INTEGRATED SYSTEMS FOR ACOUSTIC OPTIMIZATION OF GREEN ROOF STRUCTURES: A NUMERICAL APPROACH TO AIRCRAFT NOISE MITIGATION

MASTER THESIS

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Integrated Systems for Acoustic Optimization of Green Roof Structures: A Numerical Approach to Aircraft Noise Mitigation

by

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low-frequency sound, aircraft noise, green roofs, acoustic performance, sound absorption, Helmholtz resonators, sustainable solutions, impedance tube model, finite element method (FEM), COMSOL Multiphysics

PREFACE

The research presented in the current graduate thesis has been conducted in order to obtain my MSc degree in the Department of Civil Engineering and Geosciences at Delft University of Technology. It illustrates the culmination of a significant and enlightening journey that undeniably contributed to my professional and personal growth. During my studies I gained a lot of knowledge on different subjects within the civil engineering field, and through this thesis, I finalize my studies with the subject that interest me the most: the optimization of integrated systems for acoustic performance in green roof structures. This research gave me the opportunity to combine my knowledge for building physics and sustainable building solutions.

Throughout the course of my research, I realized that no task can be successfully completed without professional interaction with others. Discussions and criticism arising from different opinions or perspectives can undeniably be time consuming and sometimes painful to deal with, but I believe that not only did it keep me from making mistakes but also added clarity.

I am particularly grateful to my mentors and members of this thesis committee for their professional guidance, the sharing of their useful academic knowledge, as well as their advantageous feedback during the different phases of the research. Primarily, I would like to express my gratitude to the chair of the committee, Prof. Dr. ir. M. (Marc) Ottelé, for providing me a wealth of insightful advice and suggestions pertaining to the direction of my research. His expertise was instrumental in completing this project. I am deeply thankful to Dr. ir. M.J. Tenpierik, for his invaluable insights into acoustics, which guided my research and ensured its scientific reliability. My sincere gratitude goes to Dr. Giacomo Vairetti, my supervisor at ABT B.V. for giving me the opportunity to conduct my research at the company and for his constant guidance and encouragement. His industry expertise and practical advice not only guided my research but also provided me with a valuable perspective on real-world engineering challenges. I would also like extend my gratitude to SemperGreen and Max de Vos for providing me with all the samples necessary for my experiments. Their willingness to assist and provide any additional materials, information or support throughout the research was invaluable and greatly appreciated.

Finally, my deepest gratitude to my family for always encouraging me with their continuous support to pursue my aspirations with patience and persistence no matter the adversities. Last but not least, I am grateful to my friends, both old and new ones, for being by my side and making this journey even more meaningful.

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ABSTRACT

Noise pollution has become a significant environmental concern in urban areas. Low-frequency sounds, especially those coming from aviation activities present a major difficulty among noise sources, due to their ability to travel long distances and easily penetrate different structures. In response to the growing need for mitigating such environmental challenges, green roof structures are becoming an increasingly effective potential. Green roof systems provide several environmental benefits, including thermal insulation, enhanced air quality and stormwater attenuation that have been extensively studied. However, the potential of these systems to mitigate low-frequency noise pollution remains underexplored.

This study aims to investigate the acoustic absorption capabilities of green roof systems, emphasizing their role in reducing noise pollution and the importance of certain sustainability aspects. To achieve this, the use of resonance absorbers is being investigated, focusing on integrated Helmholtz resonators targeting low-frequencies. Initially, acoustic measurements are conducted to assess the acoustic performance of five different green roof systems provided by SemperGreen. Based on the measurements' results, different integrated resonator design concepts are developed and evaluated systematically in order to find the most optimal solution. FEM numerical simulations are performed in COMSOL Multiphysics by modeling a large impedance tube to assess the impact of different resonator configurations on the green roof system's overall acoustic performance.

The findings of the study demonstrate that the integration of Helmholtz resonators in the growing medium layer can improve the acoustic performance of the system at lower frequencies, however within a particular limited range. As a final step, optimization strategies including the introduction of cross-structure fins in the resonators' neck or adding a secondary neck alongside the primary one are explored as potentials to broaden the absorption peaks. From the findings it can be concluded that the development of more acoustically efficient green roof systems is feasible; however, further experimental validation is required to confirm and refine the proposed solutions.

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a	Absorption coefficient
z_{s1}	Surface impedance
λ	Wavelength in air
ρ	Density of air
c	Sound speed in air
Wi	Incident sound power
Wt	Transmitted sound power
f_r	Resonant frequency
s	Cross sectional area of neck
V	Air cavity volume
r	Neck radius
d	Neck diameter
l	Neck length
φ	porosity
σ	Flow resistivity
α_∞	Tortuosity
R	Reflection coefficient
δ	Neck end correction factor
ω	Angular frequency
j	Imaginary component
H_1	Incident transfer
H_R	Reflection transfer
k	Acoustic wavenumber

INTRODUCTION

1
Research Framework

1.1 Problem Statement

Amongst others, one of the main environmental challenges in urban and non-urban areas is noise pollution (EEA, 2020). According to the World Health Organization, every noise above 65 dB can be considered as noise pollution (WHO Europe, 2018). There are many sources that cause noise pollution, but the most common are road and air traffic noise, construction sites, nightlife, and even several different animals.

Several studies have been done on the impact of road traffic noise, and it has been proven that it is the primary source of community exposure to noise levels above the European threshold of 55 decibels (dB). On the other hand, while aircraft noise is a smaller share compared to road and railway noise, it has been found that exposure to road and railway noise leads to lower annoyance levels compared to aircraft noise. The generated aircraft noise is particularly noticeable during takeoff operations. The majority of the sound energy in this noise belongs to frequencies below 200 Hz. In comparison to medium and high frequencies, at these low frequencies, noise propagates over long distances, penetrates freely through buildings, and cannot be easily absorbed (Sharp *et al.*, 2001).

Nowadays, more and more research is being conducted on noise reduction technologies. However, there are many neighborhoods, especially around airport areas, suffering from noise coming from the aircraft, and the impact of this noise has been recognized by several authorities as a harmful effect that should be reduced if not prevented. Therefore, it is essential to highlight this problematic factor that has been associated not only with community annoyance but also several negative health effects, from simple sleep disturbance to complicated physical or psychological disorders like respiratory and cardiovascular ones or even anxiety, stress, and depression (Floud *et al.*, 2013). Aircraft noise pollution can become an invisible threat for several living beings on the planet. As mentioned above, exposure to this noise can be proven extremely harmful for hearing capacity and health (WHO, World Report of Hearing, 2021). Despite the fact that many health issues caused by aircraft noise exposure are similar to the effects of traffic or railway noise exposure, residents close to airports or flight paths feel most annoyed by aircraft noise and least by railway noise, with traffic noise ranging in between (Miedema and Oudshoorn, 2001).

However, the implementation of preventive measures can be essential in order to reduce the impact of this invisible threat. Apart from correct noise management (e.g., protection of certain areas) and technological improvements that can significantly minimize the number of people affected by air-traffic noise, attention should also be given to the existing as well as the new infrastructure.

Vertical and horizontal green systems on structures were generally associated with aesthetic needs. However, they can be designed with different objectives, such as increased energy insulation, noise reduction, as well as storm water management (Pittaluga *et al.*, 2011). Green roof structures are expected to be built on the top of many buildings in the coming years. Along with enhanced aesthetics and increased biodiversity, green roofs have been proven to offer advanced sound-absorbing and insulating properties. Green roof systems are multidisciplinary solutions with a relatively high mass that can not only absorb the sound but also increase biodiversity and improve the air quality. Thanks to their characteristic layers and depending on the properties of the materials they are usually made of, green roof systems can provide high acoustic performance.

There are many building materials with high absorbing properties. Soil, for example, is known for its very good absorbing properties, as it acts as a porous absorber. There have been studies into the sound-absorbing properties of different types of green roof soils, and many of those types seem to have good absorbing properties for the medium and higher frequency spectrum. Especially the higher frequencies, by reason of their short wavelengths, can be absorbed very well. Additionally, the different green roof systems (intensive, semi-intensive, extensive) present different absorption characteristics for the different frequencies. Finally, the thickness as well as the kind of the different layers determines to what extent the lower frequency spectrum is being absorbed (Pittaluga *et al.*, 2011). For instance, while the vegetation can absorb the higher frequencies, the substrate layers can block the lower frequencies more effectively. However, the low-frequency spectrum can become a real problem for areas particularly affected by noise. These areas, for example, can be neighborhoods around airports. Hence, studying the performance of green roof systems in the lower frequency range could attract particular scientific interest, and as a result, the question that arises is to what extent the green roof systems can be activated and absorb part of those problematic lower frequencies. In order to give an answer to this question, this study focuses on the selection of the different layers as well as their geometrical characteristics (e.g., an increased mass or thickness may lead to a higher low-frequency absorption). Additional attention is given to the combination of the different absorption mechanisms.

Summary

- Aircraft noise pollution is a growing concern in many cities.
- The noise generated consists of low frequencies (f < 250 Hz) which is most annoying and problematic.
- Green roofs are multi-layered systems that could be used to mitigate the problem of aircraft noise.

1.2 Research Objectives

This study provides a simple and clear overview of the impact of green roof structures on reducing the noise pollution coming from aviation. To ensure that no future development will be adversely affected by excessive aircraft noise, an additional proactive planning approach is required. As green roofs are made up of several different layers, the main objective of this research is to examine to what extent the careful selection of those materials can affect the acoustic absorption of the entire system. Additionally, the implementation of sound absorbers is being investigated as a sound absorption optimization technique.

Additionally, sustainability and circularity are two dominant parameters regarding the materials selection. It is commonly known that for many materials on the market, there is no path after the end of their lifespan. Considering circular economy as well as waste elimination, emphasis is given to the potential of recycled waste materials as green roof layers (e.g., for green roof soil mixtures) in order to achieve a sustainable solution. In other words, this study will try to include to what extent the chosen materials can originate from recycled materials or re-enter the market economy at the end of their use. In order to develop the different concepts, the project is structured around the parameters of *acoustics*, *"green"* and *materials selection*.

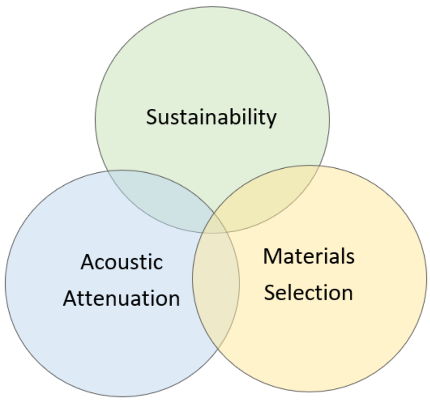


Figure 1.1: Schematic illustration of the core parameters structuring the research framework.

Finally, apart from knowledge acquisition, the results of this analysis could assist decision-makers in choosing sustainable solutions that could have potential use in real-scale experiments, especially in the application of a concept in a real-scale building (e.g. close to airport neighborhoods). Hence, this research may contribute to an overall reduction of sound levels in disturbed areas.

1.3 Research Questions

In an attempt to translate the main objective of this research into an adequate set of research questions, primarily, all the relative goals regarding the main problem statement described above need to be identified. Following that, the basic research question is then formulated and stated as follows:

How can the acoustic absorption of green roofs be improved, focusing on the low-frequency spectrum and considering the importance of sustainability and environmental footprint/impact ?

In order to be able to answer the main research question, though, there is a set of sub-research questions that are automatically generated and need to be further discussed. This set consists of the following sub-questions:

Sub-questions regarding the theoretical background and literature study:

1. What are the main sound absorption mechanisms, and which of them work in the lower frequencies (f < 250 Hz)?
2. How are green roof systems classified and how do they absorb sound?
3. Which of the green roof layers are the most efficient regarding low-frequency sound absorption?
4. What are the key sustainability challenges regarding the growing use of green roof systems?

Sub-questions regarding the empirical study:

5. How do the examined green roof components perform acoustically?
6. To what extent can sustainable sound absorbers be used in green roof structures to improve their absorption capacity?

Sub questions regarding the evaluation:

7. What level of sound absorption can be achieved through the use of alternative solutions implemented into green roof systems?

By providing answers to the aforementioned research questions, this study aims to indicate to what extent green roofs can be optimized to enhance their acoustic capabilities.

1.4 Description of Research Methodology

Considering the nature of the research question and the objective of the study, the methodology followed for this project analysis can be defined and is mainly a combination of several research methodologies, with the most essential being the literature review, experimental measurements, as well as simulation modeling . At a first level, the research is based on:

1. The Existing Literature

The scope of this phase is to provide a deeper understanding of the most important research framework aspects. Primarily, an overview of the available literature, including articles, relevant research, regulations, and guidelines, as well as results of similar analyses, is performed. In order to find relevant literature for the study, various databases are used, including the Delft University of Technology's (TU Delft) library, ResearchGate, as well as article databases like Google Scholar. Additionally, a combination of keywords is used to build the main search strings. Amongst others, the basic combinations are green roofs, environmental performance, environmental noise, sustainable materials, sound insulation, acoustic absorption, porous absorbers, and resonance absorbers. The literature review aims not only to unify the context of this research but also to highlight its contribution to the building industry through an academic prism.

2. The experimental results and simulation modeling

<u>Measurements</u>

There are two methods of measuring the amount of sound absorbed by materials. One is the reverberation room method proposed by W. C. Sabine, and the other is the impedance tube method. In the first approach, specimens of the material to be tested can be put in a reverberation chamber, and the impact of the specimen(s) on the rate at which sound decays in the chamber can be used to calculate the absorption coefficient (ISO 354, 2003). In other words, inside the reverberation room, the absorption coefficient is determined under random incident sound field conditions. The second method consists of placing a significantly smaller specimen at the end of a pipe down which sound waves are made to pass through (ISO 10534-2, 1998). Measurement microphones are placed at two positions in the tube. The absorption coefficient is then determined by observing the interference pattern between the reflected and incident waves inside the pipe. The impedance tube method considers only a direct incidence field and offers the opportunity to measure the normal incident absorption coefficient on small specimens even though the mounting conditions may have a minor impact on the observed results (ASTM E1050-12, 2012). On the other hand the reverberation chamber method gives access to the absorption coefficient under a continuous interchange of energy between the directions of sound propagation that is more indicative of practical utilization of sound-absorbing materials (ISO 354, 2003). For the purposes of this academic study and for simplicity reasons, the absorption coefficient of the acoustic materials tested is determined by the impedance tube method, as described below.

The Impedance Tube method: The impedance tube method is commonly used to determine frequency-dependent absorption capabilities of several materials. The test typically employs an impedance tube, usually cylindrical, with a test specimen holder at one end and a sound source at the other, two (or more) microphone positions, and a frequency analysis system to identify the sound absorption coefficient of sound-absorbing materials for normal sound incidence. The specimen of interest is placed at the end of the tube, and a sound source, connected to the other end, is used to generate sound waves in the tube. The sound source is connected to an amplifier, which is connected to a waveform generator that creates the broadband noise, while the microphones measure the sound pressure level at specific positions along the length of the tube. However, it is crucial to mention that when the separation distance between the microphones is half the wavelength of the test frequency, then the method might be prone to considerable inaccuracies and errors (Hiremath *et al.*, 2021).

For the current research, the setup, concepts and materials, location and frequency of measurements, variables, equipment needed, parameters validated, and the configurations developed for simulations are described in chapter 6.

The simulation modeling

The finite element method (FEM) is a popular method that serves as a powerful tool to numerically solve equations arising in mathematical and engineering problems. FEM is widely used for complex geometries and multi-physics coupled methods. In acoustics it can be used to predict the acoustic behavior of layers of porous materials. In the present study, numerical simulation is performed by using the FEM commercial software COMSOL Multiphysics. Based on the measurement results and after careful selection of the different materials to be evaluated, different scenarios are developed and tested in COMSOL Multiphysics. In particular, the use of integrated resonant absorbers is investigated. The primary goal is to measure and depict the sound absorption through the different multilayered structures and the systems integrated into them.

As this research is focused on the lower frequency spectrum and as the presence of vegetation layer has been proven to be more effective for the higher frequencies (Davis *et al.,* 2017), both measurements and simulations of this project are focused on the layers beneath the vegetation. A detailed description of the simulation process is presented in Chapter 7.

Performance evaluation

Following the conduction of comparative simulations, the evaluation of the concepts is necessary. The evaluation of the different scenarios is mainly based on their acoustical performance. As depicted in the methodology flowchart of Figure 1.2, when the design does not sufficiently meet the design criteria, a new alternative concept is developed and tested. This process is repeated until the optimal solution is reached. An overview of these evaluations will be provided at a later stage.

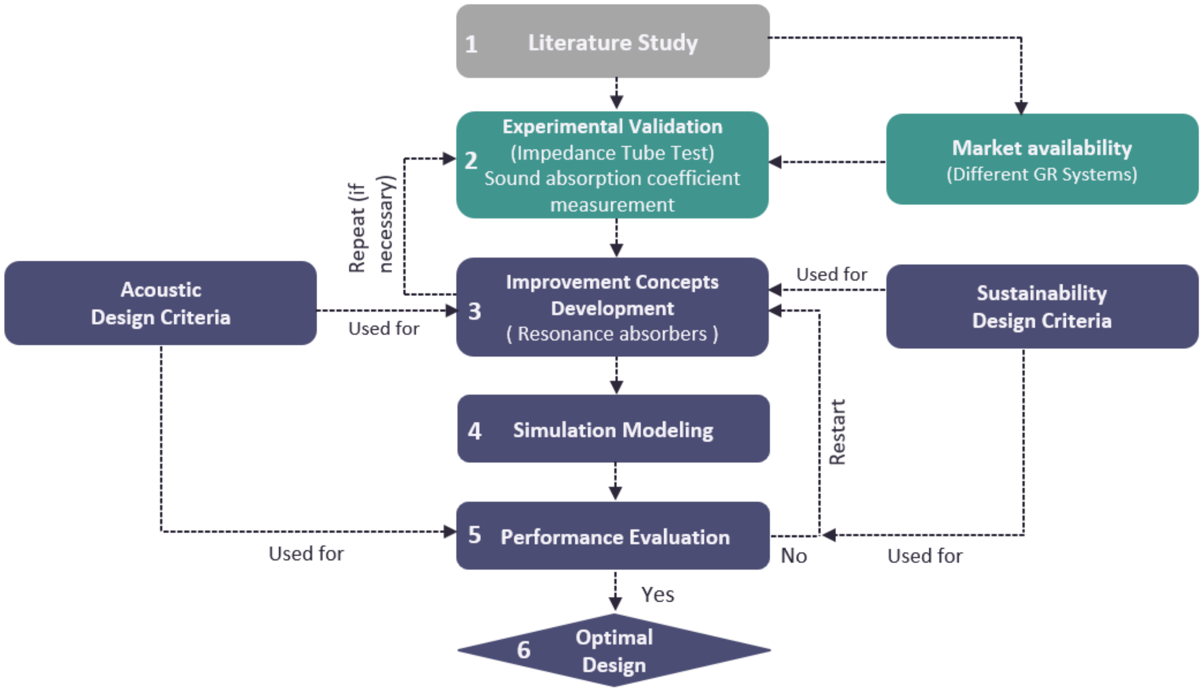
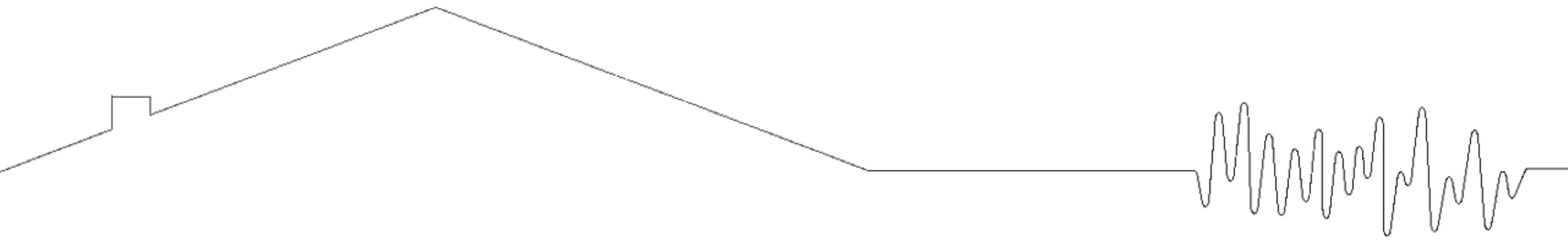


Figure 1.2: Flowchart of the research methodology.

Given the above, the main steps of the research are summarized as follows:

- Literature study/review into relevant acoustic absorbing and insulating mechanisms, green roofs and sound absorption of vegetation and soil types.
- Based on the literature study and the market availability, choosing different green roof systems to examine their absorption characteristics. To effectively evaluate the sound absorption performance of the different materials, the impedance tube method is being used during the design process. The components are chosen based on the sustainability and acoustic design criteria studied in the research.
- Based on the measurements' results, developing different concepts for green roofs absorbing and insulating against sound in the lower frequencies.
- Modeling and simulating the different concepts using COMSOL Multiphysics and using the simulation results in order to evaluate their compatibility with the chosen design criteria.
- Final evaluation of the sound reduction properties of the different concepts in order to come up with the most optimum and promising solution.



KNOWLEDGE PHASE

2

Introduction to Green Roofs

2.1 Characteristics and Typology

Roofs can represent up to 30% of the horizontal surface of urban areas; hence they can be used as an essential tool to enhance the environment (Frazer, 2005). Although these structures are widely recognized as a distinct type of urban habitat, they have been largely treated as an engineering challenge, rather than as an ecological system. Architects and engineers have applied green-roof technology worldwide; therefore decision-makers and the public become more and more aware of these systems and their potential benefits (Porsche and Köhler, 2003).

Green roofs, also known as vegetative roofs, are living, multi-layered vegetation systems that contribute to mitigating several environmental problems (Mihalakakou *et al.*, 2023). Jim (2017) defined the term green roof to refer to an artificial human-made product installed on the roof of a conventional flat or sloping roof, including the necessary amount of added structural support. A slightly different definition was given by Yu *et al.* (2017), mentioning that a green roof structure is a functional building roof partially or entirely covered with vegetation.

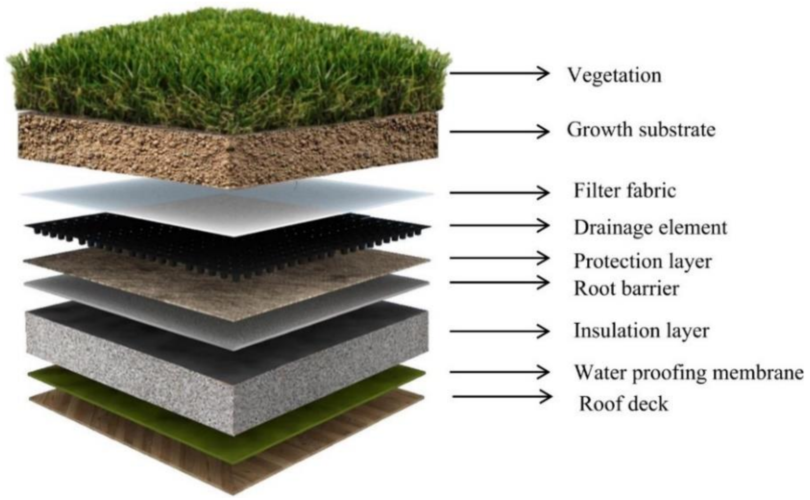


Figure 2.1: Schematic cross section of a typical green roof structure layering (retrieved from Vijayaraghavan, 2016)

The idea of green roofs was developed in order to encourage the growth of various forms of vegetation on the top of structures. Typically, green roofs are classified according to their usage, vegetation type, substrate type and depth, growing medium type, and maintenance needs (Peck and Kuhn, 2003). Figure 2.1 represents the typical structure layers of a green roof system, including the roof structure, which is usually a concrete deck designed to support the weight of the roofing system. The most important layers are the waterproof membrane, root barrier, retention and drainage layer, filtration fabric, a growing medium, and the vegetation, which differ according to the system type. Sometimes, depending on the system's function, additional geotextile membrane or a thermal insulation layer are necessary. As green roofs need to satisfy long-term client expectations, the selection of efficient green roof components is of great importance.

Extensive	Semi-Intensive	Intensive
System Height: 6-20 cm	**System Height**: 12-25 cm	**System Height**: 15-40 cm
System Weight: 60-150 kg/m²	**System Weight**: 120-200 kg/m²	**System Weight**: 180-500 kg/m²
Vegetation: sedum, herbs, grass	**Vegetation**: grass, herbs, shrubs	**Vegetation**: lawn, shrubs, trees
Maintenance: low	**Maintenance**: periodically	**Maintenance**: regularly

Figure 2.2: Classification of green roof systems according to construction factors, vegetation type and maintenance requirements. (Configurations and technical characteristics retrieved from Raji *et al.*, 2015)

Based on their purpose and characteristics, green roof structures are classified into three main types: extensive, semi-intensive, and intensive green roofs. Figure 2.2 illustrates the classification and comparison of the different green roof types that are installed on buildings based on required functions and costs. Extensive green roofs are characterized by their lightweight nature, and in their simplest design, they consist of a thin soil or substrate layer with low-level vegetation, usually sedum and grass. This basic system has been studied in diverse climates and regions worldwide. Intensive green roofs consist of growing media usually greater than 150 mm in depth and can be characterized as gardens hosting larger plants such as shrubs and small trees. Finally, Hui (2016) identified a third type known as semi-intensive, which often consists of a mixture of extensive and intensive system properties. Generally, semi-intensive systems are known as simple living roof systems; they have a slightly thicker substrate layer and usually accommodate ground covers, small herbaceous plants, and grasses. Finally, off the different systems, special attention should be given to extensive type as it is more commonly used and requires careful construction and maintenance.

Figure 2.3: Real scale green roof system applications by Sempergreen in Europe. *Upper*: Installation of an extensive lightweight traditional sedum system for the terminal of Rotterdam The Hague Airport, the Netherlands - Sustainable expansion project, carried out in 2020. *Lower*: Installation of a biodiverse system on the roof of a factory in Belgium (pictures retrieved online from Sempergreen).

2.2 History Evolution

The origin of green roofs has ancient roots. The first installed green roof system was the hanging gardens of Semiramis, which nowadays are referred as the Hanging Gardens of Babylon and considered one of the seven wonders of the ancient world, constructed around 500 BC (Vijayaraghavan, 2016). Today similar roof garden projects are designed for high-profile structures, international hotels, business centers, as well as modern houses. These systems that are known for their thick substrates and vegetation diversity are designed as intensive systems and are able to increase the amount of recreation space.

