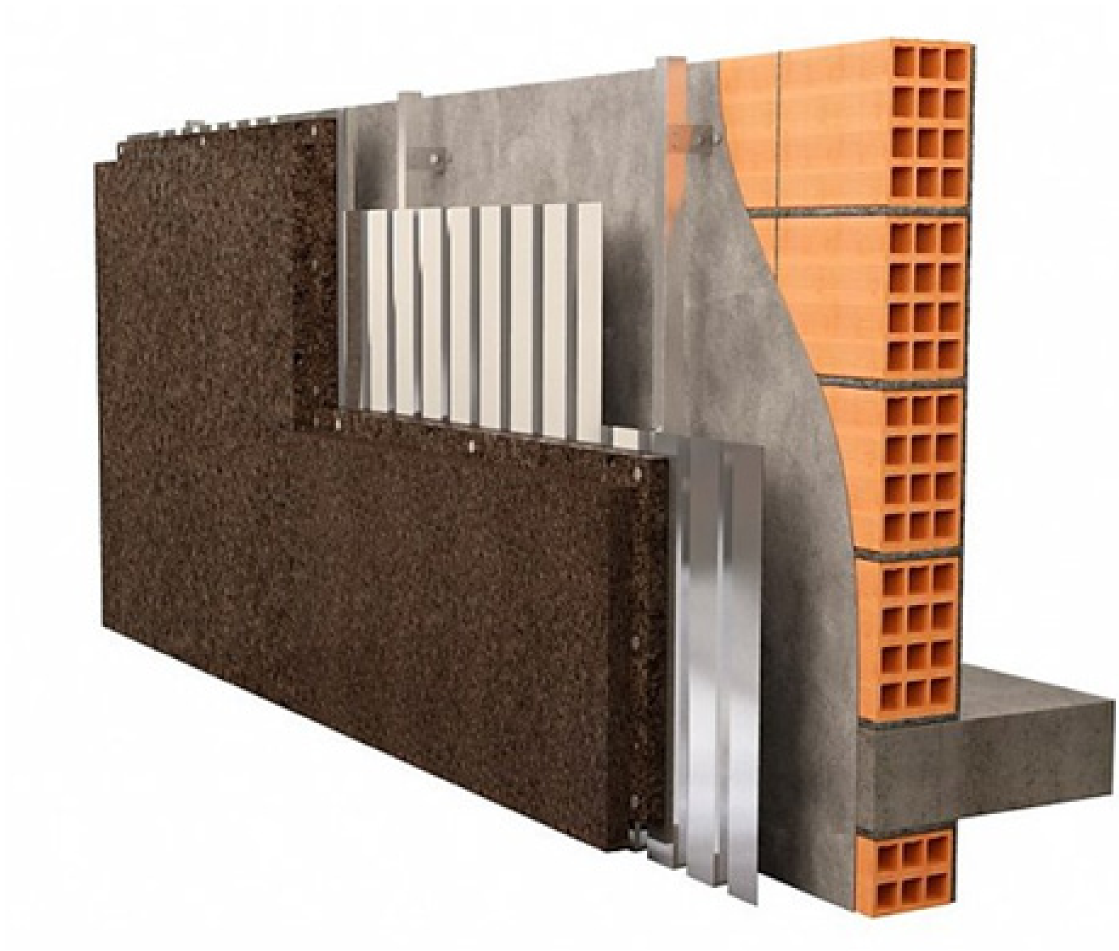
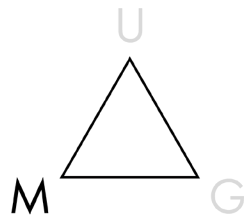


*Fig 31. Possible wall assemply with cork cladding (amorimcorkinsulation, n.d.)*

# Radiotherapiegroep Apeldoorn

*Fig 32. Radiotherapiegroep Apeldoorn (bureauberndsen, n.d.)*




## Details

Architect: Bureau Berndsen
City: Apeldoorn, The Netherlands
Program: Medical center
Built in: 2020