During the 20th century, modern architects started to implement green roofs and walls in their design in order to merge nature with construction. In the late 20th century, the innovation of the German H. Koch to mix gravel and sand with tar to create waterproof material to accommodate vegetation growing. Later in the 1960s, sand and gravel were replaced by a simple drainage system and new design for a more lightweight system (Jim, 2017). Germany became the first country in the world to accept the concept of green roofs in constructions and implement innovation in roofing technology. This was followed by North America, Northern Europe and finally a few Asian countries.

In the 1970s, growing environmental concern made individuals more conscious, and the implementation of green roofs in constructions became more accepted. As a result, the widespread environmental benefits offered from green-roof technology led to the development of technical guidelines, the first volume of which was released by the "Principles for Green Roofing" in 1982 and have been revised several times since 1990 (FLL, 2018). Several investigations have been carried out on roof construction and design guidelines, and since then, many German cities have implemented incentive strategies to encourage the use of green roof technology and improve environmental standards. According to Köhler and Keeley (2005), in Germany, green roof coverage space increases by about 13.5 million square meters (m^2) per year.

Currently, based on the climatic conditions and the unique building characteristics, nations such as the US, Australia, and Japan are already taking initiatives to install green roofs during the construction of new buildings. This served as the impetus for a rise in green roof research, with recent studies concentrating on finding new, affordable, or alternative approaches for the application of green roof systems in real-world settings (Vijayaraghavan, 2016).

Figure 2.4: *Left*: Sod house in the US prairie frontier in 1901 (Photo credit: Public domain at https://en.wikipedia.org/wiki/Sod_house). *Right*: Traditional semi-subterranean sod house in Iceland (Photo credit Christian Bickel under Wikimedia Commons at https://en.wikipedia.org/wiki/Sod_house).

2.3 Green Roof Benefits

Although their cost disadvantage is still a challenge for the building industry, over time, green roof systems have become a popular construction tool due to their environmental and social benefits. Green roofs are primarily designed with an engineering perspective. Because of their nature, though, it is not surprising that these systems also have an environmental impact. In particular, they are usually identified for aesthetic-related contributions, energy efficiency, as well as enhancement of the general environment. Once operational, green roofs can offer substantial environmental benefits, and many studies of the existing literature have recognized the benefits of green roofs at various scales. Amongst others, Vijayaraghavan (2016) highlighted several direct and indirect environmental benefits that are summarized as follows:

- ***Stormwater attenuation***. Depending on their category (intensive or extensive), growth medium type, storage capacity, and vegetation, green roofs can retain rainwater. This automatically leads to stabilization of the groundwater level, reduction of the peak load, and, as a result, minimization of any flooding risk.

- ***Thermal benefits***. Green roofs can reduce the building energy demand by reducing the amount of heat penetrating into the building. Depending on their thermal mass, the insulation provided, as long as the shading level, green roofs can improve the thermal performance of buildings.
- ***Water quality enhancement***. Green roofs can have a positive effect on water quality in a number of ways. Both the substrate composition and the vegetation play a major role in either cleaning or contaminating the rainwater runoff. In order to be able to control the magnitude of contaminants or other particles in rainwater runoff, additional attention should be given to the condition-age, the construction, as well as the maintenance of green roofs.
- ***Noise reduction***. By providing increased insulation and absorption of the sound waves a green roof can act as a noise reduction system to the indoor environment.
- ***Air pollution***. The vegetation in a green roof can filter and purify the air, thus mitigating air pollution in many urban environments.
- ***Aesthetic-related benefits***. Apart from environmental-related benefits, green roofs can promote aesthetic enhancement and restore biodiversity, especially in overcrowded urban environments.

2.4 Guidelines to design a healthy green roof system

The environmental and social contributions that green roof systems can make towards creating more sustainable living environments in cities are recognized and accepted worldwide. It is commonly believed that these "green methods" will serve as an important climate-proof construction tool (Vijayaraghavan, 2016). However, they can provide all the benefits listed in the previous paragraph, including noise reduction, only if designed and installed in a way that ensures that all parties involved work together to avoid the risk of failure. The majority of design considerations will cover aspects such as the usage, the location, or the installation costs of the system. However, it is necessary to take into consideration a number of technical requirements and practical implications to maximize the benefits and ensure that the minimum performance criteria are met.

- **Structural Design**

Most deck designs are able to host a green roof system as long as they can sustain both live and dead loads. In the case of intensive green roofs, they can only be constructed on concrete decks. It is important that all the dead and imposed loads should be calculated in accordance with the design criteria of the EU-Standards EN 1991-1-1, EN 1991-1-3, and EN 1991-1-4. When it comes to dead loads, the weight of the waterproofing system, the saturated weight of the substrate and the components of the green roofs, vegetation, and snow loads should be taken into consideration. Additionally, access by people or machinery and vehicles, as well as point loads for items such as water features and trees, should not be neglected when considering the imposed loads. Finally, in the case of new construction, weight calculation must be determined in advance, whereas for existing constructions, and only when applicable, particular attention should be given to the load-bearing capacity of the roof (RVO).

- **Wind Loads**

Due to the wind effects, building structures are subject to pressure forces, the intensity of which depends on the direction of the wind as well as the shape and height of the structure. Hence, it is essential to take protective measures for the layers of the roof structure against lifting due to wind loads, especially when the system is not mechanically fastened.

According to Eurocode EN 1991-1-4, roof areas are divided according to their different levels of wind stress. Particularly the edges and corners are exposed to higher loads, and therefore they have to be secured by relevant measures. In green roof design, the dominant goal is to keep the loads and the height of the layer structure as low as possible. In order to secure the most vulnerable areas of the roof, usage of heavier materials, e.g. grass slabs, stones, or larger aggregates, might be necessary.

- **Waterproofing and Drainage**

Waterproofing membrane is one of the most critical components of a green roof system. It has been proven resistant to several microorganisms and root penetration. Therefore, careful consideration and assurance before installation are of great importance in order to make sure that the membrane meets the durability and thickness requirements. Additionally, membranes should be carefully inspected in order to determine whether they have to be repaired or replaced before installation (FLL, 2018).

Figure 2.5: Four main drainage material types used in green roof construction. *From left to right*: cuspated sheets, entanglement sheets, granular material and structural drainage (pictures retrieved online from SOPREMA, 2023)

Ensuring a proper drainage system on a green roof is of great importance, despite the fact that they can effectively retain most of the annual rainwater that falls on them. Roof drainage design should comply with the requirements of the EU Standard EN 12056-3:2000 for gravity drainage systems inside buildings. In any case, the planning must ensure that all vegetated and non-vegetated areas can be properly dewatered. Both the roof surface and the layer structure need to have proper drainage. In order to manage the total amount of water on the entire roof safely, it is essential to determine the position of the drainage points depending on the different surface formations.

- **Substrate**

A green roof system's substrate needs to be specially built to maintain the ideal level of moisture, nutrients, and air to support sustainable vegetation growth. These substrates are often composed of mineral products with particular amounts of organic matter of specific characteristics. Depending on the green roof type there are different proportions of the substrate compositions. The ultimate requirement in any case is to select a lightweight substrate with ideal plant-growing conditions (Ampim *et al.*, 2010).

Figure 2.6: Common soil types used in green roof substrates. *From left to right*: expanded clay, sand, crushed bricks, organic compost (pictures retrieved online from LECA UK, Saint Gobain, 2024; William Mackay (precast) Ltd, 2024; US Brick, 2023; The Ground Up, LLC, 2022).

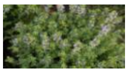
- **Vegetation Type and Compatibility**

The type of vegetation planted on a green roof's surface is critical for the system's performance. According to the *German Guidelines for Planning, Execution, and Upkeep of Green-Roof Sites* (2018), the main factors influencing the choice of plant for green roof systems are:

a) Objective: Different plants translate into different performance. If, for example, a roof is designed to fulfill a specific biodiversity objective, then a mix of different species may be selected, whereas in the case of stormwater mitigation, sedums and other succulent plants that tend to consume large quantities of water and are highly tolerant in dry conditions must be selected.
b) Plant specific factors: the plant's physiology and architecture (leaf shape, size, orientation) as well as sensitivity to light exposure or growth rate will affect the system's performance and its tolerance to sunlight/shade, wind, air emissions, and different pollutants.
c) Climate and weather-dependent factors: The regional climate conditions (air temperature, solar radiation), the local microclimate, as well as the amount and spread of annual precipitation or any period of droughts can affect the successful functionality of the system.

Furthermore, the compatibility of the different species to the different systems is strongly dependent on the green roof application. In particular, simple extensive roofs mostly represent a form of vegetation and plants that are largely self-evolving and sustaining. On the other hand, more complex intensive roof systems require a wider range of planting, such as bulbs, shrubs, and even large trees.

Table 2.1: Most common green roof plant types and their green roof suitability.

	Plant Name	**Green Roof Suitability**
	Iceland Moss (Sedum Ternatum)	Extensive, intensive, and semi-intensive green roof
	Yarrow (Achillea)	Intensive & semi-intensive green roof
	Blue Oat Grass (Helictotrichon Sempervirens)	Intensive & semi-intensive green roof
	Sempervivum	Extensive, intensive, and semi-intensive green roof
	Thyme	Intensive & semi-intensive green roof

- ### Fire Resistance

All green roof systems should be designed in order to be sufficiently resistant to the external spread of fire due to flying sparks and radiant heat. Depending on the system, consideration must be given to methods preventing fire risk. As many plant species can leave significant volumes of organic material on the surface of the roof and thus increase the risk of fire spread, increasing the content of non-combustibles in the growing medium while lowering the organic content is of great importance and should be carefully considered during the design phase. Moreover, all green roof systems should be designed to incorporate effective fire breaks. Last but not least, fire safety can also be significantly improved by making sure to prevent the system from drying out (FLL, 2018).

- ### Maintenance

Green roofs should be designed to be of low maintenance. All maintenance actions carried out on the roof must be in full compliance with the relevant health and safety regulations. Regardless of the type of roof, all systems, intensive or extensive, require some degree of maintenance. While extensive systems often require the least maintenance, intensive systems need frequent maintenance and care related to the vegetation scheme (FLL, 2018). In the Netherlands, based on the Netherlands Enterprise Agency (RVO), maintenance of green roof systems must be carried out 4 times a year.

There are some factors that can affect maintenance and therefore are recommended to be taken into consideration during the design and installation phase. These can be the plant selection, the design of the drainage system, as well as the proper testing of the waterproofing system prior to installation. Proper maintenance is a key factor in the long-term success and functionality of the green roof. Hence, all maintenance activities should be carried out by specialized maintenance staff based on the relevant checklists and maintenance manual provided by the design team.

3
Environmental Performance

3.1 Market Growth

The global green roof market is experiencing significant growth in recent years. According to the most recent report by IMARC Group, titled "Green Roof Market Report by Type, Distribution Channel, Application, and Region 2024-2032" (2022), the global green roof market size reached USD 2.19 billion in 2023 and is expected to reach USD 5.89 billion by 2030 and USD 6.80 billion by 2032. This growth can be attributed to increased environmental awareness, the establishment of new and existing building standards, as well as increased concerns regarding energy efficiency. The market is also expected to benefit from the rising demand for sustainable urban development and the integration of green roof systems into residential, commercial, and industrial buildings.

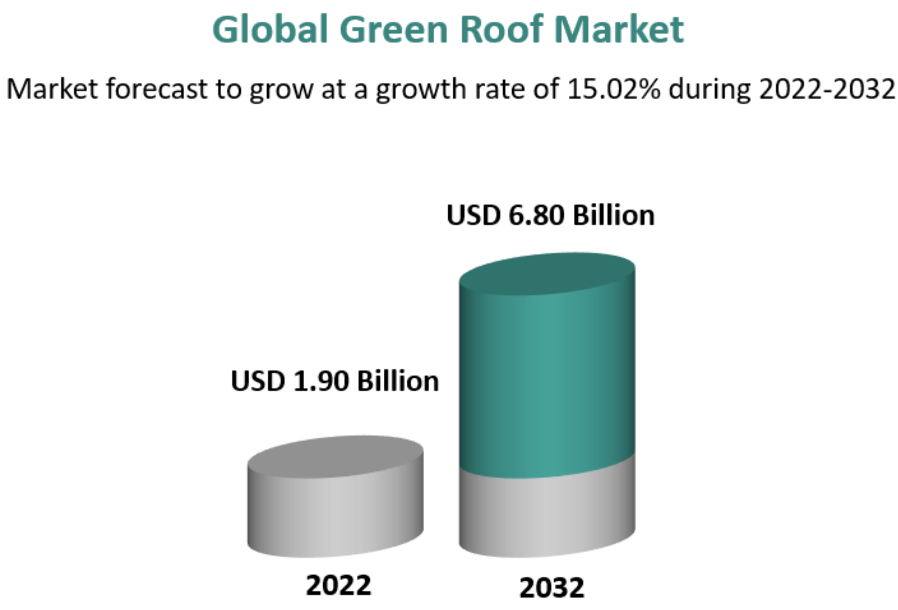


Figure 3.1: Graphic representation of the global green roof market size. Based on the most recent data the market size was valued at USD 1.9 billion in 2022 and is poised to grow from USD 2.19 billion in 2023 to USD 6.80 billion by 2032, at a growth rate of 15.02%.

Innovations related to green roof technology tend to make the installation process and maintenance more efficient. Furthermore, the integration of smart technologies for monitoring and optimization of the system's performance is supporting the market growth. Given the growing awareness around the environmental benefits of green roof systems, the market of green roofs appears to have a promising future.

3.2 Available Market Trends

The availability market trends information is based on the data coming from the latest report by IMARC Group, "Green Roof Market Report by Type, Distribution Channel, Application, and Region 2024-2032" (2022).

- **Environmental sustainability**

As environmental sustainability is becoming more and more important, people are becoming more conscious of climate change and the associated challenges, which acts as a motivation to adopt more sustainable building techniques. These objectives are perfectly aligned with the ability of green roof structures to provide several environmental benefits, such as cutting carbon emissions, minimizing urban heat islands, and enhancing biodiversity. Additionally, in order to address climate change, governments and municipalities are promoting the installation of green roof systems. Similarly, business and property owners are adopting the implementation of such systems as a responsible measure to reduce carbon footprint. As sustainability is becoming an important aspect of construction and urban planning, and at the same time there is a growing need to address environmental concerns, there is an inevitable rise in the demand for green solutions in constructions.

- **Urbanization**

Due to rapid urbanization and increasing in population density, the green roof industry is expanding. Traditional green spaces like gardens and parks are being replaced by buildings and infrastructure. In order to effectively address this challenge, green roofs could serve as a practical solution to transform unused rooftop space into functional green areas that can be used as gardens or recreation areas. Furthermore, green roof systems can reduce energy consumption in buildings and contribute to an overall enhanced and comfortable urban environment. This can result in growing demand for green roof technology in order to optimize space usage, hence positively influence the market.

- **Energy efficiency & Cost savings**

Green roofs act as natural insulators, contributing to indoor temperature control. By decreasing heat gain during summer and heat loss during winter, they lower the amount of energy required for the cooling and heating of buildings. Over time, they become financially appealing for investors since they result in substantial savings on their energy expenditures. As a result, the need for green roofs as an affordable alternative is growing as businesses and homeowners are looking for practical methods to reduce expenses and enhance sustainability.

3.3 Economic Aspects

Even if green roof systems provide a set of benefits to the environment and society, their net environmental benefit is always dependent on the use of natural resources during their construction phase. Nowadays, despite the widespread implementation of green roof structures and their overall benefits, the relatively high initial investment required for their construction acts as a barrier to their market penetration. The costs in the green roofs industry involve their initial construction, operations, maintenance, demolition, and finally their disposal (Bianchini and Hewage, 2012).

Life Cycle Costs of Green Roofs

- **Initial Cost**

Amongst the different green roof types, there is a significant price variation due to factors such as purpose and size, location of the system, and country. Based on the existing prices in Canada, the current costs for an extensive green roof system vary from \$130 to \$165 /m^2, while at the same time the cost of an intensive system is quite higher, starting at around \$540 /m^2. The installation price is also affected by the labor and equipment costs. In the already developed market of Germany, the average green roof costs range from €15 to €45 /m^2. Regarding the Dutch market, information from investment and management costs from the Netherlands Enterprise Agency (RVO) shows that the installation costs for a green roof are between a minimum of €2500 and a maximum of €5000 for a typical property.

- **Operation & Maintenance Cost**

As most of the environmental benefits of green roofs rely on their performance, operation and maintenance costs are crucial to ensure their positive impacts. Some of the parameters affecting the maintenance cost are the size and complexity of the system, the construction characteristics, the type of vegetation required, as well as the operation and maintenance market price. According to Bianchini and Hewage (2012), the annual operation and maintenance costs for green roof systems in the Canadian market range from \$0.7 to \$ 13.5 /m^2, whereas in the Netherlands the same cost for an extensive system is €4 /m^2 (RVO). These costs usually cover periodic monitoring for debris or damaged vegetation as well as ensuring proper functioning of the drainage system. When properly installed and maintained, a green roof has a life expectancy of approximately 40 years. However, those maintenance costs can be offset by the energy savings a green roof system can provide throughout its lifespan.

- **Disposal Cost**

With regard to the disposal cost of a green roof system, there are several options at the end of its life. Materials can be reused, recycled, or landfilled. Water retention, drainage, and root barrier layers can be recycled at the end of their lifespan. However, many countries do not yet have the appropriate facilities for recycling. On the other hand, landfill costs depend on several parameters such as the available landfill capacity and technology as well as the location and size of the facility. Peri *et al.* (2012) conducted a complete research study on the green roof disposal costs in European countries. According to their findings, the disposal cost for an entire green roof system is estimated at €784 /ton.

3.4 Environmental Aspects

There have been several studies analyzing the costs and benefits of green roof structures, including initial construction costs, reduction in energy demand, and air pollution. However, criticism frequently questions the extent of green roof advantages throughout their lifespan. To address these concerns, it is essential to quantify and assess the environmental impacts across the different life cycle stages of green roof systems through a transparent, repeatable, and credible methodology.

3.4.1 Life Cycle Assessment

According to Scolaro and Ghisi (2022), the life cycle assessment (LCA) is one of the most useful tools to assess the environmental and economic impact associated with green roof structures throughout their life cycle from raw material extraction to end-of-life disposal. In other words, it is the most comprehensive methodology to assess the environmental burdens associated with all the stages of the life cycle of products, materials, and human activities. This approach is based on international standards and allows the identification of improvement opportunities through identifying the life cycle phases with the most significant environmental impacts (ISO 14040, 2006). Through LCA, engineers and stakeholders can have a deeper understanding of the balance between the environmental costs and the ecological benefits of green roof systems, supporting informed decision-making for sustainable urban development (Coma *et al.*, 2018). It is, therefore, important that LCA studies explain the full design of green roofs, such as layers and materials, based on the functions required for the specific project and climate needs.

Considering the LCA of green roof systems, during the past few decades studies focused on assessing the environmental performance of extensive and intensive systems compared to conventional or other roof types (Chenani *et al.*, 2015). However, during the past 10 years, the application of LCA studies in the green roof industry has increased significantly. This interest is mainly associated with the global adaptation of sustainable development.

Balasbaneh *et al.* (2024) indicated LCA as an essential tool to evaluate green roofs. Based on the systematic literature review they presented, there is a little agreement on the best green roof choice. Many studies comparing extensive with intensive roofs claimed that extensive systems proved to be more sustainable compared to intensive systems. In particular, it was indicated that extensive roof systems have a significantly lower impact in the material manufacturing, transportation, maintenance, and disposal phase compared to intensive ones. Additionally, they showed that most LCA studies for green roofs do not account for all LCA phases, from raw material extraction to disposal. Finally, the authors detected and proposed several knowledge gaps around LCA on green roof technology to be surveyed in the future. This gap framework is illustrated in Figure 3.2.

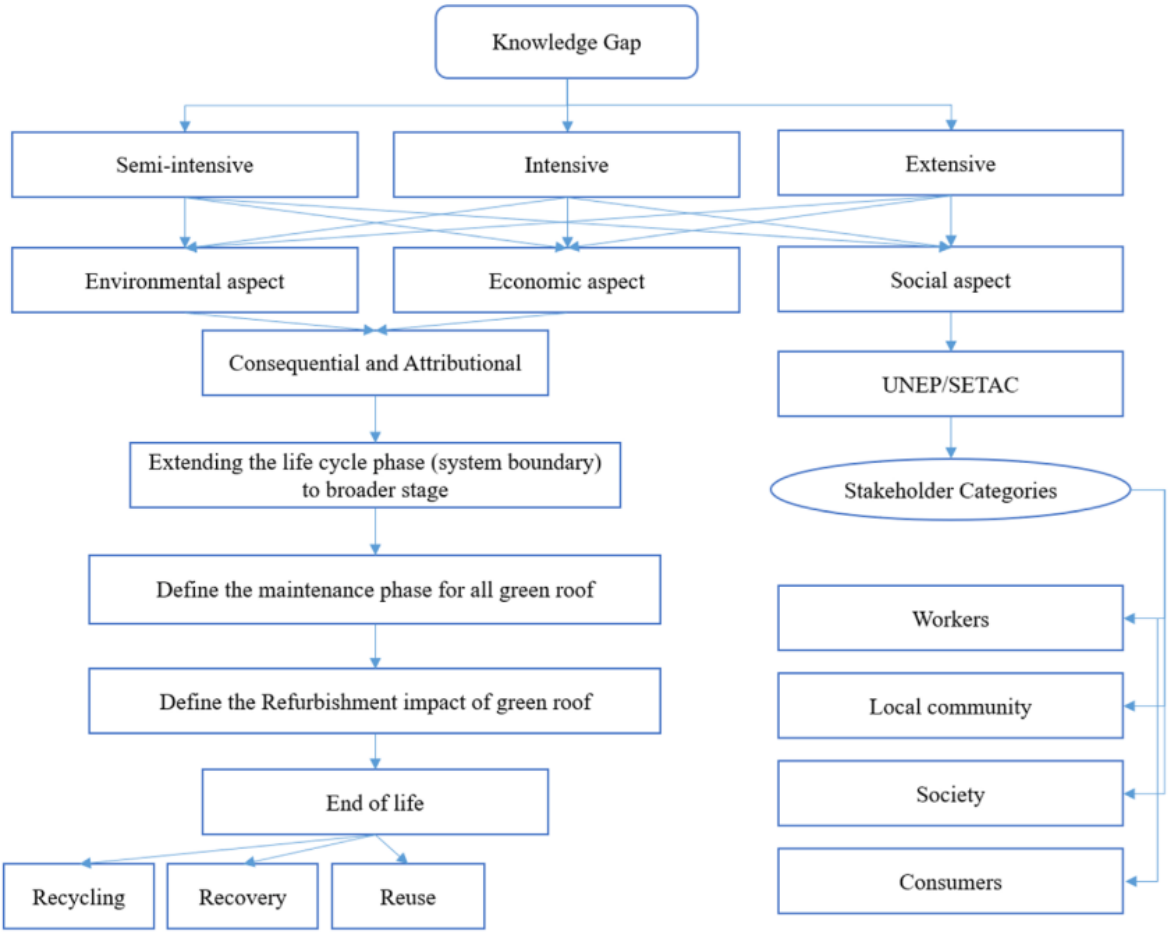


Figure 3.2: Framework of knowledge gaps and future research on LCA analysis of green roof industry (retrieved from Balasbaneh *et al.*, 2024).

3.4.2 Environmental Assessment of Green Roof Systems (Empirical Findings)

As described in paragraph 2.3, green roof structures have been pointed out as an alternative environmental solution that can contribute to a greener environment and as a key mitigation strategy for the most concerning environmental challenges, increasing biodiversity, reducing air and noise pollution, and delaying stormwater runoff.
Due to the growing use of green roof structures, it is important to understand the environmental impact linked with these systems. Despite their many benefits, compared to conventional roofs, green roofs usually demand a greater amount of materials for their construction, thus requiring additional resources. Additionally, since the majority of materials used in these systems can contribute to environmental pollution, it is crucial to first have a look at the environmental impact of the different materials used for their construction. From top to bottom, green roof systems are usually made of vegetation, growing medium, filter layer, drainage system, and root

barrier. As mentioned in paragraph 2.1, additional layers such as insulation or waterproof membrane can be added according to the system's need. Recently, the various layers and materials of green roof systems have been extensively evaluated by several researchers in order to adopt the proper materials of green roofs through LCA.

- **Vegetation**

The vegetation layer can improve the air quality and also enhance biodiversity (Dominguez *et al.*, 2020; Yang *et al.*, 2008). Due to its great adaptability, Sedum is typically the most widespread vegetation type used in many environmental impact analyses (Eksi *et al.*, 2020).

- **Growing medium**

Typically this type of layer is composed of organic matter and low-weight porous minerals such as zeolite, expanded clay, pumice, lapillus and perlite. As the substrate layer plays a major role in the system's environmental impact, its selection should be done after careful consideration. For instance, the manufacturing process of expanded clay has a large potential influence, and even at modest percentages, the effects of the production are noticeable. Similarly, compost has a high negative impact on the environment, mostly because of the gases released during the composting process (Chenani *et al.*, 2015). On the other hand, recycled building materials or industry by-products, such as crushed bricks, fly ash, and coal bottom ash can reduce the substrate's potential impacts, as the effects of their manufacture are taken into consideration during primary usage (Chenani *et al.*, 2015; Pushkar, 2019).

- **Filter layer**

Nearly all researchers that examined the effects of green roofs on the environment and took into account a filter layer did so using polyurethane or polypropylene. According to Bianchini and Hewage (2012), such materials are durable and lightweight; however polymer production process requires a lot of energy and emits harmful pollutants. Although recycled polymers are an alternative for green roofs, more environmentally friendly solutions need to be studied.

- **Drainage layer**

In most LCA studies, the examined drainage layer was made of polyethylene, polystyrene, or polypropylene. Rincón *et al.* (2014) proposed the use of recycled rubber coming from used tires as an alternate option. According to the authors, using recycled rubber instead of pozzolana can have an overall positive effect on the environmental impacts.

- **Root barrier**

The purpose of this layer is to protect the structure from plant roots and water (Bianchini and Hewage, 2012). The most common materials used for root barriers are polyethylene, polypropylene, polyvinyl chloride (PVC) or bitumen membranes. According to Chenani *et al.* (2015), polyethylene root barriers have less impact than those made out of PVC.

- **Water retention layer**

The materials usually used in water retention vary throughout the researches. Recycled or polymeric textile fabrics, expanded perlite, rockwool, polyethylene, and PVC are some of them.

After their study, Chenani *et al.* (2015) reported that in all impact categories evaluated, recycled textile fabrics have less environmental impact compared to rockwool. Additionally, rockwool was proven responsible for the highest impact when used for water retention.

- **Insulation**

Most studies consider polystyrene as an insulation layer, which is associated with high environmental impacts (Rivela *et al.*, 2013; Vacek *et al.*, 2017). However, other materials such as foam board, fibreboard, and modified bitumen can also be used.

- **Roof deck**

While in most cases the structural support is the same in distinct roof configurations and is not considered part of the vegetated roof regarding an LCA analysis, if it is included in the system, then it is the layer responsible for the largest impacts, mainly because of the materials fabrication, such as cement production. If the layer is excluded, then the insulation layer accounts for the highest impact of most impact categories assessed (Rivela *et al.*, 2013). According to the research of Bachawati *et al.* (2016), concrete and rebar were proven to be the parts of the structural support with the highest environmental impact.

Bianchini and Hewage (2012) concluded that in general, the manufacturing operation of extensive systems is less pollutant than the one for intensive systems, thanks to their smaller thickness and the overall smaller quantity of materials and maintenance requirements. However, as intensive systems are usually made with higher and denser vegetation, their air pollutant removal process ends up higher than the one of extensive systems.

Rasul and Arutla (2020) studied the environmental impact of green roof systems in Australia using the Life Cycle Assessment (LCA) method. They compared the environmental impact of several pollutants released from the different materials used for construction between a green roof and a conventional non-vegetated roof. The results indicated that green roofs impact about 3 times positively in the environment compared to the non-green roof. Similarly, Tams *et al.* (2022) compared the environmental impact of two different green roof systems: a) one conventional system with expanded clay, pumice, and compost in the substrate and a cork drainage and b) an alternative system with recycled bricks and compost in the substrate and a cork drainage. The results showed that the use of brick substrate and cork drainage provided quite promising results with regard to the reduction of global warming potential.

Another study performed by Vacek *et al.* (2017) evaluated the influence of including extruded polystyrene (XPS) and hydrophilic mineral wool into the standard green roof assembly. The results showed that XPS cannot be justified as a thermal insulation material because of its significant environmental effects associated with its production. On the contrary, different results were presented regarding the replacement of substrate using hydrophilic mineral wool. Although its production phase has high environmental consequences, there was a decrease in the environmental effects during the use phase. According to the authors' conclusion, this material can be nearly identical to natural substrates.

All in all, most researchers concluded that, as the advantages outweigh the disadvantages, it is still beneficial to install green roof systems even if they contain polymers or plastic particles. However, in order to improve the overall sustainability of green roof systems, it is crucial to look into materials that can replace the current use of polymers and plastics (Bianchini and Hewage, 2012).

3.5 Extensive accounts for the majority of the market

The green roof industry has been studied thoroughly and analyzed by type throughout the years. The choice between intensive and extensive systems can significantly influence environmental impact. Depending on the site, climate, and owner intent, both extensive and intensive systems can be successfully installed and used. However, when decision-making between intensive and extensive green roof systems, design aspects and maintenance requirements of each system are essential to be considered. Intensive systems offer a variety of design flexibility with diverse vegetation options and landscaping opportunities; however they demand a higher level of maintenance in terms of fertilization and irrigation. On the contrary, extensive systems are generally easier to maintain since they are designed with less complexity and lower plant diversity (Getter and Rowe, 2006).

According to the IMARC Group report, "Green Roof Market Report by Type, Distribution Channel, Application, and Region 2024-2032" (2022), extensive systems represent the largest segment of the market. As extensive green roofs are characterized by their low-maintenance and lightweight vegetation, they are the ideal choice for retrofitting existing buildings and structures since, in most cases, they require the minimum depth soil. These systems are known for their cost-effectiveness, as they are rather easy to install and maintain, making them a practical solution for projects with budget constraints or limited maintenance capabilities. On the other hand, intensive systems, while representing a smaller segment of the market, provide a wider variety of functionalities.

It is expected that developments in sustainability, performance, and integration with smart building systems will be the main focuses of future trends in green roof technology. As cities continue to prioritize climate resilience and green infrastructure, the development of green roof technology is expected to have a significant impact on establishing sustainable urban building practices and producing healthier, more resilient built environments.

4 Acoustic Attenuation by Green Roofs

As discussed, green roof systems have the potential to provide excellent sound isolation due to their low stiffness and high mass, and through surface absorption, reduce noise pollution in the community from traffic and aircraft as well as noise build-up in urban areas (Connelly and Hodgson, 2008). This chapter aims to examine in what way green roof systems are able to absorb sound and which absorption mechanisms perform better regarding lower frequencies. The main layers affecting a green roof's ability to absorb sound are the porous growing medium, any air voids, the water storage layer, as well as the vegetation layer. All these layers together, they form a multilayered system with a complex acoustic behavior (Van Renterghem, 2018a).

4.1 Noise Reduction Mechanisms Related to Green Roof Structures

Apart from their aesthetic perspective, green roofs, due to their characteristic layers and material properties, provide high acoustic performance. These systems are constructed boundaries between the natural exterior environment and a controlled indoor environment. They can minimize the penetrating sound waves coming from the road-rail and the air traffic. The way green roofs can contribute to sound exposure reduction is by improving the acoustic inside and outside environment because of the beneficial sound absorption and sound transmission loss through the system (Connelly and Hodgson, 2015).

Generally sound is created by the vibration of substance and is spread through sound wave that is produced because of the vibration of the medium. When sound is spreading, part of it is diffused, whereas another part is gradually weakened because of the air molecules' absorption (Li *et al.*, 2011).

4.1.1 Sound Absorption

Figure 4.1 illustrates the different paths of an incident sound wave. When the sound wave meets the surface of a material, part of it is reflected, part of it passes through the mass of the material (transmitted sound wave), and the rest of it is transferred to the material (absorbed sound wave). The amount of absorption is dependent on the porosity of the material and also on the frequency of sound that is absorbed. In general, higher frequencies are easily absorbed because of their short wavelength. When absorption occurs, the part of the sound wave transferred to the material enters the pores of the material, and part of the sound energy is converted into heat (Li *et al.*, 2011).

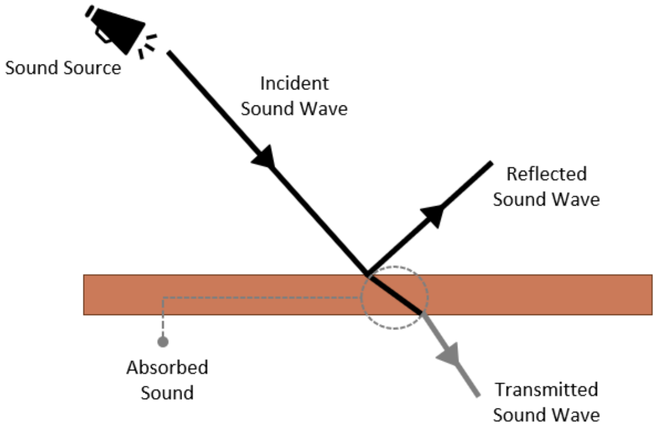


Figure 4.1: Schematic illustration of Sound Absorption Mechanism.

The most direct method for evaluating the effectiveness of sound-absorption materials is to measure its sound absorption coefficient (α). This index is adopted as the ratio of the sound energy absorbed by the material (E) to the overall incident sound energy spread and reaching the surface of the material (E_o) (Li *et al.*, 2011). In other words, the sound absorption coefficient is the ratio of the portion of sound that is absorbed and to the incident sound reaching the material. Mathematically it can be expressed as:

$$\alpha = \frac{E}{E_0} \tag{4.1}$$

Where:
α : the sound absorption coefficient of a material
E : the sound energy absorbed by the material
E_o : the overall incident sound energy spread and reaching the surface of the material

When the absorption coefficient equals one, this practically means that all the amount of sound is being absorbed (highly absorptive material), whereas when it equals zero, this means that no sound is absorbed (reflective material). A material that has an absorption coefficient of 0.20 will absorb 20% of the acoustic energy and at the same time reflect 80% of it back to the environment.

In order to reduce the level of noise by absorbing sound waves, sound-absorbing materials are usually used. These materials are typically lightweight and porous, and are designed to trap and convert sound energy into heat energy. Generally, when it comes to sound absorption in constructions, porous and resonant absorbers are used. The performance of these is evaluated using the sound absorption coefficient (α) (Arjunan *et al.*, 2024).

Through surface absorption, green roof systems have the potential to reduce the general noise build-up at the roof layer (Van Renterghem and Botteldooren, 2014). Connelly and Hodgson (2015) studied the sound absorption performance of a variety of green roof substrates and constituents. In order to do that, the normal and random incidence absorption coefficients were measured. Their findings revealed that absorption increased as the proportion of organic matter grew and reduced as moisture content and compaction increased. Amongst other findings, their study confirmed that sound absorption of green roofs is a function of substrate thickness, vegetation position, and moisture content of the substrate.

4.1.1.1 Porous Absorbers

Porous materials are materials with interconnected pores that allow sound waves to pass through and propagate in such a way that thermal effects cause acoustic energy to be depleted. Porous absorbers are generally more effective with higher frequencies. Their performance relates not only to the material thickness but also to the physical properties involved: pore size and shape, porosity, flow-resistivity as well as the complexity of the propagation paths (Fuchs, 2013; Cox and D'Antonio, 2016). Amongst others, the most common porous sound-absorbing materials are fiberglass insulation, mineral wool, as well as acoustic tiles and foams (Cox and D'Antonio, 2016).

4.1.1.2 Resonance Absorbers

Because of the size of the associated wavelengths, absorption of the lower frequencies presents a generally more challenging behavior than the higher frequencies. When large sound absorption cannot be achieved through porous materials, a different kind of sound absorber called resonant absorber can be used. Resonant absorbers are materials that vibrate when sound waves hit them, resulting in acoustic energy dissipation. The most significant difference between porous and resonance absorbers is that porous absorbers are effective for the mid and high frequencies, whereas resonance absorbers are mostly effective for low-frequency absorption. Additionally, the sound absorption for porous absorbers, depends on the material properties, while for resonance absorbers the absorption is dependent on the response of the whole system. The most common resonant sound-absorbing materials are perforated wood panels that can be used to create sound barriers and reduce undesired sound (Qiu, 2016).

There are two common forms of resonant structures: the first is the panel or membrane absorber, and the second is the Helmholtz absorber. The concepts behind resonant absorbers have been known for a very long time. While Helmholtz resonators can be designed with accuracy, membrane/panel absorbers are still designed by trial and error through experimentation (Cox and D'Antonio, 2016).

A typical absorber is formed by a cavity covered with a sheet. The sheet can either be solid and flexible to form a panel absorber (Figure 4.2a) or perforated to form a Helmholtz absorber (Figure 4.2b). According to Cox and D'Antonio (2016), in both cases the surface impedance of the resonant system is calculated as:

$$z_{s1} = r_m + j[\omega m - \rho c \cot(kd)] \tag{4.2}$$

Where:

k : in the wavenumber in air given as $k = \frac{2\pi}{\lambda}$

λ : the wavelength in air
d : the cavity depth
m : the acoustic mass per unit area of the panel
ω : the angular frequency
ρ : the density of air
c : the sound speed in air

Additionally, the terms ($j\omega m$) and (r_m) are the acoustic mass and resistance, respectively, due to the membrane/panel or perforated sheet.

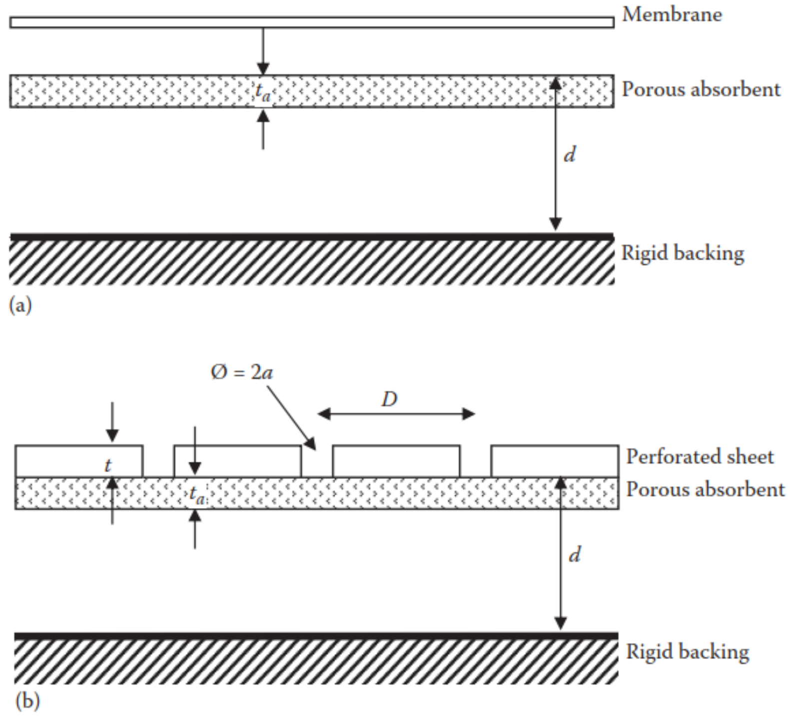


Figure 4.2: Schematic illustration of a typical construction of: (a) panel/membrane and (b) Helmholtz absorbers (retrieved by Cox and D'Antonio, 2016).

- **Panel Absorbers**

The mechanism around sound absorption of panel absorbers is energy dissipation through the vibration of the panel. This absorber is frequency dependent and is typically a panel attached to a structural element that is designed in order to absorb energy. Compared to porous and resonance absorbers, this type of resonance is not commonly used (Mobley, 2001).

- **Helmholtz Absorbers**

Resonators are used in various applications, such as musical instruments, research on acoustics, and even in engineering to reduce specific frequencies of noise. The ability of Helmholtz resonators to selectively interact with specific frequencies makes them a valuable tool in the study and control of sound waves. The simplest resonance absorber is known as Helmholtz resonator and was named after the German physicist Hermann von Helmholtz (1821-1894) who first introduced this device back in the 19th century. Usually, It consists of an air cavity, acting as a spring, with a specific volume V (m^3) connected to the area to be controlled by a narrow neck with a diameter of d and a length of l. The size and shape of the cavity, as well as the neck, determine the frequency at which the resonator acts more effectively. For single Helmholtz absorbers, the walls of the air cavity are usually rigid and the volume of the neck is smaller than that of the air cavity (Godbold, 2008). Figure 4.3 shows a schematic diagram of a single Helmholtz absorber.

When sound waves from the surrounding air encounter the opening of the neck, some of the waves are absorbed by the resonator, while others pass through it. The resonator responds most effectively to sound waves with a frequency that is determined by the volume of the air cavity and the dimensions of the neck.

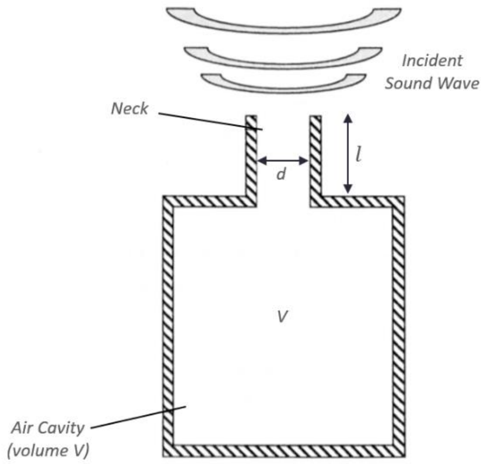


Figure 4.3: Cross section of a typical cavity Helmholtz resonator (reproduced from Godbold, 2008).

Kinsler *et al.* (1982) introduced equations to calculate the resonant frequency f_r (Hz), of a Helmholtz Resonator

$$f_r = \frac{1}{2\pi}\sqrt{\frac{s}{M}} \tag{4.3}$$

Where:
s : the stiffness of the spring calculated as:

$$s = \rho\, c^2 \frac{S^2}{V} \tag{4.4}$$

Where:
S : the cross-sectional are of the neck
V : the air cavity volume

and M: the mass calculated as:

$$M = \rho \, S \, l \tag{4.5}$$

Where:
S : the cross-sectional area of the neck
l : the length of the neck

Then substitution of the stiffness of the spring (s) and the mass (M) in equation (4.3) gives the widely used formula for resonant frequency:

$$f_r = \frac{c}{2\pi}\sqrt{\frac{S}{Vl}} \tag{4.6}$$

As the effects of the resonator's geometry on its acoustic performance should also be taken into consideration, the end correction factor δ should be added to the formula. This factor is simply used to account for the fact that the effective length of the neck is slightly longer than its physical length due to the behavior of sound waves at the open ends. For a cylindrical neck, the end correction factor, to a first approximation, is usually taken to be δ = 0.85, as is the most commonly quoted figure in texts (Cox and D'Antonio, 2016). In this case the effective length is calculated as the physical length plus the correction length 0.85r, where r is the radius of the neck.

4.1.2 Sound Transmission

Sound transmission refers to the propagation of sound waves through the different building elements. The measure of how much sound energy is reduced in transmission through the elements is called transmission loss (TL). The sound-absorbing ability of any building element can be measured in terms of a parameter called Sound Transmission Class (STC). This unit has been put forward as a class rating by the American Society of Testing and Measurement and directly describes the number of decibels (dB) of sound that is reduced when the sound waves pass through the material (Adhikari and Thapa, 2020).

Mathematically the sound transmission loss can be expressed as:

$$\text{STL} = 10 \log \frac{W_i}{W_t} \tag{4.7}$$

Where:
STL : the measured sound transmission loss
Wi : the incident sound power
Wt : the transmitted sound power

In Europe, following the international standard ISO 10140, the sound reduction index (R) is usually used to measure the acoustic properties of an insulation material (ISO 10140-2, 2010).

As a series of finite layers, a green roof system impedes sound energy as it transmits through the different layers from the exterior to the interior environment (Long, 2014). Because of their relatively large surface mass density and their low stiffness, green roofs are considered as an interesting sound insulation material. However, the existing scientific research that has assessed the transmission loss by a green roof system placed on a traditional roof system is limited.

Connelly and Hodgson (2013) studied the sound insulation in a specifically designed green roof testing set. The transmission loss of vegetated and non-vegetated systems was measured for two different sites. After evaluating different vegetated roofs varying in substrate thickness, moisture content, and vegetation type, they showed that compared to a conventional non-vegetated system, an increased transmission loss of 10 and 20 dB for the low and mid-frequency spectrum respectively, is reported for the vegetated systems. Additionally, transmission loss was found to increase in a non-linear way with substrate thickness. Particularly by increasing the substrate thickness from 50 to 150 mm, transmission loss was found to be larger at the higher frequencies.

4.2 Empirical findings on acoustic behavior of different roof systems

Given the existing literature, it can be argued that research studies on the acoustical benefits of green roofs are rather limited. The acoustical performance of green roof systems includes both the outdoor noise absorption and the insulation of indoor environments from the outside noise. With regard to this, an increase of the roof mass as well as the presence of granular material in combination with the vegetation type can highly increase the sound insulation of the system. Additionally, if there are no discontinuities like screens or skylights, the total sound insulation of the system increases highly above standards, transferring at the same time the problem to vertical structural elements, particularly glass components. Connelly and Hodgson (2008) studied the acoustical characteristics of green roofs and their contribution to the acoustical environment. Their study confirmed that this effect is particularly relevant to constructions near airport areas, where the noise sources are at a higher level than the structures. According to their empirical findings on two low-profile extensive systems of 33 m^2 total area, an increase of 5 to 13 dB in transmission loss over the low and medium frequency spectrum was indicated, whereas a 2 to 8 dB increase in transmission loss in the higher frequency spectrum was noticed, compared to the transmission loss of a conventional reference roof of the same size. In other words, they showed that in the lower frequency range, there is a slight enhancement of the absorption of the substrate-vegetation system, while at higher frequencies, the presence of vegetation leads to a decreased absorption compared to uncovered substrates.

Usually, the noise produced by the different sources in urban environments is reflected by the rigid surfaces of conventional rooftops. As the sounds bounce off the different surfaces, this results in an increase in the sound levels (Pittaluga *et al.*, 2011). On the other hand, a green roof structure usually is a non-homogeneous surface that consists of granular materials, drainage, and vegetation layers with high sound absorption characteristics. Pittaluga *et al.* (2011) compared and evaluated the acoustical performance of different green roof systems. They performed measurements on three green roof system samples, different for greenery setting, maintenance activities, and containment system. After the experimental evaluation of the absorption coefficient and acoustic impedance for the different samples, they calculated and compared the diffusive sound absorption coefficient as well as the normal and diffusive weighted sound absorption coefficients for the three different samples. Their findings showed that compared to the performance of the conventional horizontal roof, the green roof systems provided a generally better level of sound absorption.

Similarly to the aforementioned study, Van Renterghem and Botteldooren (2009) investigated the influence of a green roof structure on building façade noise load coming from road traffic at a close distance. They studied the acoustical effect of the green roof presence in two different configurations of non-directly exposed to the road façades. According to their results, an extension of the green roof surface resulted in an increase of positive effects on the façade noise load. They also discovered that by increasing the traffic speed, noise reduction effects grow more in the case of light vehicles compared to the case of heavy vehicles. A more recent study by the same authors (2011) analyzed the in-situ measurements of sound propagation over flat, extensive green roof systems for five different cases, with single or double diffraction. Their measurements showed that the vegetated roofs can have a significant noise reduction effect compared to the non-vegetated flat roof cases, when only diffracted sound waves reflect.

Despite the large use of green roofs in common practice, the experimental data to define their actual sound attenuation is still limited. This is due to the different configurations that green roofs might have, depending on their position, thickness, greenery, as well as materials used and stratigraphy. In the existing literature, these aspects are not much considered. Hence, in an attempt to reduce this literature lack, this study aims to explore a sustainable design approach for green roof systems in order to improve their acoustic absorption performance.

4.3 Noise reduction mechanisms by substrates

In the previous paragraph it was explained that vegetated roof systems can absorb sound in different ways and at different frequencies. As engineering systems that are used widely, green roofs vary in terms of design and implementation. As natural systems, they usually vary in terms of the ecological succession of the different plant species (Köhler, 2006). As described in paragraph 2.1, typical green roofs usually consist of several layers. Those that have a direct impact on the system's sound absorption capacity are the porous growing substrate, the water retention fabrics, the presence of air voids, and the plant layer. All these layers together form a multi-layered system with a complex acoustic behavior. Amongst the different layers that can be distinguished in a green roof system, one of the most complex to characterize is the vegetative substrate. Usually the substrate varies in terms of substrate mix and constituents, the thickness of the substrate, the root structure, as well as the in-situ microclimate (Ampim *et al.*, 2010). For an extensive system, usually the growing substrate consists of granular materials with open pores, which are considered a characteristic material property to allow sound penetration.

Generally, the substrate is one of the most important layers regarding sound absorption. Its high porosity facilitates the absorption of sound waves, hence making it serve as an acoustic absorber (Davis *et al.*, 2017). In order to be able to get a deep understanding of the sound absorption characteristics of an established green roof system, it is essential to primarily examine the absorption behavior of the substrate layer.

4.3.1. Requirements for a green roof substrate

Over the past few years, the substrate layer of green roof systems has become increasingly important. When considering the growth of a plant, the substrate layer is the one that serves as the base for the plant growth. The substrate must be able to accommodate not only the plants that grow on it but also the part of the plants that remain underground (Chaffey, 2006). The thickness and physical properties of a vegetation support layer is of great importance with regard to how well the plants on it are supplied with nutrients and water. The components, composition, and thickness of a green roof substrate can vary according to the type and location of the system, the climate conditions, as well as costs and materials availability. Hence, the ideal green roof substrate varies and is therefore one that can provide stable growth for plants, including a favorable rooting environment and essential nutrients, as well as a free drainage system with available plant water. According to Ampim *et al.* (2010), a green roof substrate should therefore comply with the following:

a) In order to help with the load reduction of the roof system, the substrate layer should be lightweight.
b) The substrate of a green roof must be sufficiently porous to provide internal air circulation and free drainage to prevent excessive water buildup. Most substrates have a granular structure. In other words, the aggregates are separated from each other in a loosely packed arrangement.
c) Additionally the substrate should contain a percentage of sand. The voids between the sand particles allow water free drainage and air entry into the soil. The percentage of organic matter provides a balance of drainage and water storage, while the proportion of organics to minerals varies depending on the vegetation requirements, the thickness of the substrate layer, and the maintenance protocol.
d) The substrate should also be able to retain sufficient water and nutrition in order to support long-term plant growth, but not excessive in order to prevent unnecessary plant growth or lack of oxygen required for the vegetation roots.
e) Last but not least, vegetated roof substrate should be structurally stable and capable of resisting excessive compaction in the long term.

4.3.2 Key factors in substrate sound absorption

In order to get a better understanding of the acoustic behavior of the substrate layers, it is essential to first understand the basic determinations around a set of physical parameters that have a significant impact on the acoustical properties of most porous materials. For the purposes of this study, these parameters are porosity, flow resistivity, tortuosity, and material thickness.

- **Porosity**

According to the aforementioned requirements, the substrate layer should be a porous material with open-to-the-external-environment air voids in its medium. The percentage of void space is the parameter that mainly affects the sound absorption capacity of a porous material and is also known as the medium's porosity (φ). When a sound wave enters the medium's pores, there is a loss of acoustic energy. This dissipation of energy from the propagating acoustic wave is known as attenuation. The air molecules within the existing cavities or channels start to vibrate, converting part of the sound energy slowly into heat (Arenas *et al.*, 2010). Usually soils have porosities of 10 to 40% (Rossing, 2007). Cao et al., (2018), presented an overview on the design and fabrication of the most commonly used porous sound absorption materials. In most cases, it was indicated that materials with smaller pore size and higher porosity tended to exhibit larger sound absorption coefficients at the lower frequencies.

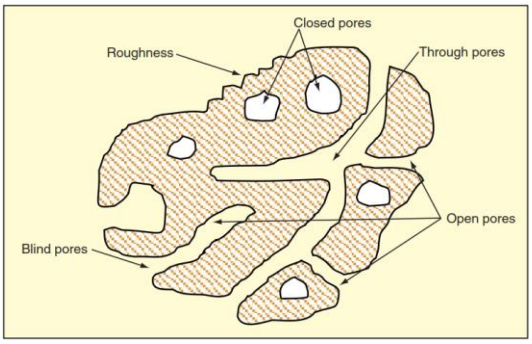


Figure 4.4: Cross section illustrating porosity. In case the grains or crystals of a material fit together very tightly, there are no gaps or pore spaces between the grains or crystals. In that case the pores are called closed, they are totally isolated from their "neighbors" and the material has no porosity (Cross section taken from Arenas *et al.*, 2010).