## Materialization

The Radiotherapy building located in Apeldoorn is designed with the philosophy of ‘Healing Environment’, which led to their decision to implement green walls in this project.(architectenweb, 2021) SemperGreen Outdoor is a living wall system (LWS) that was applied to this building. A LWS contributes to the stimulation of society’s urban health, biodiversity and many other benefits for human beings. (Bakker, 2021) Initially, a LWS doesn’t offer interesting acoustic properties, because most vegetation has a low contribution to an acoustic skin. Yet, the porous substrate of the LWS can act as an absorbing material. A substrate is usually made from soil, but hydroponic rock wool separates itself as a substrate by having good sound absorption values. An ‘Acoustic LWS’ has an absorption coefficient of 0,98 with 500 Hz, which is very promising for low-frequency sounds. The scattering coefficient is a department where the Acoustic LWS doesn’t excel in, namely 0,4 with 500 Hz compared to concrete’s 0,1 and glass’ 0,05 with 500 Hz. (Bakker, 2021) Even though vegetation doesn’t have the capacity to distinctively perform well acoustically, it can contribute to the acoustic performance of other systems. “In the case of Winter Primula vulgaris, which is characterized amongst the other plants with the highest leaf area density, an increase of up to 80% in the soil absorption coefficient has been observed at frequencies below 400 Hz. For this type of plant/soil system, there is a 15%–20% increase in the soil absorption coefficient at frequencies above 800 Hz.” (Horoshenkov, Khan and Benkreira, 2013) The high acoustic performance that the acoustic LWS is presenting on a low sound frequency, can be effective when addressing traffic noise. The acoustic performance, health and environmental benefits make the Acoustic LWS a versatile system that can offer great benefits to the living environment.