- **Flow-resistivity**

The ability of a porous material to attenuate sound depends on its flow resistance, which is the degree of difficulty with which the air can flow through the open pores of the material (Arenas *et al.*, 2010). According to Rossing (2007), flow resistivity (σ) is one of the most important characteristics of a ground porous surface that can influence its acoustical properties. If a substrate has a high value of flow resistivity, this means that the air has difficulty flowing through it. The values of flow resistivity can be determined either empirically through laboratory experiments or by analytical calculations. Additionally, porosity and flow resistivity present an inverse proportionality relationship; as porosity decreases, flow resistivity increases.

- **Tortuosity**

Porosity itself is not enough as a parameter in order to characterize a substrate. The pores should be interconnected, forming air void passages. A measure of the shape of the air void passages and the effect that this can have on the material's sound absorption properties is known as tortuosity (α_∞) (Crocker and Arenas, 2007). In particular, when an acoustic wave enters the air void passage, in most cases it has to propagate through a complex path instead of simply flowing in a straight direction. The complexity of this propagation can be expressed as the tortuosity of the medium. Tortuosity is completely dependent on porosity. The most common measuring method of tortuosity is based on ultrasonic sound velocities (Cox and D'Antonio, 2016).

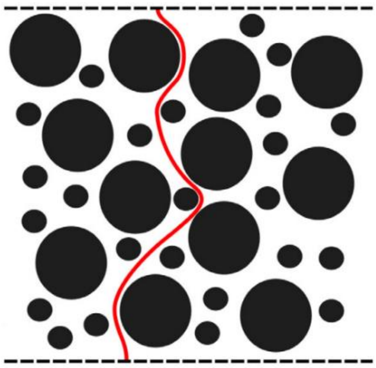


Figure 4.5: Schematic illustration of the concept of geometrical tortuosity (taken from Tjaden *et al.*, 2016).

- **Substrate's thickness**

As it is generally the case with most common porous materials, sound absorption typically increases with substrate thickness and frequency (Van Renterghem, 2018c). Moreover, the thickness of a porous material has a great influence on the position of the peak value in the frequency spectrum. Particularly, the higher the thickness of the material, the lower the frequency at which the peak value occurs (Knapen *et al.*, 2003). Generally speaking, an increase of the absorption in the low and mid frequency spectrum usually can be regarded as a result of the material thickness increase (Cox and D'Antonio, 2016). Hence, if low and mid frequencies are not of great importance, then a less thick substrate can be chosen. In his study, Van Renterghem (2018c) mentioned the importance of porous substrates in order to properly allow sound penetration and particle interaction, leading to sound absorption.

Van Renterghem and Botteldooren (2009) examined the influence of substrate thickness on the building façade load noise because of light and heavy traffic for both intensive and extensive roof systems. According to their findings, in the case of light traffic, the influence of the different thicknesses (5, 10 and 20 cm) in both extensive and intensive systems was rather insignificant. On the other hand, the influence of substrate depth in the case of heavy traffic was large in case of the extensive roof systems. For the intensive systems, the influence of different substate thicknesses was very small. The same authors showed that a relatively small substrate thickness and vegetation presence seem to have more positive results for higher frequencies, while for noise reduction in the lower-frequency spectrum, a larger substrate thickness is required.

Davis *et al.* (2017) studied the acoustic performance of vertical green modules with and without vegetation. Six different configurations were examined and assessed. Their findings revealed that an increase in the substrate thickness results in a higher sound absorption coefficient in the low frequency range. Additionally, it was observed that regardless of the significance of low frequencies in a study, a substrate thickness of 8 to 10 cm appeared to be an optimal minimum, yielding satisfactory sound absorption outcomes overall.

Finally, Yang *et al.* (2013) examined how the absorption and scattering coefficient values are affected by considering various factors such as the soil thickness, moisture content, as well as the vegetation density and size. Their measurements showed that amongst the different substrate thicknesses (50, 100, 150 and 200 mm), even the soil with the smallest thickness of 50 mm provided a significant value of absorption coefficient (around 0.9 for the frequency of 1000 Hz), while an increase in the soil thickness provided a very slight change of the absorption coefficient.

4.3.3 Acoustical characterization of different soils

Unlike most natural soils, which develop in situ over time, green roof soils are manufactured substrates that can contain a variety of natural or modified ingredients. Aggregates coming from natural minerals such as sand and clay or modified minerals like expanded shale and slate are common in many applications (Hakeem *et al.*, 2016). The main challenge with these manufactured soils is the achievement of a balance between optimal physical properties like water drainage and optimal plant growth properties. In acoustical terms, most green roof structures can be characterized as granular, sound-absorbing materials. In order to determine the best-fitting mix proportions, it is recommended to conduct a preliminary study using a prototype, prior to the initiation of a green roof structure installation.

There is little published literature reporting the relationship between the properties of a green roof substrate and its acoustical characteristics. In order to determine which physical soil properties contribute more to the absorption of sound energy, Connelly and Hodgson (2015) conducted an experimental investigation of the sound absorption characteristics of six different substrates. The different samples represented a range of vegetated roof systems composed of natural materials. The main soil constituents were sand, compost, and pumice. The six samples differed in organic matter percentage, particle density, water storage capacity, particle size distribution, and total porosity. According to their measurements, the absorption coefficients of the examined substrates corresponded positively with organic matter percentage and negatively with moisture and compaction. With the conditions of moisture and compaction removed, sand seemed to have the lowest values of absorption coefficient. Compared to sand, pumice had a higher absorption coefficient, whereas amongst the three, the compost sample provided the highest absorption range for the low frequencies (f < 300 Hz).

4.3.4 Influence of water content on sound absorption capacity

The presence of water in any porous material can affect its absorbing characteristics. An increase in water content can cause several negative effects, like reduction of the effective layer thickness, swelling of the substrate particles, pore clogging, as well as water exchange between the different system layers. Especially in dense substrates, a high water content can significantly disadvantage its absorption characteristics. On top of that, when fully saturated, the substrate surface can be compared to a perfectly reflecting layer (Van Renterghem and Botteldooren, 2014).

Generally the moisture content in the substrate of a green noise control element is a physical property that affects the system's acoustical characteristics (Horoshenkov *et al.*, 2011). In general, the less the water content is in a substrate, the more enhanced the sound absorption will be. Water content is one of the most difficult parameters to manage. Typically, the substrates used in extensive green roofs have a lower water-holding capacity than those used in intensive systems. Clay-based substrates have the ability to keep a relatively good moisture content and also provide surface that attract plenty of nutrients plants need. However, clay substrates can often become waterlogged and deprive vegetation roots of oxygen. Therefore they are not predominant in green roof substrates as in natural soils (Conelly, 2011).

Yang *et al.* (2013) measured the sound absorption for eight different soil conditions, starting from no watering (dry) condition and for seven increases in the moisture content. The total amount of moisture added to the soil was 10 lt/m^2. Based on their measurements, decrease in absorption coefficient was observed to be proportional to the increase in the soil water content.

Similarly, in an attempt to evaluate the influence of rainfall on the noise shielding through a green roof system, a real-scale sound propagation experiment, conducted by Van Renterghem and Botteldooren (2014), was set up near the edge of a tall building equipped with an extensive green roof system. The results showed that the sound propagation was especially sensitive to the substrate's water content in the frequency range of 250 Hz to 1250 Hz. Moreover, the difference in the system's noise attenuation between a relatively dry and a fully saturated substrate was up to 10 dB.

Finally, Horoshenkov *et al.* (2011) studied the acoustical performance of soil types used as substrates in green noise control elements as a function of moisture. The evaluated substrates consisted of two different soil types: a lightweight substratum with polymer gel and an ordinary clay-based soil. It was shown that compared to the low-density substratum, the addition of a relatively small amount of water to a clay-based soil sample can result in significant variations of its sound absorption coefficient values. As the degree of saturation is remarkably different for the two soil types, addition of the same amount of water to the low-density substratum sample seemed to have a considerably smaller effect on the sound absorption coefficient values for the low and mid-frequency spectrum and slightly larger for the high-frequency spectrum.

4.4 Noise reduction mechanisms by vegetation

In the last few decades, studies on sound propagation through vegetation have been a quite popular research topic. Several studies have been conducted to demonstrate the effect of vegetation on noise reduction. The sound absorption characteristics of vegetation become more and more important as it is increasingly grown on building roofs and façades. Vegetation consists of two main components, including the growing media and the plant (both the underground and the aboveground part). The influence of the plant layer on sound absorption is not directly obvious. Although Horoshenkov *et al.* (2011) showed that specific plants are able to absorb acoustic waves reasonably well, the acoustic system formed by grass and vegetation on top of a porous material is quite more complex. They also reported that the density of plant leaf area as well as the angle of leaf orientation have been recently proven to affect vegetation sound absorption .

Additionally, Yang *et al.* (2013) examined the influence of vegetation type, size, and density on the sound absorption coefficient. It was shown that sound absorption was dependent by the vegetation's dimensional characteristics as well as the proportion of each species. In particular, vegetation with relatively large leaves, when planted in large density, can be essentially beneficial for the higher frequency spectrum. In general, the absorption coefficient is increased with increasing vegetation density and coverage. Their results indicated that with increasing the vegetation coverage, a slight increase in the absorption coefficient was observed at low and mid-frequency spectrum.

4.5 Conclusion

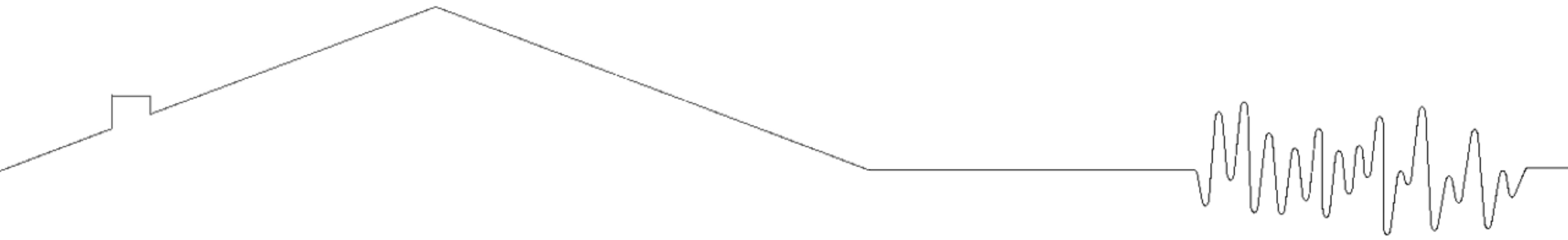
The theory summarized in the current paragraph is an attempt to answer the research sub-questions related to the literature study and, in particular:

1. What are the main sound absorption mechanisms, and which of them work in the lower frequencies ($f < 250$ Hz)?
2. How are green roof systems classified, and how do they absorb sound?
3. Which of the green roof layers are the most efficient regarding low-frequency sound absorption?
4. What are the key sustainability challenges regarding the growing use of green roof systems?

- Being able to mitigate the impact of aircraft noise is critical in order to maintain a healthy living environment.

- Green roof structures are increasingly used as part of sustainable building constructions. Due to their sound absorption and transmission-loss characteristics, they present several potentials to improve the acoustic conditions not only to the indoor but also outdoor environment.
- First of all it is of great importance to maintain a healthy and well-designed green roof system. Therefore it is essential to ensure that through the design and maintenance process the basic criteria are met. Some of the key parameters are:
    a. Structural factors like additional loading is some of the main parameters affecting the sustainability of a vegetated system.
    b. It is vital that the waterproofing and drainage systems of the structure are robust in order to ensure long-term root resistance and proper management of the excessive water.
    c. Substrate and vegetation type must be carefully selected based on the system's application.
    d. Fire and wind loads should also be taken into consideration during design.
    e. Easy access to the structure is important considering the installation and maintenance processes.
- Green roof systems have many advantages compared to conventional roofs. However, as they are made out of several layers, they require a greater amount of materials for their construction, hence more resources. It is therefore essential for decision-makers, to fully understand the environmental implications associated with these systems during their lifecycle.
- Several studies have shown that the sound absorption of a green roof structure is strongly dependent on the substrate thickness, vegetation type and moisture content. Compared to a conventional non-vegetated roof system, it has been proven that depending on the substrate thickness and moisture content, transmission loss of up to 10 dB for frequencies lower than 300 Hz is possible for green roof systems.
- As green roof substrates are the most important part of any green roof system, they can play a major role with regard to sound absorption. An appropriate substrate is expected to be stable, lightweight, and porous enough to facilitate water drainage and unhindered plant growth. Studies have shown that due to its porous nature and composition, substrate is the main absorber material of a vegetated system.
- Although substrate is considered primarily responsible for the biggest part of sound absorption, vegetation can also attenuate sound in different ways. Based on their type and density, it has been proven that dense vegetation can be essentially beneficial for higher frequency sound absorption and less so for the low and mid-frequency spectrum.

This chapter showed that the presence of green roof systems can contribute to the reduction of sound levels. Especially the porous substrate layer is the one that can absorb the lower frequencies more effectively. However, in order to achieve enough sound attenuation, an increased required substate thickness can occur, which, however, does not comply with several sustainability principles. Therefore, it would be inefficient to use porous absorbers for mid and lower-frequency sound absorption. In an attempt to address this problem, the potential of an integrated, separate, low-frequency absorbing system will be further investigated.



EMPIRICAL PHASE

5
Testing Procedure

With the present developing focus on noise control issues and the rise of sound quality as a significant part of product design, acoustic material testing is turning out to be progressively relevant to specialists, engineers, and manufacturers of different industries. During acoustic material testing, different acoustic characteristics of materials are determined in terms of absorption, reflection, impedance, and transmission loss (Tie *et al.*, 2020). For the purposes of this academic research, focus is given on the acoustic absorption. In order to determine the acoustic properties of materials, many different methods can be used. These methods mainly involve exposure to known sound fields and measuring the effect of the material's exposure to the sound field. The selection of the most suitable method depends on the complexity, boundaries, as well as the context of each research. With regard to their classification, the measurement techniques can be categorized to reverberation chamber techniques, used for large-scale applications, impedance tube methods, and free field measurement techniques (Hiremath *et al.*, 2021).

5.1 Impedance Tube Method Principle

When a travelling sound wave comes into contact with a sound-absorbing material, it cannot propagate without being changed. Among the numerous wave phenomena that can occur during this circumstance, reflection is the one with the greatest practical significance for an impedance tube measurement. In an impedance tube, the measurement is limited to the measurement of sound pressure level, and usually, only a resultant sound pressure level is measurable (Hiremath *et al.*, 2021).

The impedance tube method is one of the most common techniques to quantify the sound absorption performance of acoustic materials. Generally, measurements using an impedance tube require relatively small specimens. Specimens with small diameter (≤ 30 mm) are generally used for high-frequency tests, whereas specimens with larger diameter (between 30 mm and 100 mm) are used for low-frequency tests. In the impedance tube, the test sample is placed at one end of an airtight, smooth, and circular tube. Generally, impedance tube measurements are performed using different techniques, including pressure-based and velocity-based methods. One of the most widely used methods to measure the acoustic properties of a material is the transfer function method, which typically requires the use of one, two, or multiple microphone points (Tie *et al.*, 2020)

- **The Two-microphone Transfer Function Method**

Nowadays, the transfer function method is the more widely used technique to measure the acoustic properties of several materials. This method requires two mounted microphones within the tube. Figure 5.1 shows the schematic diagram of the transfer function method. The transfer function method, in contrast to the standing wave method, which uses a tone signal to measure the absorption coefficient for each of the frequencies, uses a wide range of frequencies, and the measured transfer function of the spectra from the two microphones is used to calculate the absorption coefficient (a). As a result, a single measurement can calculate the absorption coefficient for a wide range of frequencies of interest.

According to the ISO 10534-2 Standards (1998), the sound absorption coefficient is then determined by:

$$\alpha = 1 - |r|^2 \tag{5.1}$$

Where:
R : the measured reflection coefficient calculated as:

$$R = \frac{H_{12} - H_1}{H_R - H_{12}} \cdot e^{2jkx} \tag{5.2}$$

where H_1 and H_R are the incident and reflection transfer respectively and are calculated as:

$$H_1 = e^{-jks} \tag{5.3}$$

$$H_R = e^{jks} \tag{5.4}$$

Where:
j : an imaginary component
k = $\frac{2\pi f}{c}$ the acoustic wavenumber, f the frequency, c the speed of sound
x : the distance of the sample from the nearest microphone calculated as:
$x = s + x_2$ with s the distance between the two microphones and x_2 the distance between the sample and the microphone located in position 2
H_{12} is the transfer function between positions 1 and 2. For complicated acoustic transmission function, the following equation holds:

$$H_{12} = \frac{p(x_2)}{p(x_1)} = \frac{S_{12}}{S_{11}} = H_r + jH_i \tag{5.5}$$

where:
H_r : the real component of the transfer function H_{12} ,
H_i : an imaginary component of the transfer function H_{12} ,
S_{11}: the power auto-spectral density of the signal (from microphone 1),

S_{12} : the cross power spectral density of the signal (from microphones 1 and 2).

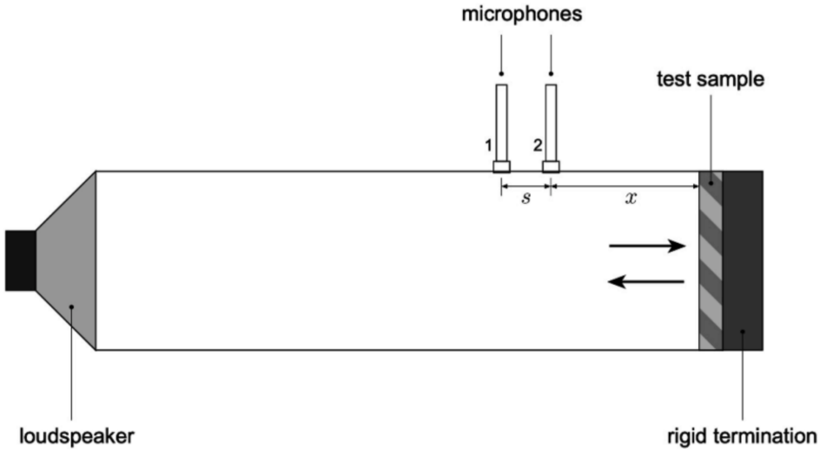


Figure 5.1: Schematic representation of the transfer function method.

5.2 Sample Testing

5.2.1 Selection Procedure

In order to identify the acoustic properties of each system, it is essential to determine its acoustical behavior. Based on the literature study and the research conducted on the market's available systems, it was essential to consider green roof types that offer flexibility both in installation and maintenance. Another critical parameter affecting the selection procedure was the potential application of the system in noise mitigation strategies. After extensive research on green roof typology and on industry representatives, Sempergreen, one of the market-leading organizations in green wall-roof construction, offering a variety of green roof systems and products to meet many different needs, was contacted with regard to the project's requirements. For the impedance tube measurements, one intensive and four extensive systems were chosen. Their easy installation and adaptability with the local climate, combined with their layering and system thickness, make them valuable candidates for investigation and validation of their acoustic performance. The systems selected from Sempergreen for the study are briefly presented below:

Traditional Sedum Roof

A Traditional Sedum roof is an extensive green roof system that can be applied to a flat or slightly sloping roof (0-5°). The structure of this system consists of a protective cloth, drainage layer, substrate layer and a Sempergreen Sedum mix mat made out of different Sedum types. The substrate layer contains soil and nutrients, providing life for several insects, and is produced in accordance with the German FLL guidelines for the planning, execution, and upkeep of green roof sites. In this light but nutritious soil, the different Sedum plants ensure a stable rooting, so that they can grow fast and remain strong after installation. This, in combination with the fact that strong Sedum species are used, eliminates the maintenance requirements of a Traditional Sedum System.

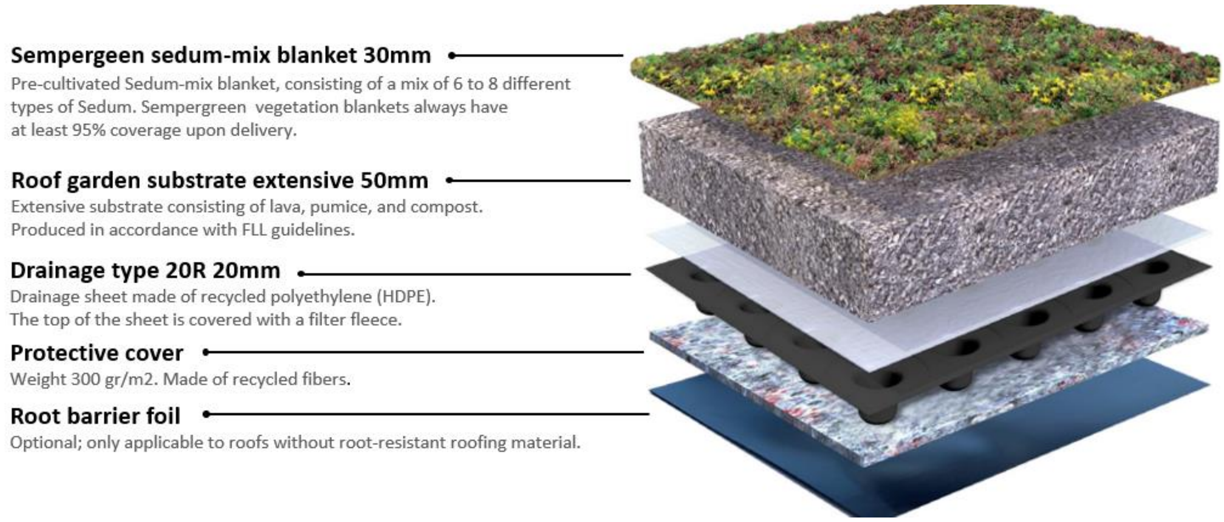


Figure 5.2: Cross section of the Sempergreen Traditional Sedum Roof (retrieved online from Sempergreen).

Lightweight Sedum Roof

This system consists of a drainage layer, a lightweight substrate roll made out of mineral wool fibers, and a Sempergreen Sedum mix mat. The eight times lower weight of this system makes it an alternative solution for roof decks with lower load-bearing capacity that cannot support the weight of a typical Traditional Sedum system. As a result, almost any roof is possible to become greener. The Lightweight Sedum System can be used on roofs with a maximum inclination of 20°. Due to the open structure of the substrate roll, satisfactory root growth and distribution is ensured, whereas the capillary behavior of the mineral wool ensures effective rainwater buffering. Finally, the fact that the layers of this system are supplied as rolls makes the overall installation a fast and easy process.

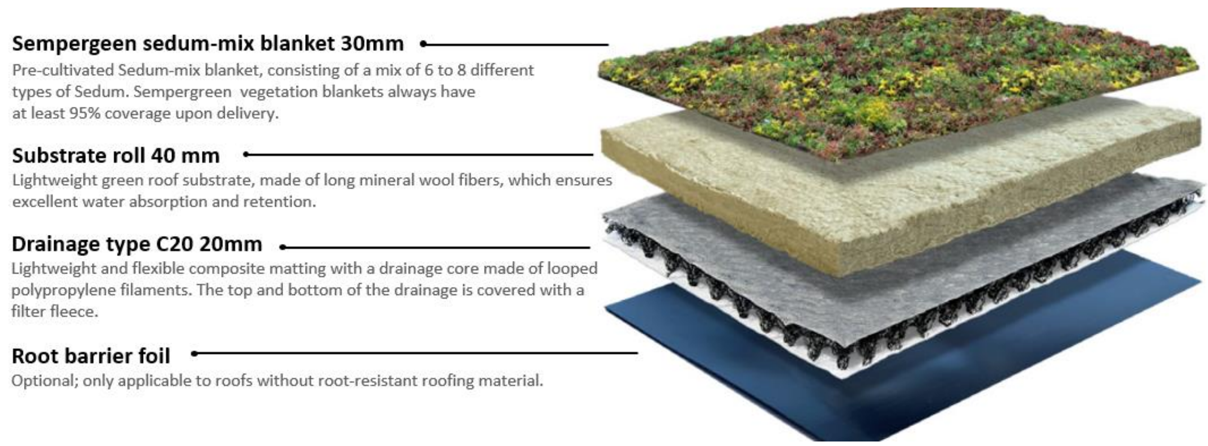


Figure 5.3: Cross section of the Sempergreen Lightweight Sedum Roof (retrieved online from Sempergreen).

Biodiverse Green Roof

The Biodiverse green roof system consists of a drainage layer and a layer of intensive roof substrate of at least 120 mm thickness, covered with a flowery Sempergreen Biodiverse mat. This mat, called Bees & Butterflies, has been bred with a mix of more than 20 native plants that are attractive for bees, butterflies, and other kinds of insects.

Figure 5.4: Cross section of the Sempergreen Biodiverse Green Roof (retrieved online from Sempergreen).

Lightweight Biodiverse Green Roof

Similarly to the Biodiverse system, its lighter version, the Lightweight Biodiverse System consists of a drainage layer and a layer of 70 mm extensive roof garden substrate, on top of which the Biodiverse Sedum mat is placed. The lightweight system is ideal for structures with limited load-bearing capacity.

Figure 5.5: Cross section of the Sempergreen Lightweight Biodiverse Roof (retrieved online from Sempergreen)

Detention Roof

The Sempergreen Detention system is used to temporarily collect rainwater in such a way as to effectively control and delay the drainage of water. Due to its lightweight construction, this system is an ideal retention solution for sloped roofs of existing buildings and renovation projects. The construction of this system consists of a detention layer, a storage layer made out of solid-wall tubes, a mineral wool-based substrate roll, and a Sedum mix mat. The detention layer uses frictional force to ensure that the rainwater collected in the storage layer is drained slowly.

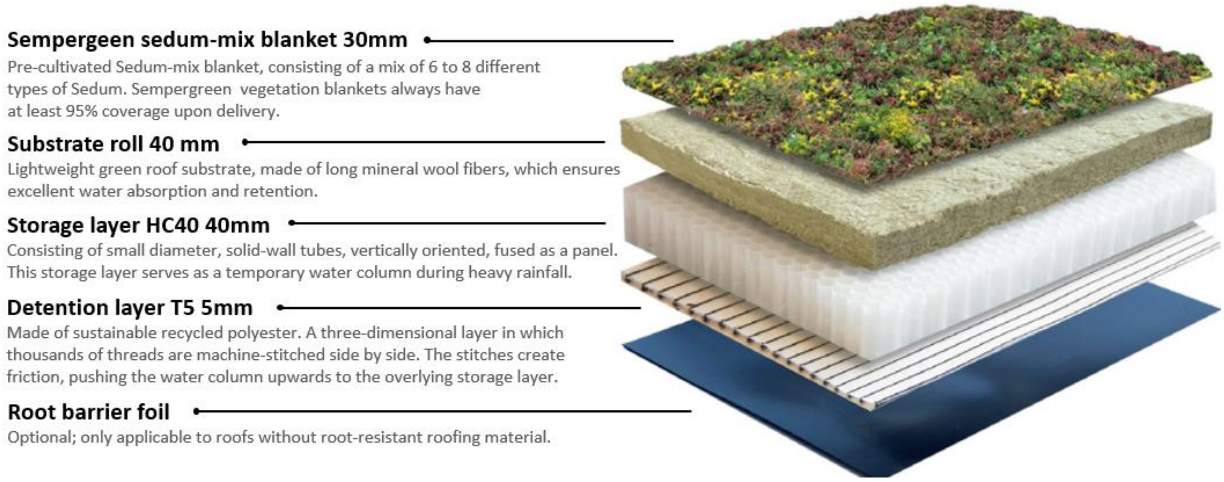


Figure 5.6: Cross section of the Sempergreen Detention Roof (retrieved online from Sempergreen).

After the green roof systems were selected, the collection of the materials followed. A visit to the head facilities of Sempergreen in The Netherlands was conducted, and all the necessary layers were collected. Ensuring practical transportation was important; therefore cutting the materials into pieces of particular size was necessary to ensure that everything is possible to be lifted and transported. Furthermore, in order to ensure that the quality of vegetation and substrate layers remain unaltered, careful storage and an appropriate environment had to be ensured until the construction of the relevant samples.

5.2.2 Preparation Procedure

In order to conduct the impedance tube measurements and make sure that the testing samples were compatible with the measurement equipment, preparation was required once the materials were collected. While the procedure for the different covers, foils, and sheets was straightforward and only required precise cutting to the appropriate diameter, as illustrated in Figure 5.7, the process for the extensive and intensive substrates and the vegetation blankets was slightly more challenging. Figures 5.8 and 5.9 illustrate the procedures for preparing the vegetation and substrate test samples, respectively. To prepare these samples, it was necessary to construct particular sample holders. Since the sample holders needed to be flexible in order to achieve a smooth cylinder shape, it was decided they be made of corrugated cardboard. The use of cardboards ensures, firstly, that the enclosed material is evenly distributed throughout the entire volume of the sample holder, achieving the most homogeneous distribution possible, and secondly, that a protective net is possible to be attached on the top and bottom of the sample holders.

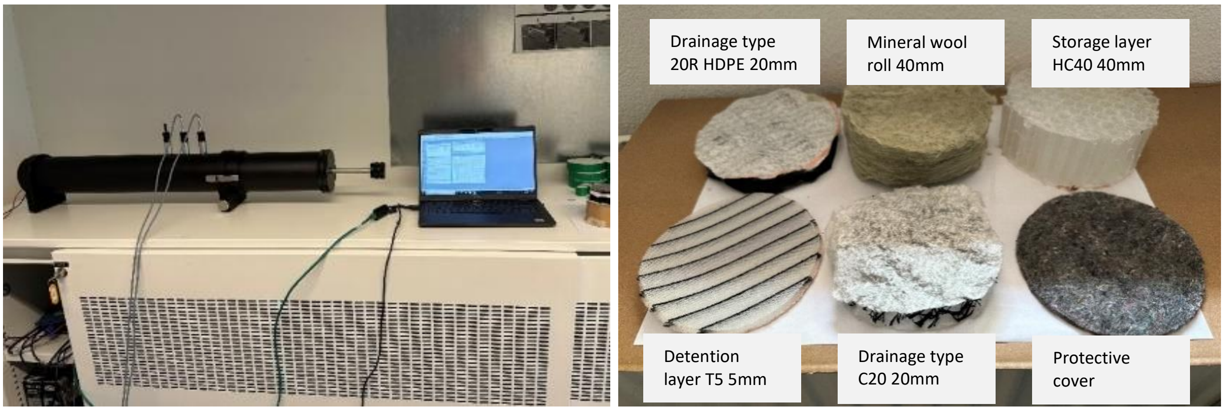


Figure 5.7: *Left:* The Impedance Tube setup used for measurements. *Right:* The different materials needed for the examined systems adjusted in circular shape with a diameter of 10 cm.

Conducting measurements in the impedance tube presents significant challenges, as the required procedure can alter the original specimen morphology, especially for vegetation layers. To minimize these challenges, sample holders were carefully selected to accommodate the vegetation blankets without excessive compression or interrupting the height of upper grass and herbs. However, the procedure proved to be slightly challenging for the vegetation blankets, where a few stems had to be trimmed as their size exceeded the diameter of the sample holders. By ensuring that all the different layers are suitably adjusted to fit in the impedance tube in the best possible way, the desired intention was to achieve realistic settings to the fullest extent.

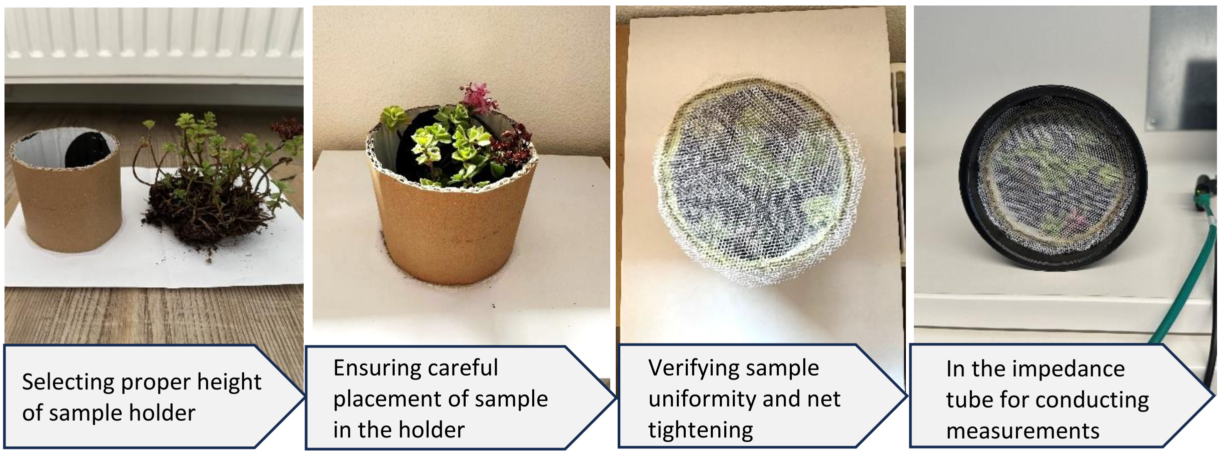


Figure 5.8: Procedure of preparing the vegetation blanket samples to fit in the impedance tube.

Similar sample holders were constructed to accommodate the intensive and extensive layer of substrate consisting of lava, pumice, and compost. Three different heights were used for the different systems: 5 cm, 7 cm and 12 cm. Due to the substrate's loose nature, it was essential to ensure that the protective nets would be properly stretched to hold the soil particles in place. Furthermore, it must be ensured that there are no gaps in the vertical orientation so that the substrate can remain tightly contained within the sample holder (Figure 5.9).

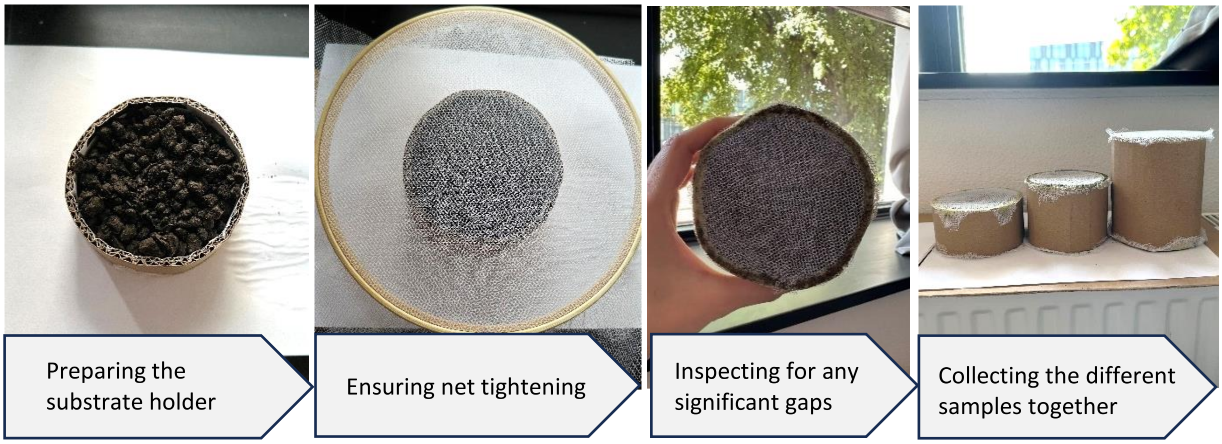


Figure 5.9: Procedure of preparing the extensive substrate test samples to fit in the impedance tube.

5.3 Measurement Setup

For the measurements of the testing samples, the Impedance Tube Kit Type 4206 from Brüel & Kjær was used, as depicted in Figures 5.7 and 5.10. Measurements were conducted based on the two-microphone transfer function method described in ISO 10534-2. A large tube with a diameter of 10 mm was used, with a microphone spacing of 50 mm and a frequency range from 50 Hz to 1.6 kHz. The measurements were conducted using the Pulse Acoustic Material Testing LabShop Software (Version 19.0.0.128) by Brüel & Kjær. A power amplifier was connected to the impedance tube loudspeaker that was emitting quantified sound waves. The produced random sound waves propagated within the tube, interacting with the specimen an causing reflection. By measuring the sound pressure level at two specific microphone locations along the length of the tube and by making calculations that meet the ISO 10534-2 standards, the sound absorption coefficient of the multilayered specimens was determined.

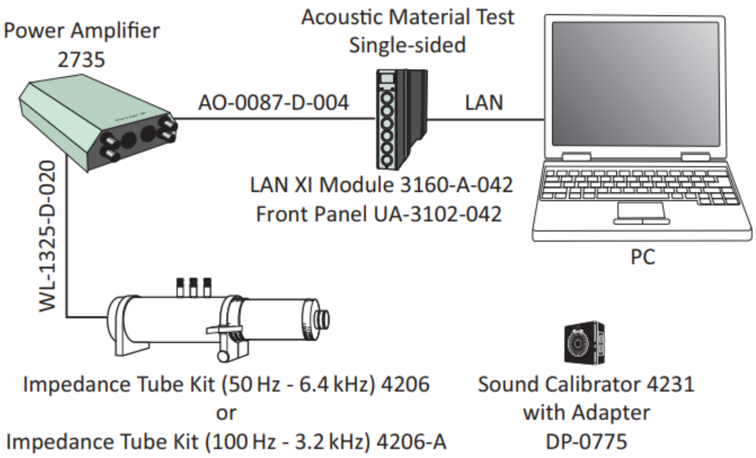


Figure 5.10: Schematic illustration of the measurement set up kit from Brüel & Kjær.

As the Pulse measuring system complies with the ISO 10534-2 standards, prior to the beginning of measurements, there was a set of correcting actions that had to be taken with regard to any microphone mismatch, involving microphone calibration as well as determination of the transfer function between the two microphone locations.

5.4 Results Analysis

Impedance tube measurements were conducted in order to obtain the sound absorption coefficient (α) data for each testing sample across different frequencies. In this paragraph the evaluation and comparison of the initial measurement results are presented. To evaluate the damping properties of the selected multi-layered samples, the dependence of the sound absorption coefficient on the frequency range was considered from 50 Hz to 1600 Hz. For the five different systems examined, two measurements were performed for each system, from which the average value was determined. In order to evaluate the contribution of each layer in the system's sound absorption, certain materials were tested separately as single-layer specimens following the same measurement procedure.

The results of measurements for the five different multilayered systems are presented in Figure 5.11. Graph (a) shows the acoustic absorption coefficient as a function of frequency for the systems tested across a wide range of frequencies (50 Hz - 1600 Hz), whereas graph (b) is focused on the lower frequency range (50 Hz - 250 Hz). Each curve of the graph corresponds to a different system. At first glance, the Biodiverse system (black-colored line) and the Biodiverse Lightweight System (orange-colored line) show high absorption coefficients, especially at lower frequencies. The Sedum Traditional System also exhibits high sound absorption, particularly in the mid-frequency range. In order to get a deeper understanding of the acoustic performance of each system across the different frequencies, a detailed analysis is being conducted for the low, mid, and high frequency spectrum, respectively.

1. **Low-Frequency Performance (50 Hz - 250 Hz)**:
   - **Biodiverse System (black-colored line)**: Shows a steady increase in absorption, peaking early around 250 Hz with a coefficient near 0.95. This indicates that the Biodiverse System is highly effective at absorbing low-frequency sound.
   - **Biodiverse Lightweight System (orange-colored line)**: Similar to the Biodiverse System, it shows steady but slightly lower increase in absorption coefficient until 250 Hz, and peaks around 300 Hz with a high absorption coefficient, around 0.95.
   - **Detention Roof (green-colored line)**: Also follows a similar trend and performs well with lower frequencies. It peaks early around 270 Hz, reaching around 0.70 at 250 Hz.
   - **Sedum Lightweight System (purple-colored line)**: This system has a lower absorption in the low-frequency range, with a peak slightly above 0.60 at 250 Hz.
   - **Sedum Traditional System (blue-colored line)**: Has good absorption values, reaching 0,70 at around 250 Hz, indicating good low-frequency absorption.

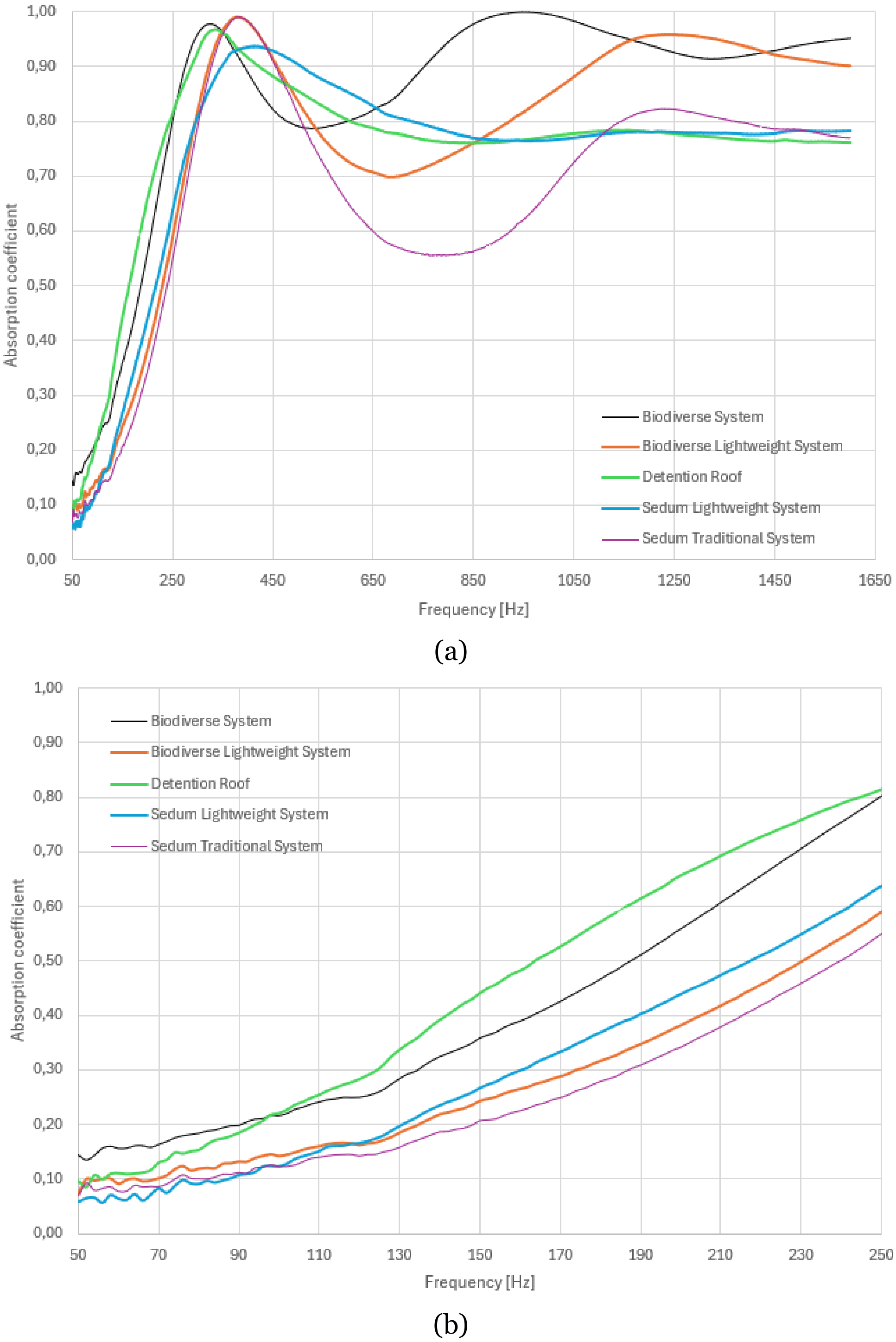


Figure 5.11: Graphic representation showing the sound absorption coefficient of the five green roof systems tested as a function of frequency for : (a) overall frequency performance (50 Hz – 1600 Hz) and (b): low-frequency performance (50 Hz – 250 Hz)

2. Mid-Frequency Performance (250 Hz - 1000 Hz):

- **Biodiverse System**: After peaking, the absorption drops slightly but stays consistently high, around 0.80 to 0.90, throughout the mid-frequency range.
- **Biodiverse Lightweight System**: Similarly, it maintains a high absorption coefficient, though slightly lower than the Biodiverse System, around 0.70 to 0.85.

- **Detention Roof**: Maintains high absorption, with coefficients hovering around 0.80 to 0.85, showing consistent performance across this range.
- **Sedum Lightweight System**: After peak, the absorption decreases slightly in the mid-range, maintaining high values between 0.80 and 0.90.
- **Sedum Traditional System**: This system shows a dip around 650 Hz, where the absorption coefficient drops to around 0.60, indicating less effectiveness in this mid-frequency range.

3. High-Frequency Performance (1000 Hz - 1650 Hz):

- **Biodiverse System**: The absorption remains high, with a slight increase as the frequency rises, stabilizing around 0.90.
- **Biodiverse Lightweight System**: This system shows an increasing and steady behavior at a high-frequency range, fluctuating between high values of 0.85 to 0.90.
- **Detention Roof**: After the slight dip in the mid-range, the absorption stabilizes around 0.75.
- **Sedum Lightweight System**: After the mid-range dip, the absorption stabilizes around 0.75 to 0.80.
- **Sedum Traditional System**: After the noticeable dip around 650 Hz, the absorption increases and remains fairly consistent, close to 0.80 in high frequencies, showing strong performance in this range.

Looking at their overall performance, it can be argued that the Biodiverse, Detention and Sedum Lightweight System stand out as the most effective systems, offering high and consistent sound absorption across the entire frequency range. The Biodiverse Lightweight System offers similar benefits with slightly reduced effectiveness in the mid-frequency range but might be preferred where a lightweight solution is required. Finally, the Sedum Traditional System shows more variability, with strengths in certain frequencies but not across the board. Focusing now on the low-frequency range, the Biodiverse and Detention Roof systems are the most effective in sound absorption. On the other hand, the Sedum Traditional System presents the lowest absorption coefficient.

<u>Effect of Thickness on Low-Frequency Absorption:</u> Similarly, the graph of Figure 5.12 shows the influence of substrate thickness on the absorption coefficient among the different frequencies. What is observed is that the thicker substrate (120 mm) shows higher absorption at lower frequencies, peaking close to 500 Hz with an absorption coefficient near 1. After the peak, the absorption decreases gradually. Coming to the medium thickness substrate (70 mm), it also shows relatively good absorption at lower frequencies, but the peak is shifted towards higher frequencies, around 900 Hz. Finally, the absorption peak of the thinner substrate line (50 mm) is shifted even higher in frequency compared to the 70 mm and 120 mm substrates. Additionally, its maximum absorption is lower than both the 70 mm and 120 mm substrates, indicating a less effective layer at low frequencies. This phenomenon can have a theoretical explanation. As sound waves are longer at lower frequencies, thicker materials provide a greater mass and depth to absorb these long wavelengths, reducing the energy reflected back into the environment.

Additionally, it can be seen that the sound absorption coefficient increases with increasing frequency, and all three thicknesses show broad, periodically spaced, high absorption peaks associated with quarter-wavelength resonances, separated by reduced absorption troughs. The first peaks for all thicknesses achieve very good sound absorption; however the magnitude of subsequent peaks progressively seems to reduce with further increasing frequency. As expected, increasing sample thickness shifts the corresponding quarter-wavelength peaks to lower frequencies. This behavior may be attributed to material properties, such as particle size. Dasyam *et al.* (2022) investigated the sound absorption characteristics of granular aerogel agglomerates of different particle sizes for two different sample thicknesses. They showed that the sound absorption behavior of the aerogels was strongly correlated to their particle size. The measured sound absorption coefficient for the largest aerogel particles presented an almost identical graph yo Figure 5.12 behavior. However, as the average particle size reduced, the sound absorption behavior was primarily characterized by successive, sharp, closely spaced high sound absorption peaks separated by very low dips. This difference in behavior can be explained by the overall physical structure of granular materials. Samples with larger particles behave as conventional granular agglomerates; on the other hand, samples with finer particles are significantly more consolidated, with an appearance of a bulk material that flows freely under dynamic excitations.

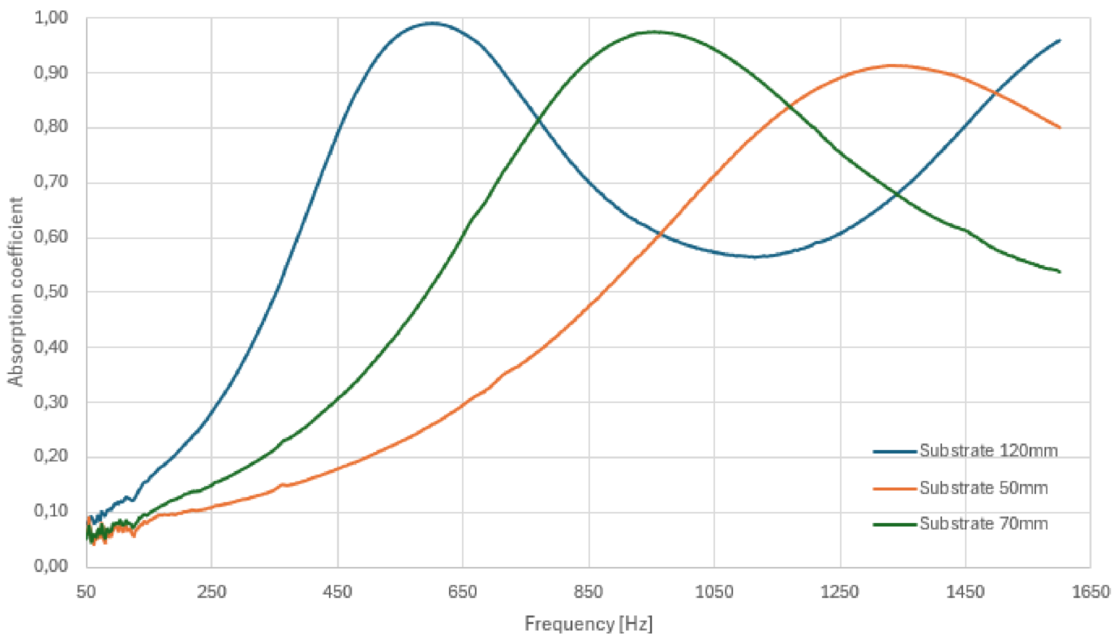


Figure 5.12: Graphing representation showing the effect of substrate thickness on the sound absorption coefficient across different frequencies (50 Hz – 1600 Hz).

<u>Shifting Peaks</u>: As the substrate thickness decreases, the absorption peak shifts to higher frequencies. This can be easily explained because thinner materials are less capable of absorbing the longer wavelength associated with low-frequency sounds. Therefore, they start to absorb more effectively at higher frequencies, where the wavelengths are shorter and better match the properties of materials.

Generally, increasing the thickness of an absorbing material improves its effectiveness at absorbing lower frequencies. However, there's a balance because firstly, very thick materials can end up being less sustainable, and secondly, they can be less effective at higher frequencies where the wavelengths are much shorter.

All these findings suggest that depending on specific needs, each system might be chosen based on what the absorption frequency-range priority is. As this study prioritizes noise reduction in the lower frequencies, the next chapters will investigate to what extent sustainable absorbers can be integrated among the tested systems in order to improve their acoustic performance, especially in the lower frequencies.

6
Concepts Development

6.1 Design Criteria

After reviewing the relevant literature and conducting the first acoustic measurements, a list of design criteria is created, based on the existing literature. These criteria serve as systems' requirements and are used to evaluate the systems' acoustic performance. Based on the results from the acoustic measurements and the design criteria formulated, then the procedure of concepts development follows.

6.1.1 Criteria for Acoustic Absorption

a) The system is required to yield an absorption coefficient that is as high as possible for all octave bands between 63 Hz and 250 Hz.
b) The substrate and integrated absorber composition is required to be optimized for acoustic absorption.

6.1.2 Criteria for Sustainability

<u>Environmental Impact</u>

a) The green roof system must contribute to the overall minimization of energy consumed during design and manufacture.
b) The integrated materials should act as low-carbon materials, reducing or eliminating the overall CO_2 emissions and resource depletion.

<u>Circularity</u>

a) The system should consist of durable materials, with a long life span that reduces the frequency of component replacement.
b) The used components should be designed to be reused multiple times, either for the same purpose or repurposed for different uses.
c) The used components should be designed to be easily recyclable at the end of their life, minimizing the complexity of separating materials and maximizing the quality of recycled output.

<u>Durability</u>

a) The entire system should ideally have a lifetime of several decades, so that in the end it can become a long-term investment.

b) The system has to be suitable for the Dutch climate.
c) The selected materials should be lightweight, and resistant to physical wear, corrosion, and environmental factors such as UV light, moisture, or extreme temperatures.
d) To ensure long-term functionality and minimize the need for repairs, the overall lifespan of any integrated material should ideally match or exceed the expected lifespan of the green roof system.