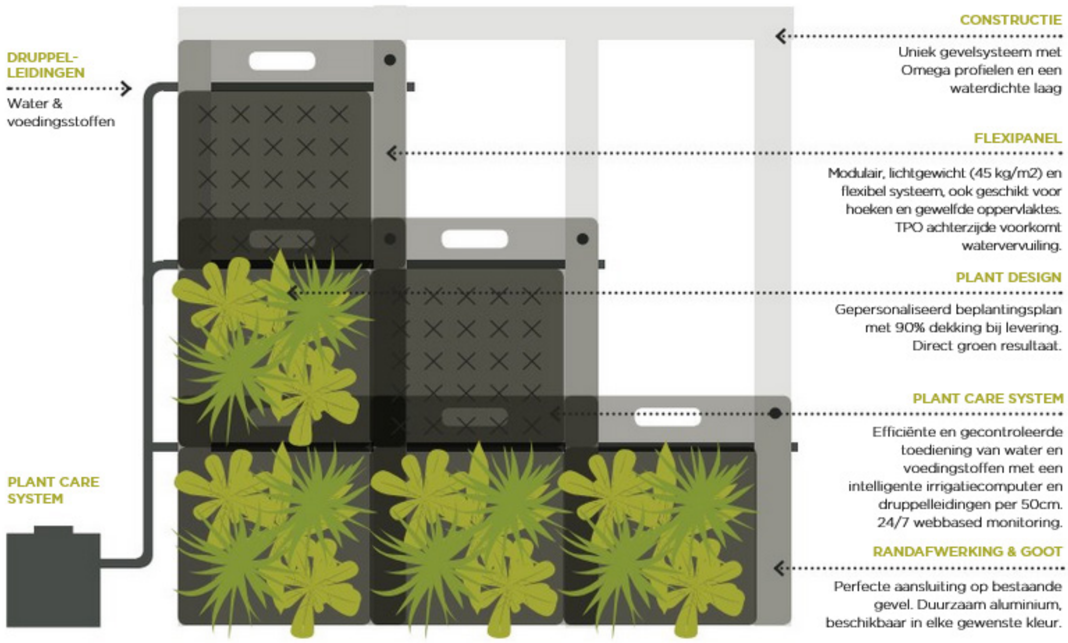



*Fig 33. SemperGreen living wall system (sempergreenwall, n.d.)*

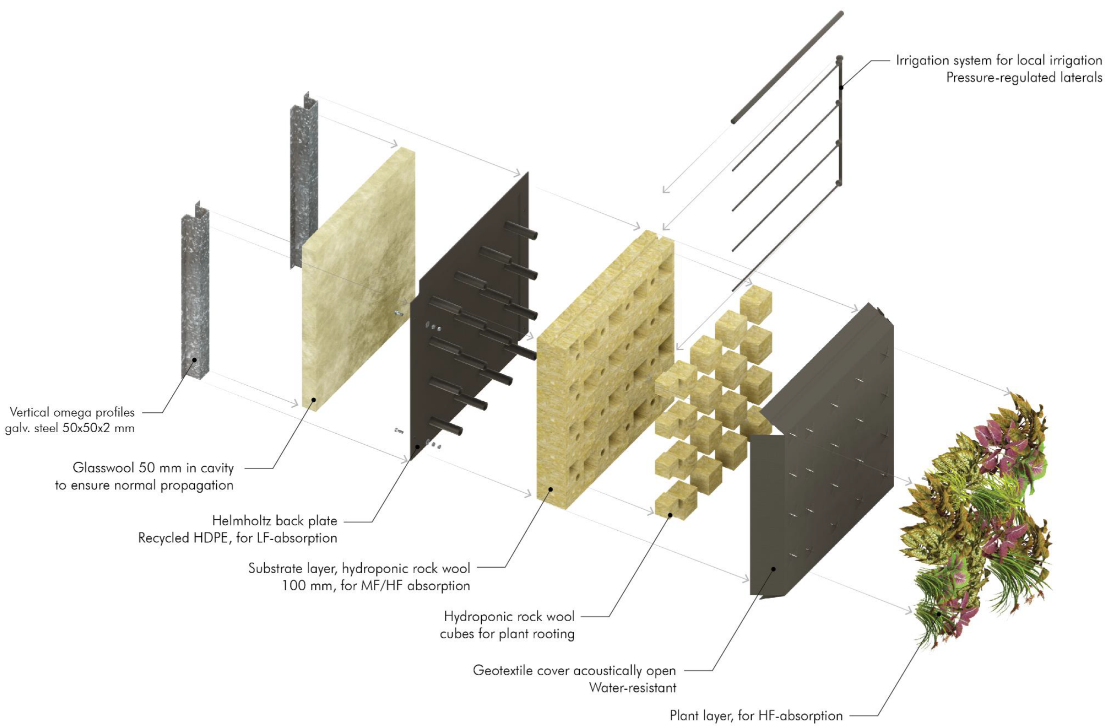


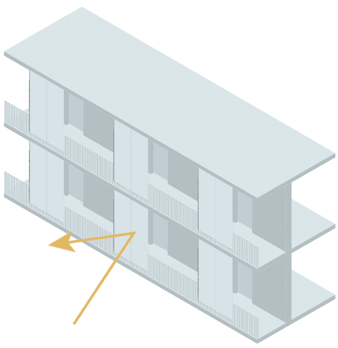

*Fig 34. Possible configuration of an acoustic living wall system (Bakker, 2021)*