6.2 Analysis of sound absorbers for integration and improvement

The previous chapters showed that adding green roof systems on structures can improve sound absorption. However, the low-frequency absorption performance is not sufficient to attenuate aircraft noise. In an attempt to solve this problem, the implementation of a low-frequency absorbing system in green roof systems is examined. The selection of the most suitable sound absorbers was performed through a process of trial and error, according to the different options and designs that were presented in the literature, considering compatibility with the examined green roof systems as well as the results from the acoustic measurements.

Perforated panels

As described in paragraph 4.1.1.2, resonant panel absorbers are rigid panels, usually attached to structural elements that are designed to absorb sound energy and engineered to resonate at specific frequencies. These panels typically consist of a rigid perforated panel, with an air cavity or porous medium that can enhance sound absorption, located behind the panel. When sound waves reach the surface of a perforated panel, air particles in the perforations begin to vibrate. The interaction of the vibrating air particles with the walls of the perforations results in friction. This friction dissipates the vibrational energy of the air particles into heat, reducing the energy of the sound wave. The effectiveness of the sound absorption depends on several factors, including the size and shape of the perforations, the percentage of open area, the thickness of the panel, and the backing material. These parameters influence the resonant behavior of the system, allowing the panel to target specific frequency ranges for sound absorption. (Cox and D'Antonio, 2016). Perforated panels could potentially be used in green roofs; however their application depends on the design of the system, and challenges such as moisture resistance, air access requirements, additional weight, and durability of the panels in outdoor conditions should be carefully considered.

In practice, placing a resonant panel within the layered structure of a green roof structure would present several challenges. These challenges are primarily related to the unique functional requirements of resonant panels and characteristics of green roof materials. First of all, for resonant panels to operate effectively, they should have access to air environment, both for resonance and for sound wave interaction. As resonant panels function by allowing air to move in and out of cavities or perforations, creating oscillations at specific frequencies that absorb sound energy, if embedded within a green roof structure, the panels would be covered by the layers of growing medium and vegetation mat. These layers would not allow for adequate airflow to reach the resonant panel, as they are quite dense and compact, particularly when fully saturated or vegetated. This restriction would diminish the panel's ability to resonate and absorb sound effectively, especially at lower frequencies. Additionally, the presence of a thick growing medium above the resonant panel may alter the frequency response of the system, potentially shifting the resonant frequency out of the desired range. Finally, the pressure added from the growing medium and vegetation layers may exert additional damping on the panel, preventing it from reaching full resonance. Consequently, implementation of resonant panels directly within the green roof layering is inherently challenging, and the low-frequency absorption efficiency of the resonant panels would be significantly compromised, making the approach likely ineffective for targeted low-frequency sound control within a green roof structure.

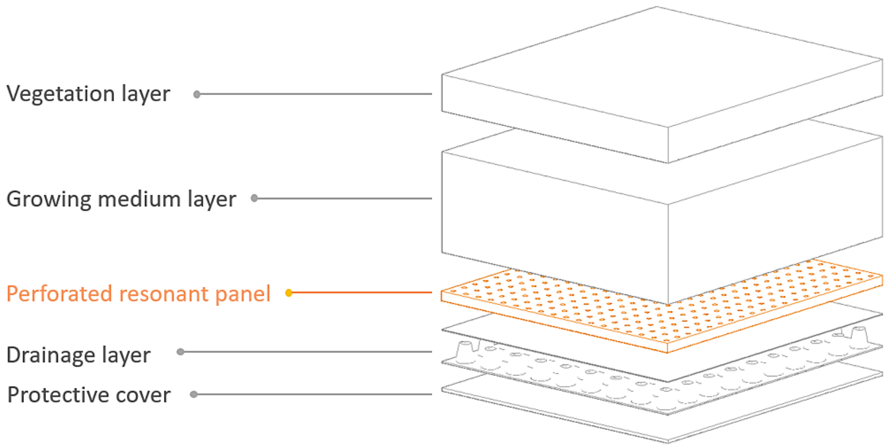


Figure 6.1: Placement of resonant panels within the layered structure of green roof system is rather challenging and not recommended due to the lack of necessary air exposure and the potential attenuation and scattering of sound waves by the overlying layers.

Microperforated Panels (MPPs)

Microperforated panels are panels that are characterized by a series of regularly spaced, milimeter-scale pores or perforations that allow sound attenuation due to viscous friction in the pores. Microperforated panels and resonant panels are different in design, function, and acousic properties (Yeang *et al.*, 2024). The idea of microperforated panels was initially proposed by Maa (1998) decades ago, where an analytical model was proposed, describing the acoustic impedance of MPP by considering the viscous losses in the perforation. In general, the absorption characteristics of a microperforated panel (MPP) are adequate in the mid-to-high-frequency range but deficient at low frequencies, with a narrow bandwidth of absorption. MPPs' absorption characteristics are also influenced by the size of the perforations, the backing material, and the air space depth. The panel itself may not vibrate but does allow sound waves to interact with a backing material, such as a porous absorber or an air gap, resulting in acoustic absorption.

Placing a microperforated panel in a green roof system is theoretically possible; however there are a plethora of practical and functional issues that need to be taken into account. As previously stated, MPPs are typically thin, rigid panels with sub-milimeter size perforations that are initially designed for indoor applications; hence they are suited for controlled environments, free of moisture or other detrimental to their performance conditions. On the other hand, green roofs are consistently exposed to various forms of moisture, such as rain, irrigation, and humidity. MPPs, particularly those placed in an outdoor environment, are susceptible to clogging through the penetration of moisture into their small perforations, which in effect diminishes the ability of the panels to absorb sound. In addition, if the panels are not designed to withstand outdoor conditions, the prolonged exposure to moisture may further lead to corrosion or degradation of the materials. Green roof systems contain substrate, vegetation, and organic materials, which tend to accumulate on the surface of the MPPs. This accumulation would impede the microperforations, thereby substantially restricting the sound-absorbing capabilities of the panel. In order to eliminate these obstructions, consistent maintenance would be necessary. However, the feasibility of conducting suc maintenance in a green roof system would be constrained.

To summarize, the integration of MPPs into green roof systems may be challenging due to environmental concerns and functional restrictions. MPPs are built and optimized for indoor use, making them less appropriate to the dampness, debris, and overall requirements of a green roof environment. As a result, MPPs are not further investigated in this research, and alternative materials and design methodologies are proposed.

Helmholtz Resonators

A Helmholtz resonator can be tuned to absorb specific frequencies; hence integrating this into a green roof system could help to mitigate noise pollution, particularly in areas with high levels of ambient noise, such as highways and airports. As described in chapter 4, Helmholtz resonators have the ability to perform well for low-frequency sound absorption, usually more effectively than the equivalent required thickness of a porous absorber. A Helmholtz resonator has a basic structure, usually consisting of a cavity and a neck. This provides the flexibility of straightforward design and integration into a variety of systems. Furthermore, Helmholtz resonators are customizable in the sense that by adjusting the size of the cavity and the neck, the resonators may be set to resonate at certain frequencies, making them suitable for a variety of applications. The fundamental disadvantage of Helmholtz resonators is that their absorption bandwidth is confined to a small region near the resonance frequency. To avoid potential collapse, resonators designed for usage at very low frequencies should have adequate dimensions and a sufficient side-wall thickness.

Helmholtz resonators can be integrated into green roofs, but their application necessitates careful consideration of design and functional objectives. Employing Helmholtz resonators in a green roof system, like employing resonant panels, requires integrating their shape and structure without compromising the system's essential functions.

1/4 wavelength tubes (QWT)

Quarter wavelength tubes (QWT) are tubes that are capped at one end. They are resonators that function similarly to Helmholtz resonators, in that a spring vibrates against a mass in a confined container, and their concept is significant in acoustic engineering and noise reduction. These tubes are very good at reducing low-frequency noise, such as traffic and aviation noise, which can be difficult to control with traditional materials (Van der Eerden, 2000). One tube is typically open at one end and closed at the other, with resonance frequency that can be calculated using the following formula:

$$f_{\text{res}} = \frac{(2m-1)c_o}{4L} \tag{6.1}$$

where c_o is the speed of sound in the air, f is the frequency, and m an integer (Catapane *et al.*, 2023).

As a result, the length of a QWTs is determined using the targeted frequency of sound and should be equal to one-quarter of the wavelength of the desired frequency. The closed end of the tube creates a point of no displacement, while the open end produces a point of maximum displacement. Due to their geometry, QWT offer the possibility of higher order modes in the tube, which allows for additional resonant peaks at higher octaves. The tubes can be made out of durable plastic, metal, or concrete and can be tuned for low-frequency sound attenuation, as the resonant frequency depends on the tube's length and diameter. One of the main drawbacks of QWT is its required length. As an example, to have a 100 Hz resonant frequency, a straight QWT should have a length of 0.85 m.

Even if the length L of a QWT is halved, as in the case of U-shaped tubes, the resonator's frequency response will probably be altered, leading to a shift in resonance patterns. This differentiation can eliminate some resonant peaks, as with a half-length configuration, the tube now will only respond strongly to frequencies at even multiples of its fundamental frequency, particularly affecting odd harmonics and reducing the tube's ability to cover a broader range of low frequencies effectively.

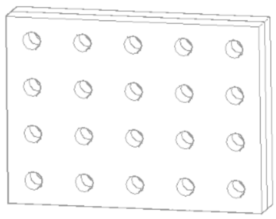
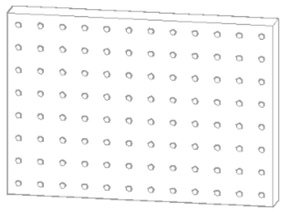
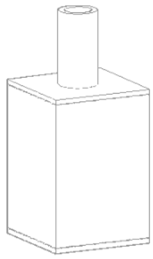
6.3 Selection of low-frequency sound absorber

To find the best integration solution, a comparative analysis of the various possibilities is required. Table 6.1 summarizes the advantages and disadvantages of the various options, showing the strengths and limitations of each technique and giving useful information for informed decision-making in the selection of effective sound control solutions.

In addition to this comparative analysis, each system should be carefully evaluated for its adaptability to real-world environmental conditions. While some systems may behave similarly under controlled conditions, others may be capable of functioning in a variety of situations, such as the damp environment found on a green roof system. This flexibility potential is critical for achieving a combination of maximal acoustic performance and balanced integration.

- **Comparative matrix of <u>the advantages and disadvantages</u> of potential integrated systems**

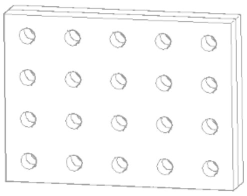
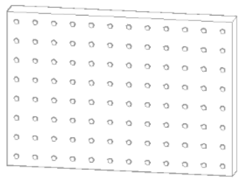
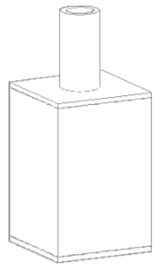
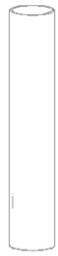
Table 6.1: Overview of advantages and disadvantages of the different options offered for integration.

Resonant Panels	Microperforated Panels (MPPs)	Helmholtz Resonators	¼ wavelength tubes
			
(+)	(+)	(+)	(+)
Easy fabrication	Easy fabrication	Well-studied and well-documented	
Relatively slim	Relatively slim	Simple structures	Simple design
Easy tuning by adjusting the panel's mass or air cavity behind it	Easy tuning by adjusting panel's mass or air cavity behind it	Simple tuning by altering the neck and cavity dimensions	Easy tuning by adjusting tube diameter and length
Highly effective at low to mid frequency sound waves	Highly effective at mid to high frequencies		Multiple resonant peaks are allowed
(-)	(-)	(-)	(-)
Narrow absorption bandwidth	Less effective at low frequency sound waves	Narrow bandwidth of operation	Narrow bandwidth of operation
Large surface area required	Large surface area required		Long required length
Resonance behavior might be blocked if placed within the green roof layering	Resonance behavior might be blocked if placed within the green roof layering	Complex calculations to achieve desired resonant frequency	
Integration in green roof structures might hinder the system's water drainage	High exposure to moisture, irrigation and humidity can clog micro perforations.	Less accurate for complex geometries	

After careful consideration of the different options, a more detailed analysis was conducted in order to evaluate the performance of each absorber with regard to the design criteria. A detailed overview of this analysis is presented in Table 6.2. Finally, in an attempt to make decision-making an easy procedure, most of the information provided in Table 6.2 is translated into a scoring system provided by Table 6.3 that concludes the selection procedure. It is evident that Helmholtz Resonators seem to be able to provide a better balance between acoustic performance and integration with the existing green roof system.

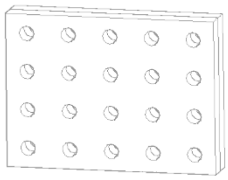
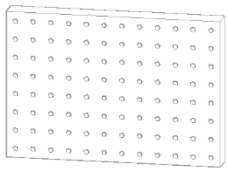
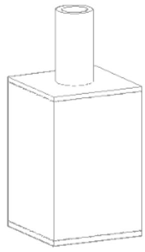
- **Comparative matrix <u>with regard to design requirements</u>**

Table 6.2: Selection matrix for suitable sound absorber. Each type is evaluated based on the developed design criteria related to its application in a green roof system.

	Resonant Panels	**Microperforated Panels (MPPs)**	**Helmholtz Resonators**	**¼ wavelength tubes**
Criteria				
Sound absorption effectiveness	Might not be able to reach full resonance due to air-access obstruction.	Effective for mid-to high frequencies but less effective for low frequencies. Effectiveness in outdoor environments is limited.	Highly effective for specific low-frequencies.	Effective for narrow frequency range.
Tuning	Versatile and can be tuned for specific frequencies.	Needs tuning for each frequency.	Needs tuning for each frequency.	Tuning depends on accurate dimensions.
Installation and Integration	Integration with the system might be unsuccessful if panel loses ability to resonate effectively.	Can be integrated into the system or placed in visible areas.	Can be integrated into the substrate or placed in visible areas. May not blend as seamlessly into the design	Can be installed and integrated when space allows.
Cost and Complexity	Moderate cost and relatively simple to implement	Requires precise construction.	Potentially higher cost and requires precise construction	Moderate cost; requires careful design and placement
Circularity	Modular design can allow for easy replacement or upgrades, enhancing longevity	They can be reused depending on accurate tuning.	They can be reused or recycled depending on accurate tuning and material choice	Practical reusability may be limited due to specific dimensions
Durability	Usually made of durable materials that can be easy to maintain	If they are made of robust material, they can be durable over time.	While durable, they have more intricate components (cavity, neck) that might be more vulnerable to external conditions.	If made form non-metallic or non-plastic materials they can be more susceptible to degradation. Their elongated form can increase vulnerability.

- **Selection of suitable sound absorber**

Table 6.3: Scoring matrix assessing the performance of the four low-frequency sound absorbers.

	Resonant Panels	**Microperforated Panels (MPPs)**	**Helmholtz Resonators**	**¼ wavelength tubes**
				
Simple tuning	1	1	1	1
Space-efficiency	1	1	1	0
Easy integration	0	0	1	0.5
Circularity	1	1	1	1
Durability	1	1	0.5	0.5
Total	**4**	**4**	**4.5**	**3**

After careful consideration of all aspects that need to be fulfilled, implementing Helmholtz resonators in green roof structures can be an innovative way to combine acoustic optimization with ecological design. Therefore, the option that is further examined for integration is the use of Helmholtz resonators.

This selection scoring matrix is a useful systematic approach to evaluate different design options, including the choice of Helmholtz resonators. However, what is important to be mentioned is that while this matrix helps to quantify various criteria such as acoustic performance, durability, and integration feasibility, it is important to acknowledge that such a method is inherently subjective. And that the assignment of weights to criteria and the scoring of individual options depend on the priorities and judgment of the evaluator. As a result, while the matrix indicates that Helmholtz resonators are the most suitable option for this project, this conclusion should not be viewed as entirely objective. To support this decision, paragraph 6.3 provides a thorough argumentation explaining why Helmholtz resonators align more effectively with the project's goals. These arguments include their ability to target specific frequencies, compatibility with the green roof system, and long-term performance under environmental conditions. This dual approach, including quantitative scoring supported by qualitative reasoning, ensures that the selection process is transparent and well-justified.

6.4 Concept Generation

According to the results obtained from the impedance tube measurement, described in Chapter 5, the Biodiverse System appears to be the most promising solution for integrating resonator systems. This system displays good sound absorption performance, including in the low-frequency range, making it suitable for further optimization with integrated acoustic solutions. Although the Detention System also demonstrates strong acoustic performance, which is most likely attributed to the honeycomb structure acting as a natural resonator, it does not provide appropriate space and practical opportunities for integrating additional technologies that could improve its acoustic performance. Therefore, while this system performs well in terms of sound absorption, its design constraints make the integration of additional acoustic solutions challenging. For these reasons, the biodiverse system is selected for further analysis and acoustic optimization.

6.4.1 Key Considerations and Design Challenges

Besides the design criteria that need to be fulfilled in order to get optimal acoustic performance, there are some key considerations that need to be taken into account before the concept generation. These considerations are mostly related to design, integration with the green roof components, acoustic performance, environmental impact, and also the system's maintenance.

1. Design and Structure

   - The Helmholtz resonators can be embedded within the substrate layer. By embedding the resonators in the substrate, the system could potentially minimize the visual and spatial impact of the roof. However, integration would require ensuring that the resonators are securely held in place without compromising the substrate's function, such as plant growth, root expansion, water retention, and drainage. The main challenge is ensuring that the acoustic properties of the resonators are not negatively impacted by their placement within a heterogeneous and moisture-retaining layer, such as the substrate.

   - The resonators can be designed as modular units that fit within the substrate and vegetation layers of the green roof structure. Designing the Helmholtz resonators as modular units will allow for flexibility and ease of installation, maintenance, and replacement. These modular units can be adjusted to fit seamlessly between the substrate and vegetation layers. Modularity will also facilitate scaling the design based on the roof's surface area and required acoustic performance.

2. Integration with the green roof components

- The resonators can be placed within the substrate layer. It should also be ensured that they do not interfere with the vegetation growth and water drainage while having their neck endings exceeding the vegetation mat in order to ensure that they are still effective with noise absorption.

- To facilitate efficient drainage in the event of water ingress into the cavity, small water outlet perforations or micro perforations should be positioned at the bottom of the resonator cavity. In the case of single outlet perforation, to ensure effective drainage, these drainage holes shall be positioned centered or off-center at the lowest point of the resonator cavity. This design consideration accommodates any slight inclination of the green roof system and the resonator, thereby preventing water from pooling within the cavity. Alternatively, the use of perforated cavity base design can be used to prevent the accumulation of standing water. Consequently, prolonged saturation that could negatively impact both sound absorption and durability will be effectively avoided.

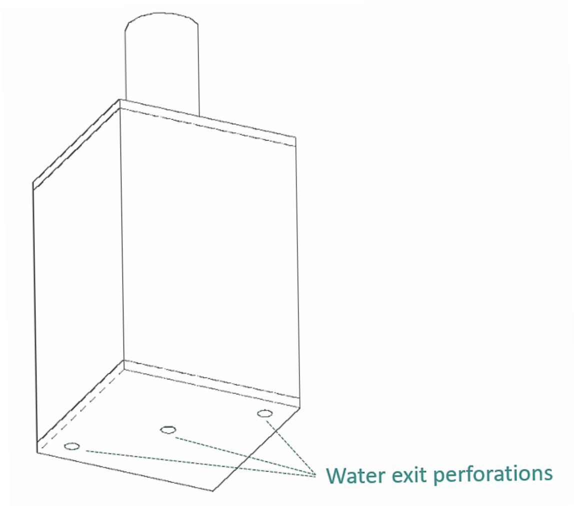


Figure 6.2: Schematic representation of the small exit perforation concept at the cavity base of the resonator.

3. Resonator Geometry and Dimensions

- The internal volume of the Helmholtz resonator cavity is a critical parameter that dictates its resonant frequency. The resonant frequency f_r is inversely proportional to the square root of the cavity volume V. Therefore, larger cavity volumes are associated with lower resonant frequencies, making them suitable for absorbing low-frequency noise, while smaller cavities usually target higher frequencies. This relationship can be expressed by the general formula (4.6), given in paragraph 4.1.1.2, for the resonant frequency of a Helmholtz resonator:

$$f_r = \frac{c}{2\pi}\sqrt{\frac{S}{Vl_{eff}}} \tag{6.2}$$

where:

f_r is the resonant frequency

c is the speed of the sound in air (approximately 343 m/s at room temperature)

S is the neck cross-sectional are

V is the volume of the cavity and

l_{eff} is the effective length of the neck, accounting for end corrections

For the low-frequency sound absorption, the volume of the cavity must be examined within practical constraints. Therefore, careful consideration of available space within the green roof's growing medium is required to ensure that the resonators can be effectively tuned to target noise in the desired frequency range. In other words, to effectively target low-frequency sound absorption, the cavity volume needs to be as large as possible within the available space. However, this volume must be balanced with the substrate's volume and function. Increasing the cavity volume of the resonators will improve low-frequency absorption but will reduce the available space for the growing medium. This could potentially impact the overall structural integrity and water retention capabilities of the green roof, compromising its primary functions, such as supporting unhindered plant growth and managing excessive stormwater. Additionally, if the resonators occupy an excessive amount of space, the volume of the substrate may be reduced to a degree that adversely impacts plant health and root stability.

Given that the primary function of a green roof is often ecological, compromising the volume of the growing medium for the sake of acoustic performance may prove counterproductive. Conversely, if the volume of the resonators is too small, they may not provide sufficient absorption of low-frequency sound, thereby limiting the acoustic benefits and potentially undermining the effectiveness of the noise mitigation strategy. As such, one of the design challenges is to maximize the cavity volume of the resonators while retaining enough substrate space to maintain the roof's ecological function. Therefore, the ratio between the cavity volume of the resonators and the substrate volume should be optimized, and the final design should ensure that the resonators can reach the desired low-frequency range without excessively reducing the substrate, which could hinder the system's primary functions.

- The geometry of the resonator's neck significantly influences both the target frequency and the bandwidth of absorption. A longer neck can increase the effective mass of air within the neck, thereby lowering the resonant frequency of the resonator. Conversely, a shorter neck would reduce the air mass, raising the resonant frequency. The effective length l_{eff} incorporates an end correction factor to account for the additional virtual length caused by sound wave propagation at the neck's opening. Additionally, the diameter of the neck governs the cross-sectional area *S,* which, in combination with the cavity volume and effective length, influences the resonant frequency and absorption bandwidth. A narrower neck increases acoustic impedance, resulting in a lower frequency but often narrows the absorption bandwidth. In contrast, a wider neck elevates the resonant frequency and offers the potential to broaden the absorption bandwidth (Wu et al., 2019).

- The geometry and shape of the resonator's cavity - whether cylindrical, rectangular, or even spherical - can also be a critical determinant of both acoustic performance and practical feasibility, as it directly influences the distribution of resonant frequencies, impedance characteristics, and sound absorption efficiency (Zhao *et al.,* 2022).

  Cylindrical resonators: Cylindrical cavities are simple to design and widely utilized due to their symmetry and ease of calculation. They have well-defined axial and radial modes, which lead to distinct resonant frequencies based on their height and diameter. These resonators tend to exhibit more predictable and narrowband performance, making them suitable for targeting specific frequencies. Regarding any practical considerations, cylindrical resonators can be characterized as straightforward to manufacture and can be easily integrated into layered systems, such as a green roof.

  Rectangular resonators: These resonators with flat surfaces and sharp edges often have a more complex and broader range of resonant modes due to the different dimensions of the length, width, and height. Due to the presence of multi-dimensional resonance paths, this shape may support more distributed sound absorption over a wider frequency range but with potentially less sharp resonant peaks compared to cylindrical or spherical cavity shapes. Compared to cylindrical resonators, their more complex behavior can potentially lead to unpredictable acoustic performance, making it challenging to achieve targeted sound absorption.

  Spherical resonators: Spherical resonators can potentially provide a more uniform distribution of resonant modes due to their symmetrical shape, which allows sound waves to propagate evenly in all directions. However, their design can pose practical challenges for implementation on green roofs due to the complexities involved in manufacturing and installing them within a green roof structure.

Zhao et al. (2022) experimentally investigated the transmission loss of resonators with different cavity shapes. Among their findings, they proved that compared to rectangular cavity resonators, cylindrical ones are more effective to dissipating sound. Additionally, they showed that cylindrical resonators were able to achieve more sound pressure level reduction in comparison to the rectangular ones. Similarly, Farooqui et al. (2012) investigated the effect of the geometry shape of Helmholtz resonators on their resonant frequencies and noise attenuation capability. Their simulation and experimental validation showed that cylindrical resonators provide better results in sound attenuation than conical and spherical cavity shapes.

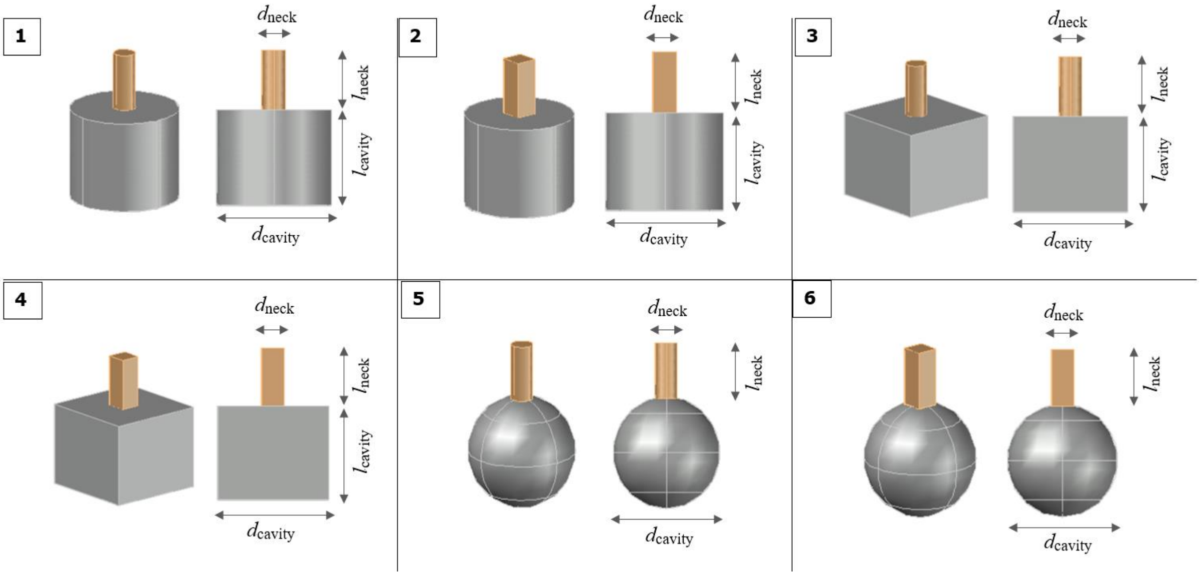


Figure 6.3: Different resonators configurations. Three different cavity shapes in combination with two different neck shapes.