# Case studies - solutions

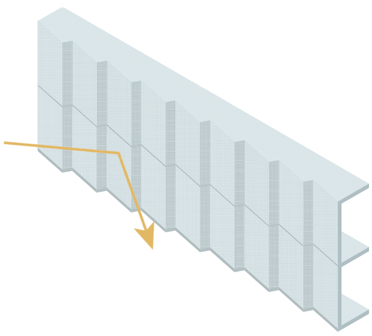
## Urban form

Habitable noise barrier that protects
underlying neighborhood

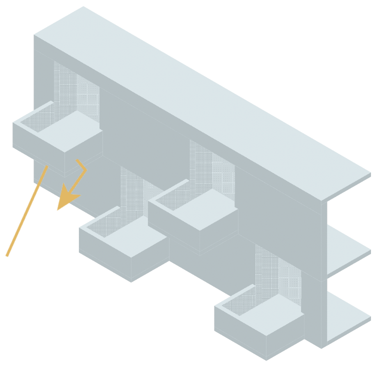
## Geometric shape



Gallaries with glass barriers

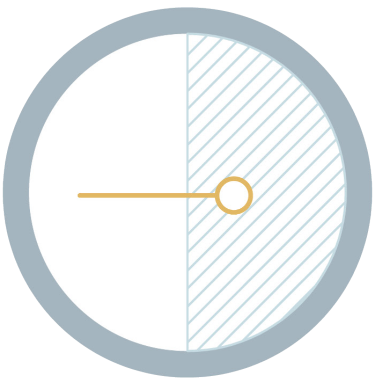


Glass facade with
zigzag shape

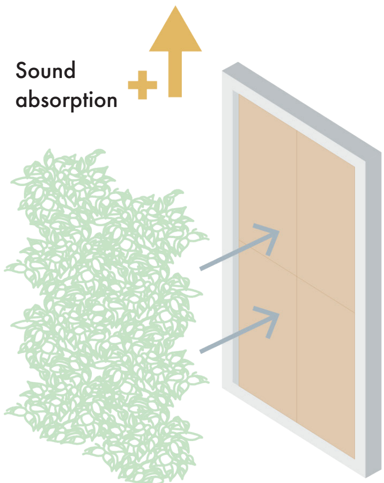


Dense balconies and
facade plasticity

## Materialization



Natural materials have
great absorption qualities




Plants increase the absorption qualities
of the substrate of living wall system

## Het Funen - Noise reduction estimation

To estimate how much noise acoustic interventions can reduce, a calculation of the context of Het Funen was made. The calculation includes measurements from the building and context, the maximum noise exposure permitted for railways, noise requirements from residential housing, and the STC-ratings from acoustic interventions. This calculation determines if the building applies to the noise requirements of the Dutch government. Moreover, it is important to state that there are multiple noise sources outdoors that will influence the total noise exposure that needs to be addressed, as the decibel-unit functions on a logarithmic scale. In this case, only the maximum railway exposure of 70 dB will be considered in the calculation.

### Measurements

Through the Inverse square law calculation in fig. 35, The Funen's noise-affected facade of 48 dB was determined with a 25m distance from the railway. A noise barrier of at least 42 dB is required according to Dutch regulations for residential housing.

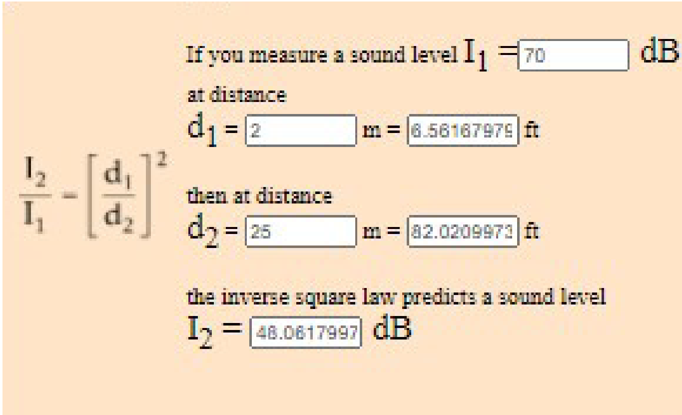



Fig 35. Calculation of noise exposure on the facade (hyperphysics, n.d.)


Fig 36. Sound measurements diagram Het Funen (NoiseTools, n.d.)

### Urban form

In figure 36, a diagram of the context illustrates the influence of a building as a noise barrier. The habitable park of Het Funen is completely protected by the building from the railway noise exposure.

### Geometric shape

The sawtooth shape of the facade contributes a 6 dB noise reduction.

### Materialization

The laminated glass facade contains a STC-rating of 43, which means the facade material reduces noise by 43 dB.

### Conclusion

The park neighborhood is completely free from noise exposure from the railway. This creates an harmonious atmosphere where people experience alluring sounds of nature.

Combining the noise reduction of the geometric shape and the material leads to a total noise reduction of 49 dB, which is sufficient based on Dutch regulations. Also, this completely solves the noise exposure produced by the railway nearby.

As stated, in reality, the level of noise exposure might be higher, but Het Funen has solved the acoustic issues of its environment adequately.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