For these reasons, while rectangular and spherical resonators may have acoustic advantages, cylindrical resonators seem to be the most practical option for integration into the growing medium to enhance low-frequency absorption while minimizing interference with water drainage. In terms of acoustic performance, they can be precisely tuned for low-frequency absorption by adjusting their height and diameter, while their shape can facilitate efficient water drainage. Their vertical orientation can reduce the risk of clogging or water drainage hindering, as water and debris can maybe move more freely around them compared to bulkier resonant designs, such as rectangular ones. This way it is ensured that the resonators can enhance acoustic performance without compromising the green roof's primary functions.

4. <u>Acoustic performance and Target frequencies</u>

- In order to effectively absorb noise across a broad range of lower frequencies, it is crucial to target specific problematic frequencies in the surrounding environment. This requires tuning resonators to different frequencies, with variations in cavity volumes and neck dimensions to address a wide range of acoustic challenges. Additionally, achieving the right balance between acoustically effective resonator shapes and preserving the system's functionality is essential. Consequently, precise tuning is necessary, and an iterative parametric approach should be employed to optimize the design. The approach of targeting multiple frequencies can also provide redundancy, in the sense that if one resonator becomes clogged or stops functioning effectively, neighboring resonators can continue to perform at their respective frequency.

5. Environmental Considerations

- Particular attention should be paid to the reduction of substrate volume that is caused by the installation of the resonators. Maintaining the right amount of substrate volume required for both drainage and plant growth is a prerequisite of the study. However, installation of the resonators in the substrate layer inherently involves a reduction in the substrate volume. While a minor reduction can generally be deemed acceptable, provided that the substrate retains its capacity to support plant growth and maintain proper water drainage, experimental validation is necessary to accurately assess the extent of this reduction. Such testing is essential to ensure that the reduction remains within permissible limits while achieving the desired acoustic performance. Hence, in order to preserve the system's functional integrity, the resonators must be designed and positioned in a way that ensures the least possible loss of substrate volume. This restriction can serve as a key design criterion, balancing the acoustic benefits of the integrated resonators with the environmental requirements of the system.

- The materials used for the resonator concepts should be durable and environmentally friendly to avoid or at least minimize any negative impact on the system's ecological function over time. They should be ideally sourced from sustainable or recyclable materials. This will minimize any potential negative effects of the system's ecological functions.

- The design should also consider the weight load on the system, as adding resonators could increase the overall load. However, it is important to note that the addition of resonators may involve reducing the amount of substrate in the system. As a result, the overall weight of the system might even decrease, depending on the balance between the materials removed and added. To ensure that the roof can support the adjusted weight without compromising its structural integrity, a thorough structural assessment is required. Therefore, lightweight, yet sturdy materials should still be prioritized to minimize the impact on the structural load while maintaining effectiveness.

- Finally, it is important that the materials used for the resonators can be easily recycled or repurposed at the end of their lifecycle. This will promote a circular economy, reducing waste and ensuring that resources can be reused efficiently. As already mentioned, using modular design and materials with low environmental footprint can further enhance the circularity of the system, contributing to its long-term sustainability.

6. Material Selection

- Considering the high-moisture environment of a green roof structure, material selection is a crucial factor in the design of integrated Helmholtz resonators in green roof systems, as it can directly influence durability, acoustic performance, and environmental sustainability. The chosen materials must withstand harsh outdoor conditions, including moisture, temperature fluctuations, UV exposure, and potential biological growth, ensuring long-term functionality without significant degradation. Water resistance is particularly essential to ensure that the resonators continue to operate well in the face of frequent exposure to rainwater and humidity. Additionally, in order to reduce additional structural loads that could compromise the structural integrity of the roof, the chosen materials should be lightweight.

- The material selection procedure requires the consideration of environmental sustainability alongside structural and durability factors. Additionally, taking into account the Life Cycle Assessment (LCA) in material selection enables a more sustainable approach. Materials that have little negative impact on the environment during manufacture or are recyclable at the end of their lifespan are desirable since they match with the overall eco-friendly objective of green roof systems (Aggarwal *et al.*, 2024). For example, using materials with a high recycled content or that can be repurposed after usage as resonators can help to reduce the system's carbon footprint. Furthermore, it is beneficial to select low-maintenance materials, as this could result in reduction of frequent replacements and repairs, especially for green roof systems with limited accessibility. The LCA's capability to highlight the potential environmental costs of maintenance over the lifespan of the different materials can support the selection of materials that strike a balance between durability and minimal environmental deterioration.

- Finally, material selection also accounts for acoustic performance. The substance must facilitate the resonator's ability to effectively target particular frequencies. In order to optimize the acoustic performance of the system, materials with low damping properties are generally more effective at increasing sound resonance, enhancing the resonator's ability to target desired frequencies (Aydın & San, 2024). However, to ensure that the acoustic benefits do not have a substantial environmental impact, these considerations should be carefully weighed against other Life Cycle Assessment (LCA) outcomes.

In summary, selecting materials for resonators in green roof systems necessitates a careful balance of acoustic efficiency, environmental sustainability, and mechanical durability. By adding Life Cycle Assessment (LCA) into the decision-making process, materials that meet performance and durability specifications while minimizing environmental effects can be identified during the resonator lifecycle. This selection method ensures long-term functionality and maximum acoustic performance.

Based on these criteria and industry standards, there are some materials that have been identified as potential candidates for use in green roof Helmholtz resonators. There are particular guidelines and standards, such as ISO 14040 and ISO 14044 for Life Cycle Assessment (LCA), ASTM standards for water resistance and UV durability, and finally the FLL Green Roof Guidelines, which provide several practices for materials that should be used in green infrastructure. Particularly, materials used in green roof systems must adhere to certain requirements and specifications to assure performance, longevity, as well as environmental compatibility, as outlined by the FLL Green Roof Guidelines (2018). These guidelines emphasize the importance of using materials that are durable and resistant to environmental conditions such moisture and water, UV radiation, and biological degradation. As stated in these guidelines, materials must be able to survive prolonged moisture exposure and resist root penetration while retaining structural integrity. Furthermore, FLL guidelines recommend excluding wood as a permanent safeguard due to its susceptibility to decay, emphasizing the need for materials with strong water resistance characteristics and low maintenance requirements, while also addressing environmental aspects of material selection by emphasizing the importance of materials that exhibit sustainability through recyclability and low life cycle environmental impact. These thorough requirements serve as a benchmark for evaluating the feasibility of various material possibilities, ensuring that their performance is appropriate for the rigorous conditions of a green roof environment while adhering to ecological principles.

Given the aforementioned principles and standards requirements, material selection should be a meticulous process that ensures compliance with the special demands of a green roof system. Five materials have been identified as candidates for further investigation based on their balance of durability, recyclability, environmental sustainability, water resistance, and acoustic performance. These materials are rigorously evaluated to ensure that they meet both the functional and environmental criteria necessary for maximum performance.

- High-Density Polyethylene (HDPE)

High-Density Polyethylene (HDPE) is a strong, flexible, and cost-effective thermoplastic polymer recognized for its high strength-to-density ratio. Because of its recyclability potential and extended lifespan of 50 to 100 years, it offers a wide range of applications in a variety of industries, combining longevity and affordability (Guo et al., 2019). It is chemically and UV-resistant, making it perfect for outdoor applications. Its versatility makes it a popular choice for a variety of products and projects, including use in buildings, pipes, and acoustics applications that require lightweight but durable materials (Accel Polymers, 2021). While HDPE is a useful material for a variety of structural purposes, it is not well known for its acoustic properties. In particular, HDPE is considered to have low sound absorption and dampening ability, resulting in poorer acoustic performance when compared to other materials.

- Fiberglass Reinforced Plastic (FRP)

Fiberglass Reinforced Plastic (FRP) is a composite material, known for its strength-to-weight ratio and its ability to harsh extreme environmental conditions (Rajak *et al.*, 2019). It offers great water resistance and durability properties, and its lifespan can be affected by exposure to UV radiation or extreme temperatures, typically lasting up to 30 years (Harle, 2024). However, along with its composite structure that makes it difficult to recycle, FRP presents significant drawbacks in terms of its sustainability, as its production process is energy-intensive, resulting in considerable CO_2 emissions (Qureshi, 2022). Finally, on the acoustic side, FRP’s damping properties seem to make it a potentially suitable candidate for sound absorption applications (Nurzyński, 2023).

- Stainless Steel

Stainless steel is a long-lasting material with remarkable resistance to corrosion and environmental degradation. It is completely recyclable, and its long lifespan of approximately 50 years reduces the demand for frequent maintenance (ASTM International, 2020). However, similarly to FRP, its energy-intensive production process results in a significant increase of its carbon footprint. As far as its acoustic performance is concerned, stainless steel is a reflective material with a relatively low damping effect, meaning it does not absorb significant sound energy (Pardeshi *et al.*, 2022). Additionally, it provides rigid and smooth surfaces, which are essential for accurate wave reflection and resonance within the cavity. This could enhance the efficiency of sound absorption at the target frequency.

- Treated Plywood

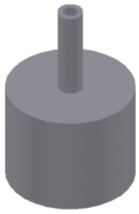
Treated plywood is a sustainable, natural resource with modest durability, especially when utilized for outdoor applications. It is biodegradable and has a low environmental impact, which aligns with the basic sustainability principles. Its lifespan can range between 5 to 10 years and is normally determined by the quality of the treatment as well as the environmental conditions that it is subjected to. While it may be water resistant, extended exposure to moisture can lead to degradation (Castanié *et al.*, 2023). Finally, its porous and fibrous structure provides significant acoustic dampening (Pinchevska *et al.*, 2019), which may not be desirable for Helmholtz resonator applications.

- Cork

Cork is a renewable, natural, and biodegradable lightweight material known for its superior environmental performance, low carbon footprint, and recyclability. Its water resistance characteristics are moderate, as cork tends to swell when exposed to prolonged moisture, such as a green roof environment, for an extended period. Hence, depending on the exposure conditions, it has a relatively short lifespan, ranging from 5 to 10 years. Despite this, cork is highly valued for its acoustic properties, particularly its ability to absorb and dampen sound waves, adding to its desirability for sound absorption applications under particular conditions (Gil, 2015). However, similarly to treated plywood, this high damping behavior is not conducive to the performance requirements of Helmholtz resonators, where low damping and high rigidity are crucial for maintaining sharp resonance.

To make the decision-making an easy process, the aforementioned data is translated into a scoring system presented by Table 6.4, which accomplishes the material selection procedure.

Table 6.4: Selection of suitable resonators materials. Each material is evaluated based on the design criteria related to their application in the green roof system.

	High-Density Polyethylene	**Fiberglass Reinforced Plastic (FRP)**	**Stainless Steel**	**Treated Plywood**	**Cork**
Criteria					
Durability	1	1	1	0.5	0.5
Recyclability	1	0.5	1	0.5	1
Lifespan	1	1	1	0.5	0.5
Water Resistance	1	1	1	0.5	0.5
Acoustic Performance	0.5^{+}	1^{-}	1	0.5^{-}	0.5^{-}
TOTAL	**4.5+**	**4.5^{-}**	**5**	**2.5^{-}**	**3^{-}**

In conclusion, the assessment of prospective materials for resonators in the green roof system highlights the necessity of balancing various design parameters. Based on the overall performance and the evaluation matrix, rigid materials such as stainless steel and plastic materials are preferred due to their reflective acoustic properties, durability, lifespan, and water resistance. However, their performance should also be weighed against costs and the feasibility of implementation in the roof system. On the other hand, wood-based materials, such as treated plywood and cork, are not preferred for use in Helmholtz resonators.

7. <u>Maintenance and Accessibility</u>

- The resonators should be designed for minimum maintenance, but accessibility may be required for occasional inspection or adjustments.
- Additional consideration should be given to the accessibility of the resonators for inspection and maintenance, ensuring that this is done without compromising the integrity of the vegetation and the other green roof layers.

6.4.2 Challenges

The implementation of Helmholtz resonators in green roof structures presents undoubtable challenges and significant complexity compared to a standard green roof design, as it requires specialized knowledge in both acoustics and green roof technology. The main objective lies in integrating their structure into the green roof without compromising the system's primary functions.

Primarily, the integration of resonators can alter the physical composition of the substrate layer, creating cavities and interfaces that interact both acoustically and mechanically. These interactions may result in unforeseen outcomes, including shifts in target frequencies or modified absorption curves. Additionally, compared to the resonators that are inherently tuned to target specific frequencies, the green roof system is designed to provide a broader-spectrum sound absorption. This incompatibility might result in absorption gaps or range overlap, causing inefficiencies, and aligning resonator performance with the substrate's intrinsic properties to achieve multi frequency absorption can be a significant challenge. Therefore, achieving compatibility between the resonators and the substrate while maintaining overall performance may require fine-tuning and an iterative analysis.

Another challenging parameter is the degradation of the resonators over time. Environmental factors such as soil compaction and biological activity can pose a danger to the resonator's long-term performance and continued functionality. Therefore, the resonators must be constructed from water-resistant material capable of withstanding prolonged exposure to moisture, ultraviolet radiation, and potential interference from the plant root system. In order to ensure long-term functionality, adequate sealing and maintenance are also essential.

In order to identify the most suitable solution, it is essential to estimate the approximate design of the integrated resonators. To calculate the dimensions of Helmholtz resonators, different configurations are initially assumed, and their resonance frequency is evaluated. A precise explanation of the procedure that is followed to estimate the design as well as the amount and distribution of resonators is presented in Chapter 7.

6.4.3 Final Concept Design

Integrated Helmholtz resonators in the growing medium

Once all design criteria have been considered, the final concept design includes cylindrical Helmholtz resonators implanted within the system's substrate layer to target various low frequencies. The ultimate conceptual design can be defined as follows:

Key Design Features

- Cylindrical Hlemholtz resonators of vaying dimensions (heights and diameters) are integrated into the substrate layer and are positioned right above the drainage layer. This configuration allows for acoustic optimization across different frequency ranges while ensuring the maintenance of the system's functionality.

- The resonators are distributed throughout the growing medium, with their necks extending 2 cm above the vegetation layer. This placement ensures that the resonators remain operational without being hindered by dirt or vegetation while also integrating into the green roof system.

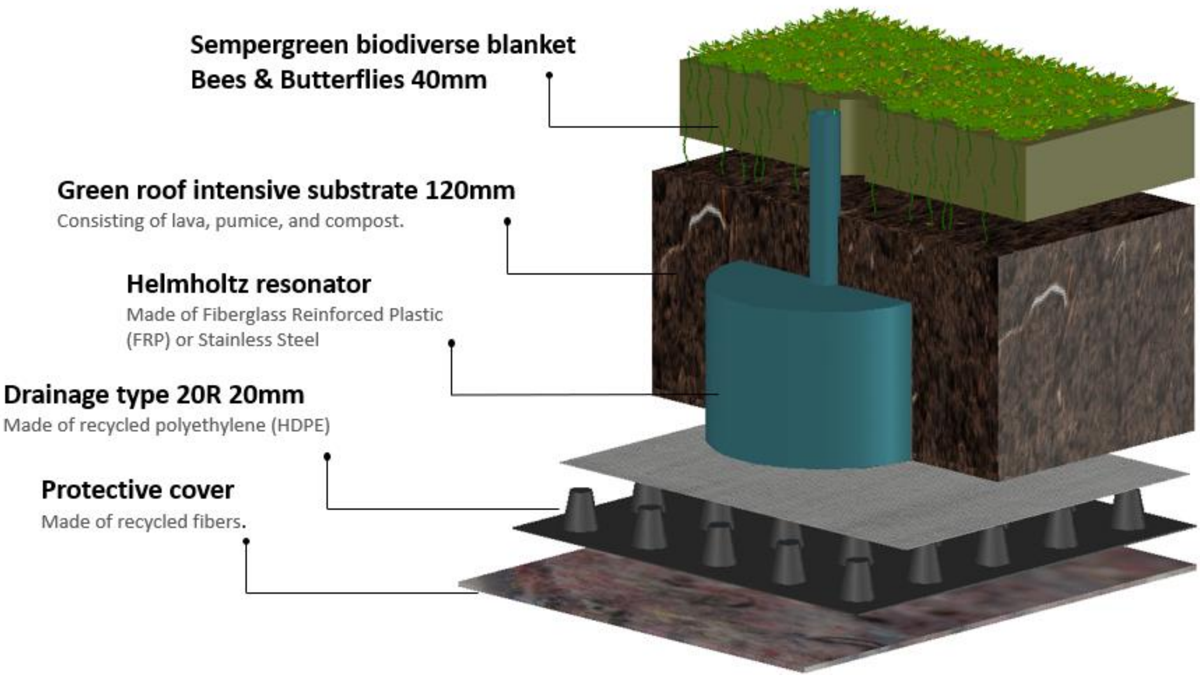


Figure 6.4: Final concept design.

- To prevent clogging and dirt accumulation in the resonators' necks, a geotextile or fabric net is installed over the orifices. This design enables constant airflow while keeping the system's acoustic performance consistent over time.
- To ensure unhindered water drainage, the base of the resonators includes small perforations that allow water to drain efficiently, reducing water clogging within the cavity while preserving the resonator's structural integrity and durability. These small outlets are intended to ensure that the resonators function properly while preserving the green roof's drainage capability. All resonators are modeled with a minimum of four outlet perforations evenly distributed around the perimeter of the cavity base.

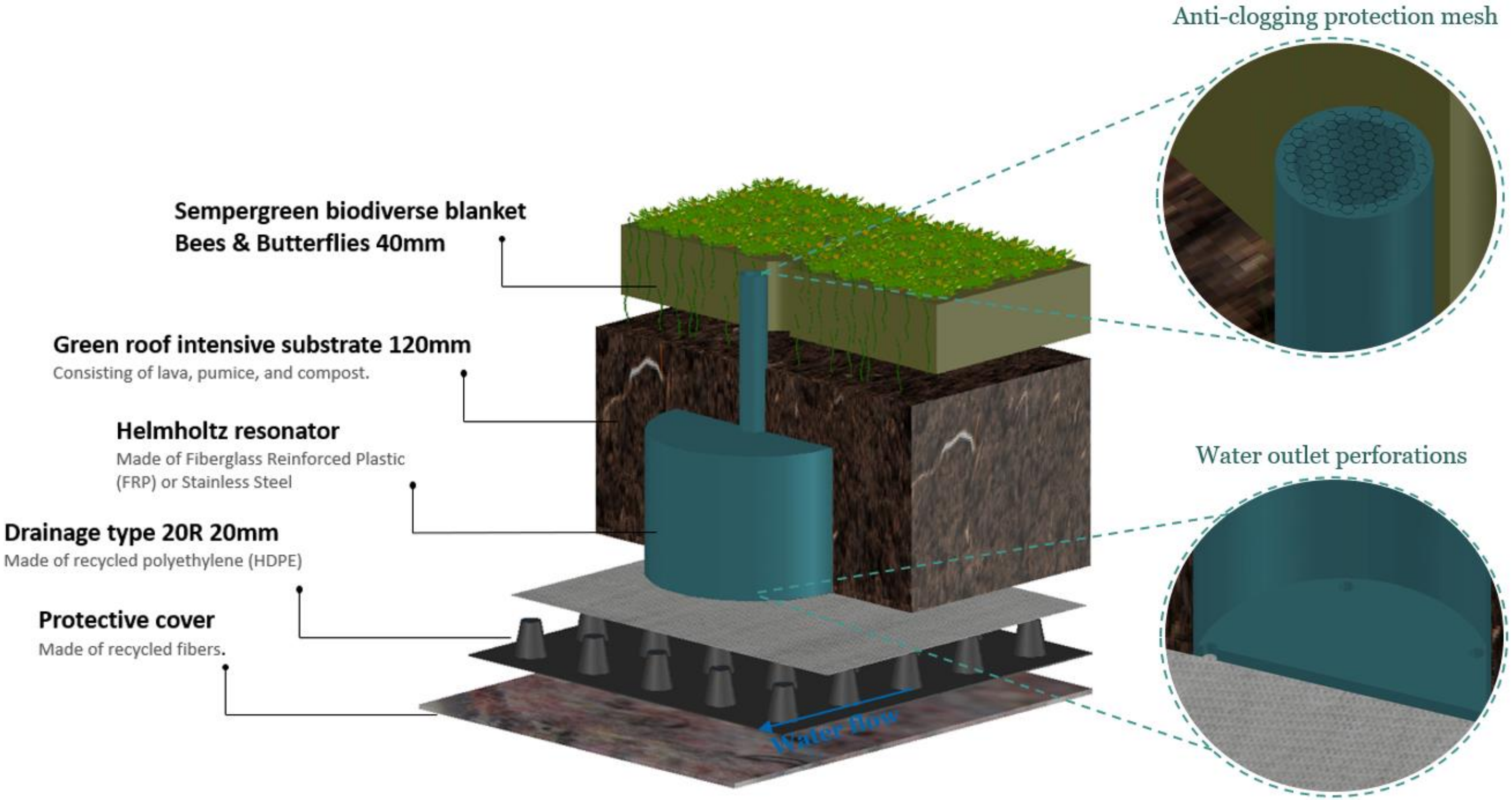


Figure 6.5: Key design features of the concept desi

7 Simulation Modeling

7.1 Objective

The sound absorption qualities of the green roof system with integrated Helmholtz resonators must be analyzed using simulation modeling. This is especially significant given the complexity of interactions between the many layers and acoustic factors. The green roof system consists of several layers, including the vegetation layer, the growing medium, the resonators, and the drainage system, each of which contributes distinct acoustic qualities that collectively influence the overall sound absorption. Simulation software provides a solid foundation for modeling these complex interactions, capturing crucial elements such as wave propagation, impedance effects, and the influence of resonator geometry under specified and controlled settings. Moreover, it enables frequency-dependent analysis, which is crucial for tuning the system's design to achieve specific absorption characteristics within the targeted frequency range. By allowing for iterative design adjustments, such as optimizing resonator dimensions, material properties, and layer arrangements, this approach not only provides insights into the expected acoustic performance but also reduces the need for costly physical prototypes and experimental testing, making it an invaluable tool for design and optimization.

7.2 The Simulation Software: COMSOL Multiphysics

After the most promising design is developed, the simulation procedure begins. COMSOL Multiphysics is a popular and suitable software solution for modeling acoustic parameters, including the absorption coefficient. COMSOL is a very adaptable finite element analysis (FEA) software that is commonly used to simulate a variety of physical phenomena, including acoustics, structural mechanics, fluid dynamics, and electromagnetics (Dickinson *et al.*, 2013). Regarding acoustic simulations, COMSOL'S Acoustic Module is particularly well-suited to studying sound propagation, absorption, and resonance phenomena. For designing systems like resonators, sound-absorbing layers, or other acoustic solutions, COMSOL provides a powerful toolkit for optimizing and verifying designs before physical testing (*Simulation Software For Analyzing Acoustics And Vibrations*, n.d.).

COMSOL's efficiency in acoustic simulations stems from its unique combination of features. COMSOL excels in handling coupled physics scenarios, which involve acoustic behavior interacting with other physical phenomena such as fluid dynamics or structural mechanics. This makes it excellent for complicated systems, including sound and structural interactions.

Furthermore, it allows users to create bespoke physics, which is useful for simulating innovative materials or sophisticated sound absorption systems that do not have predefined models. Furthermore, its user-friendly interface enables users to define geometries, material properties, boundary conditions, and meshing in a highly configurable manner, allowing for the modeling of specific acoustic features.

7.3 The Impedance Tube Model

To simulate the green roof structure in COMSOL and assess its acoustic absorption, first define the required model. This requires designing the system's multiple layers in 3D CAD software, then importing the geometry into COMSOL Multiphysics. In order to obtain the most realistic results, the simulation adheres to the standards of real-world measurement setups. In COMSOL, the Impedance Tube model is commonly employed to analyze the interaction of sound with the material sample or structure by simulating the reflection and transmission of sound waves within the tube. Figure 7.1 illustrates the geometry of the modeled system, in which an incident sound field representing a sound source is connected to one end of the tube and the green roof system test sample is mounted at the other end. In order to get a deeper understanding regarding the way COMSOL simulates the absorption coefficient of the system, it is essential to get a step-by-step outline of the process that is followed.

1. Setting Up the Geometry

During setting up the model, it is important to start by defining the geometry based on the specific components involved. This included establishing the shape and dimensions of the different elements, such as vegetation, substrate layer, resonators, and drainage layer. In order to ensure accurate representation of the layered structure, after the geometry of the multi-layered system, along with the integrated resonators, is first modeled in 3D CAD environment, it is then imported into the COMSOL environment. For the Helmholtz resonator configurations, it is important to accurately model both the cavities and neck dimensions, as their parameters significantly impact the resonance behavior and, consequently, the sound absorption characteristics of the system. Precise setup is crucial for achieving reliable and realistic simulation outcomes.

Following the standard test method for impedance and absorption of acoustical materials using a tube, two microphones, and digital frequency analysis system (American Society for Testing and Materials, 2012), the tube must be sufficiently long to ensure that plane waves are fully developed before reaching the specimen and microphone positions. Therefore, a minimum distance of three tube diameters should be maintained between the sound source and the nearest microphone. Additionally, the minimum distance between the test specimen and the nearest microphone is influenced by the surface characteristics of the specimen, and for nonhomogeneous surfaces, the closest microphone may be placed as close as one tube diameter from the specimen. Based on these standards and considering the green roof system being simulated, with a surface area of 1 m^2 the impedance tube is designed with a length of 4.5 m.

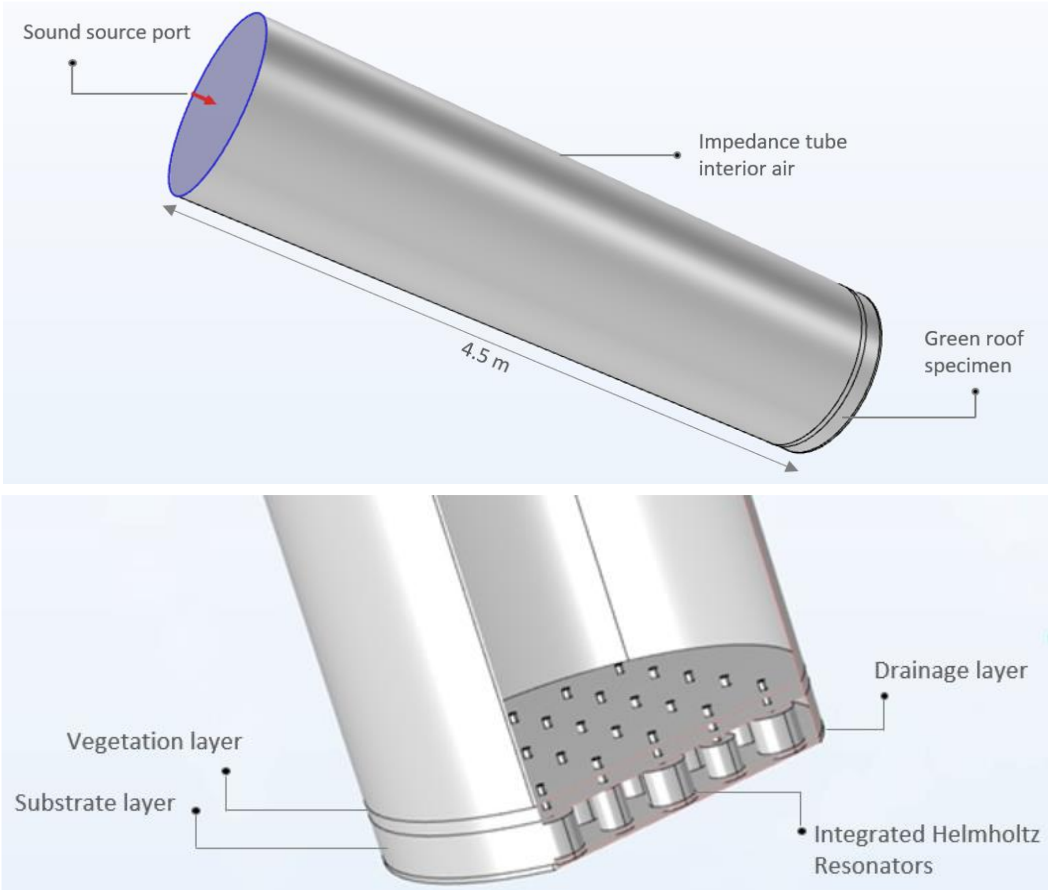


Figure 7.1: Geometry-Impedance tube model setup used in COMSOL.

2. Defining Material Properties

After correctly configuring the geometry, it is critical to give material properties to each component in the model. COMSOL's comprehensive materials library includes predefined parameters such as density, sound speed, and porosity, which might help to speed up the setup procedure. Properties for special or custom materials, such as the composite substrate layer, can be defined by the user and must be entered manually to assure accuracy. Custom materials, such as the composite substrate layer and the vegetation layer in the study, must have their properties carefully defined to assure correctness and conformity with the design parameters. As the acoustic behavior of the green roof system is primarily influenced by the porous substrate layer, properties like porosity, flow resistivity, tortuosity, and viscous and thermal lengths are significant parameters and need to be defined for the simulation. Furthermore, it is important to define the properties of the surrounding medium, in this case air, and specify the acoustic impedance for boundaries as needed. As these parameters influence sound propagation and interaction at the boundaries, they are essential for realistic simulations.

3. Configuring Physics Settings

The next step is to configure the required physics settings. This begins with choosing the proper interfaces in the Acoustic Module, such as Pressure Acoustics, Frequency Domain, or

Poroacoustics Model, based on the materials in the model. As each interface governs how sound waves propagate, interact, and are absorbed by the different materials in the system, they are critical for accurately simulating the model's acoustic behavior. For instance, using the interface Pressure Acoustics, Frequency Domain allows precise modeling of airborne sound waves, essential for analyzing how external noise is attenuated by the green roof layers and resonator cavities. Meanwhile, the *Poroacoustics Model* interface is necessary to capture the acoustic behavior of materials such as the porous substrate, which contains porous media like compost and pumice. The correct selection of interfaces ensures that each component's unique acoustic properties are realistically represented, thereby providing reliable and relevant results for sound absorption in the system. In any case, it is important to establish boundary conditions that closely reflect the real-world scenario.

For the study's simulations, different physics are assigned to the different parts of the model in order to accurately capture the acoustic behavior of the complex system.

- The *Pressure Acoustics, Frequency Domain* interface is used for the impedance tube simulation. This interface models the propagation of the acoustic waves in the air, accounting for pressure variations and their interaction with the boundaries and materials.
- *Poroacoustics* is assigned to the vegetation layer and the porous substrate layer of the system. This interface is critical for modeling the sound absorption behavior of these layers and considers the interaction between acoustic waves and the porous structure of these materials, using parameters such as porosity, flow resistivity, thermal and viscous characteristic length, and tortuosity factor.

  Material Properties Assigned in the Simulation

  1. Substrate Layer:
     - Porosity: 0.85
     - Flow Resistivity: 8,000 Pa·s/m²
     - Viscous Length: 0.002 m
     - Thermal Length: 0.003 m
     - Tortuosity: 2.7
  2. Vegetation Layer:
     - Porosity: 0.8
     - Flow Resistivity: 2,000 Pa·s/m²
     - Tortuosity: 1.8
     - Viscous Length: 0.0025 m
     - Thermal Length: 0.003 m

- *Narrow Region Acoustics* is assigned to the necks, cavities, and water exit perforations of the resonators. This physics interface can be used for regions with geometrically constrained spaces where viscous and thermal losses are important, such as the narrow regions of the Helmholtz resonators.

4. <u>Generating the Mesh</u>

After creating the geometry and assigning the appropriate physics to the model, the next significant step is to build the mesh layout. The mesh that is used for a model geometry plays an instrumental role in how the model is solved, as it determines factors such as how the geometry is divided, with what shape or element type the geometry is divided, the size, density, and number of elements in the geometry, as well as the quality of the different elements (*How To Build A Mesh in COMSOL Multiphysics®*, n.d.). A well-considered mesh strategy is essential for achieving both computational efficiency and accuracy in simulation results. Mesh refinement, particularly through COMSOL's adaptive meshing options, allows for targeted improvements by increasing mesh density only in areas where it is mostly needed. This approach is especially valuable in simulations focused on specific frequency ranges, as it enhances accuracy in capturing frequency-dependent phenomena without imposing excessive computational demands (*Simulation Software For Analyzing Acoustics And Vibrations*, n.d.). In other words, in areas with complex wave interactions and small geometric features, such as the necks of the resonators, it is important to apply a fine mesh in order to capture the detailed behavior of sound waves accurately. For more uniform regions, such as the surrounding air, coarser meshing can be used to minimize computation time without sacrificing result precision. For the current simulation, a predefined *fine* mesh is used to ensure accuracy and precision and capture all the narrow geometric regions where sound waves interact with the structure.

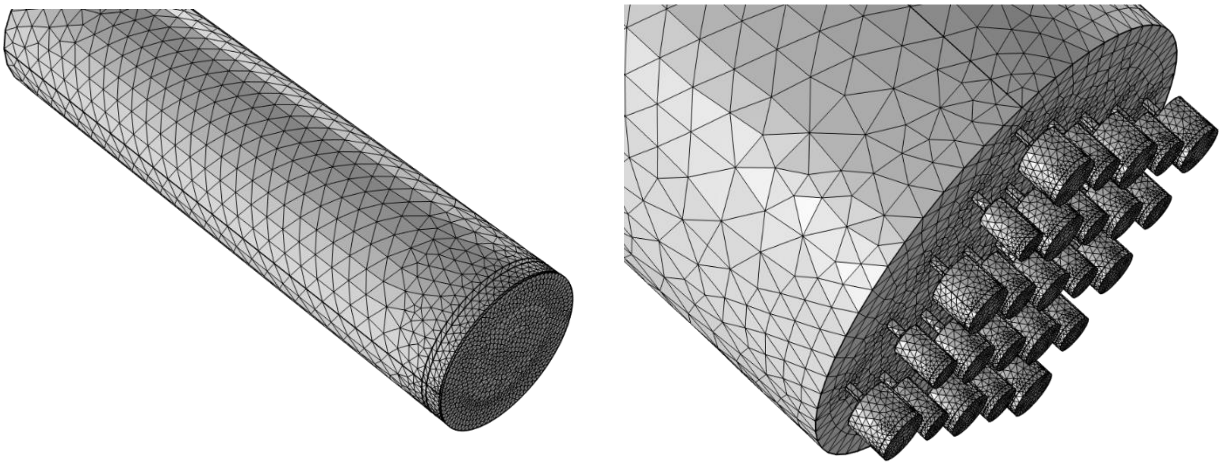


Figure 7.2: The used model mesh. A fine mesh was used both for the smaller geometries but also for the area representing the impedance tube interior.

During simulations, the use of a coarser mesh in the area representing the impedance tube interior air is observed to result in some irregularities in the absorption curves, particularly an oscillatory behavior at higher frequencies. This can be attributed to the inability of a coarser mesh to accurately resolve shorter acoustic wavelengths at higher frequencies, resulting in numerical dispersion, artificial reflections, and phase inaccuracies. These factors compromise the precision of the acoustic pressure and impedance calculations, leading to fluctuations in the absorption results. To mitigate these issues, a fine mesh is then applied to the entire geometry, increasing computation time but ensuring accurate resolution across the different frequencies. Overall, using the appropriate mesh is crucial because it directly influences the model's ability to represent wave propagation, reflection, and absorption with fidelity. An optimized mesh layout ensures that the simulation effectively captures the acoustic behavior of the system, providing reliable and high-resolution results where they are most relevant.

5. Setting up the solver

Once the model setup is complete, including geometry, material properties, boundary conditions, and meshing, the next step is to configure the solver settings and run the simulation. In order to analyze the system's response over the desired range of frequencies, it is essential to set up a frequency sweep. This allows for observing variations in the absorption coefficient and other acoustic parameters at different points within this spectrum. With everything configured, the model is ready to be simulated, providing detailed insights into its acoustic performance across the specified frequency range.

6. Post-Processing and Analyzing Results

After running the simulation, the next important step is the post-processing of the obtained results. This mainly involves analyzing the data generated from the acoustic simulation and identifying critical parameters that reflect the system's performance. The simulation's main output for this study is the absorption coefficient values, which are used to evaluate and compare the system's sound absorption over the intended frequency range. The absorption coefficient graphs provide a visual assessment of how well the integrated Helmholtz resonators can contribute to enhanced sound absorption in the low frequency range.

7.3.1 A Systematic Iterative Design Approach

The process of developing resonator concepts relies on a systematic approach to a step-by-step methodology, involving a combination of analytical design, numerical modeling, and design optimization. This approach ensures that each design iteration is based on results obtained from previous steps, ultimately leading to progressive improvement and a new optimized solution.

The initial step involves the analytical design of resonators, where the dimensions of the cavity and neck are calculated for the desired frequencies. The designs are based on Helmholtz resonance principles, considering the desired frequency range and the physical-geometrical constraints of the green roof system. Using the initial design parameters, a MATLAB analytical model, developed by Professor M.J. Tenpierik at TU Delft, is utilized to calculate resonance frequencies and impedance values. Details of the code can be found in Appendix A. At the same time, a single-resonator COMSOL simulation is conducted to predict the acoustic behavior of each resonator arrangement. The compatibility of those two models enables a first-level validation for the resonator's design. An overview of the different resonator configurations that are used for the analysis is presented in Figure 7.4.

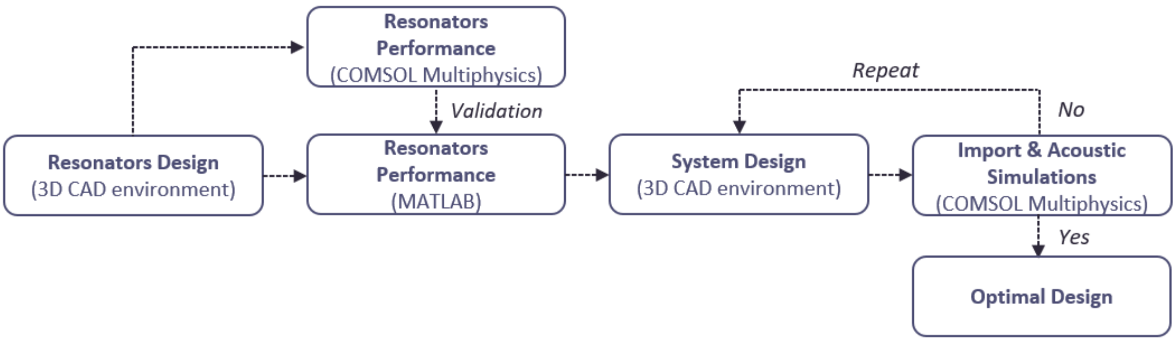


Figure 7.3: Overview of the workflow used for the systematic design process.

Once the green roof system with the integrated resonators is modeled in 3D CAD environment, it is subsequently converted into a numerical model within COMSOL Multiphysics. The simulation allows for extensive analysis of the system's sound absorption performance within the controlled setting of the impedance tube model. The integrated green roof system, including the different resonators, is modeled to assess its overall performance, and based on the simulation findings, the resonator designs are then refined iteratively, involving a procedure of geometrical and design modifications. While emphasis is given on achieving uniform distribution of sound absorption on the low-frequency spectrum, the effects over a wider frequency range are taken into consideration. However, wide absorption dips between target frequencies or insufficient absorption at specific frequencies lead to design modifications, and parameters such as the cavity volume, neck dimensions, and number of resonators are adjusted in order to refine resonance frequencies and optimize absorption distribution across the desired frequencies. In particular, the system goes through an iterative optimization process that involves the following adjustments:

- Changing the number of resonators: adding or removing resonators that target specific frequencies in order to achieve a wider absorption spectrum.
- Increasing target frequencies: adding resonators to address significant gaps in the frequency response, ensuring a higher overall coverage.
- Fine-tuning individual designs: although rarely required, changing the dimensions of certain resonators when integrated into the system to improve their performance.

This procedure is repeated until the most promising configuration is determined. The ultimate goal is to identify an arrangement that, considering the system's restrictions, provides good sound absorption across the desired frequency range, balances resonator integration with the substrate, and satisfies practical constraints and the system's functions, such as water drainage. The methodology followed for this iterative approach is summarized in the diagram of Figure 7.3. The combination of tools ensures a solid and rigorous approach to developing a design with integrated resonators. The entire process followed is documented in order to provide a clear understanding of the design decisions and their influence on the system's overall performance.

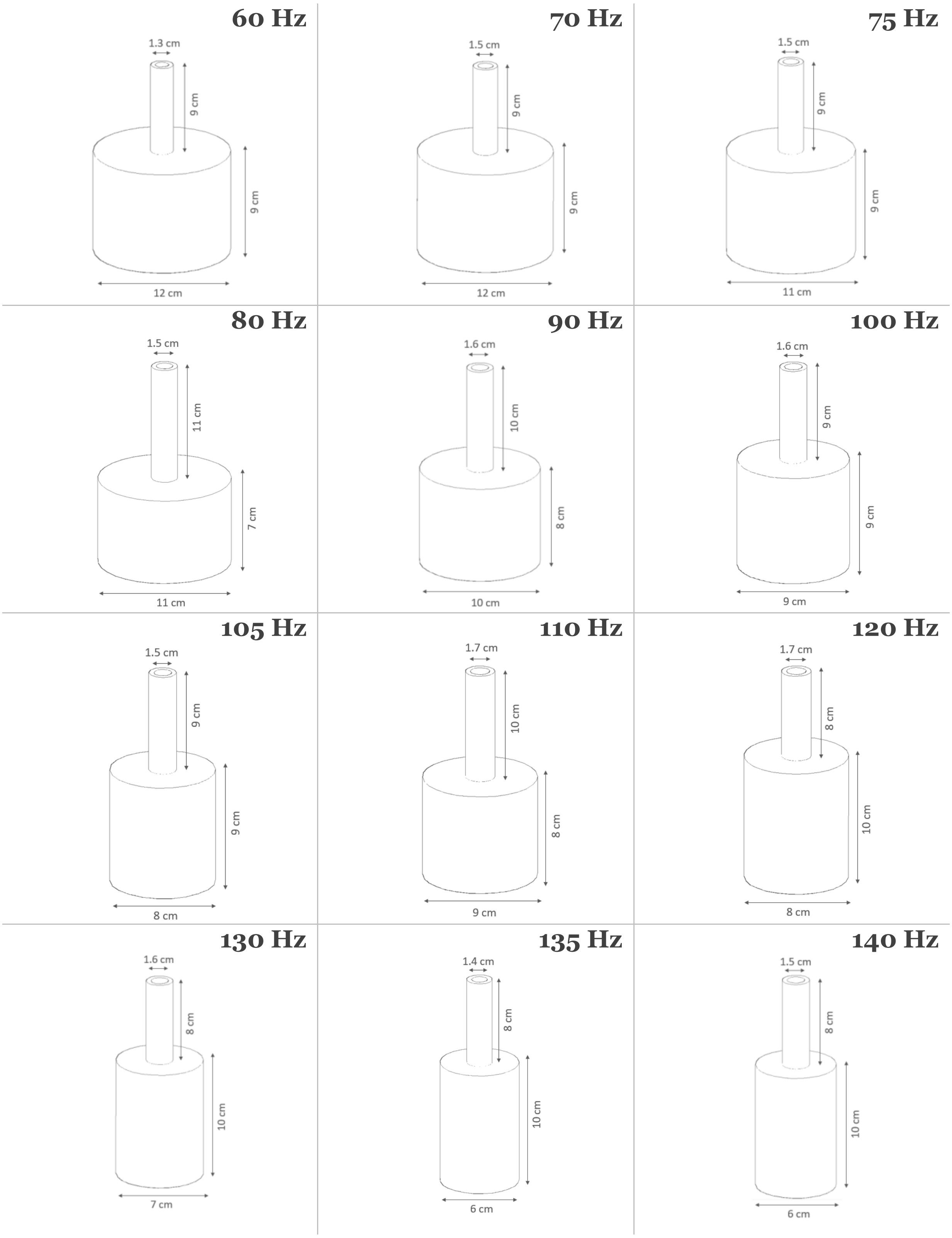


Figure 7.4: An overview of the resonator configurations used for the acoustic analysis.

7.3.2 The effect of adding water outlet perforations in a Helmholtz resonator

The following analysis demonstrates the influence of **position**, **size,** and **number** of water outlet perforations that are placed at the base of a resonator's cavity on the resonator's frequency peak. In this case, the resonator designed to target a frequency of 60 Hz is examined.

1. Water outlet perforation placed in the **center** of the base.

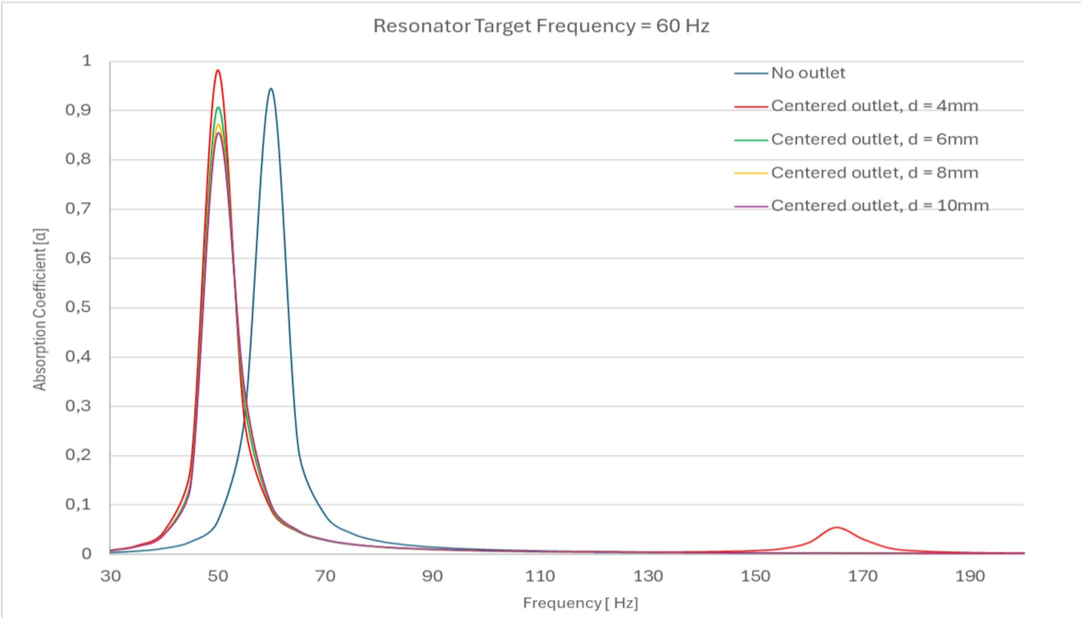


Figure 7.5: The effect of the outlet perforation's size on the resonator's frequency peak (case: centered perforation).

2. Water outlet perforation placed **off-centered**.

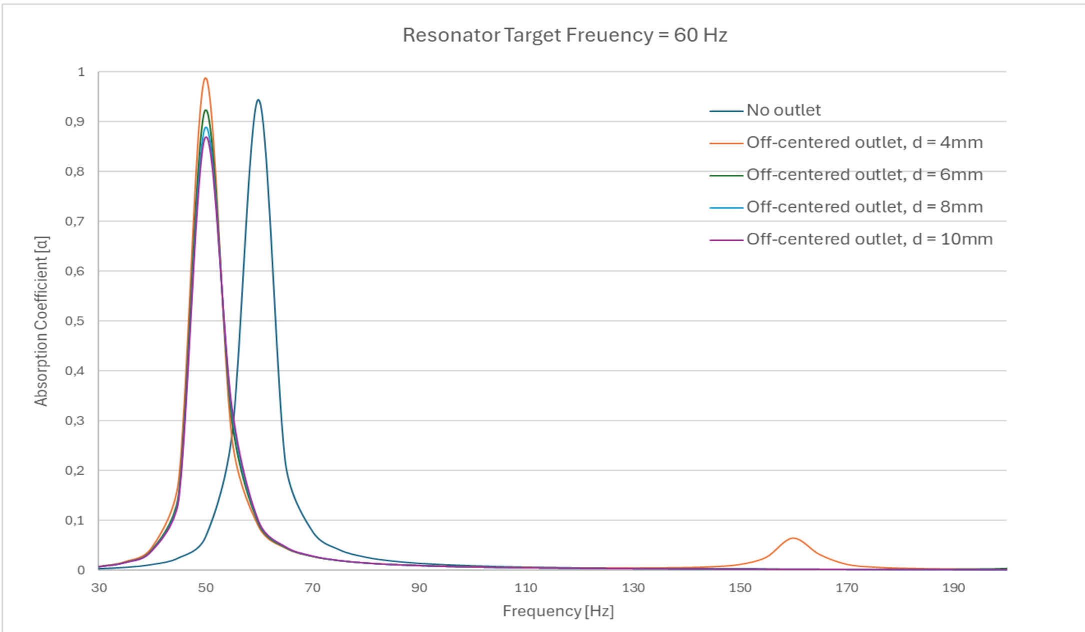


Figure 7.6: The effect of the outlet perforation's size on the resonator's frequency peak (case: off-centered perforation)

Position of Perforation

The comparison between centered and off-centered outlets shows that there is little to no noticeable difference in absorption characteristics between centered and off-centered outlet perforations at various diameters.

Size of Perforation

The size of the water outlet perforation is essential in determining the resonator's absorption coefficient and peak frequency. As the diameter of the perforation increases (from 4 to 10 mm), the magnitude of the absorption coefficient across both centered and off-centered designs is reduced. This can be explained, as larger perforations allow more airflow, which can reduce the resonance effect, leading in a less effective peak.

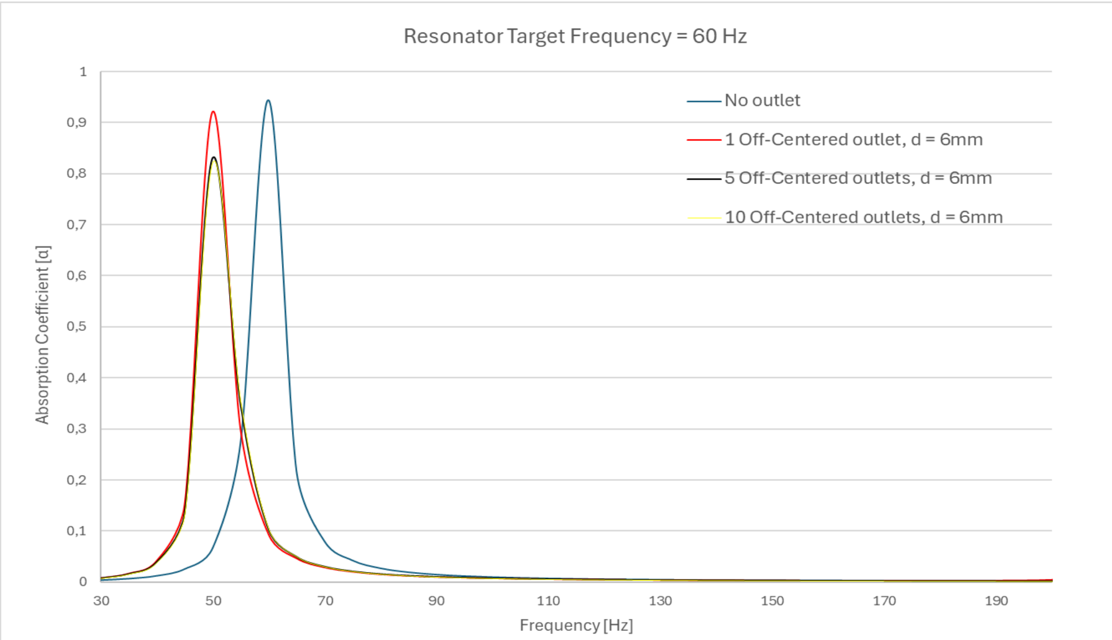


Figure 7.7: The influence of perforations' number on the maximum absorption coefficient value.

Number of Perforations

The number of outlet perforations seems to have an impact on the resonators performance. In particular, increasing the number of outlets seems to reduce the effective resistance within the resonator cavity, resulting in a reduction of the absorption peak. However, Figure 7.7 indicates that beyond a certain number of outlets, adding more perforations does not result in a significant further decrease in absorption, revealing a diminishing return in absorption performance.

In any case, all graphs indicate that adding even one outlet perforation shifts the frequency peak to lower values.

Introduction of a secondary resonance

Additionally, the incorporation of water exit perforations facilitates the development of a secondary resonator system situated beneath the primary resonator. This secondary system occurs from the interaction of the newly introduced perforations and the air cavity located beneath the resonators, which represents the water drainage layer and effectively forms a coupled acoustic structure.

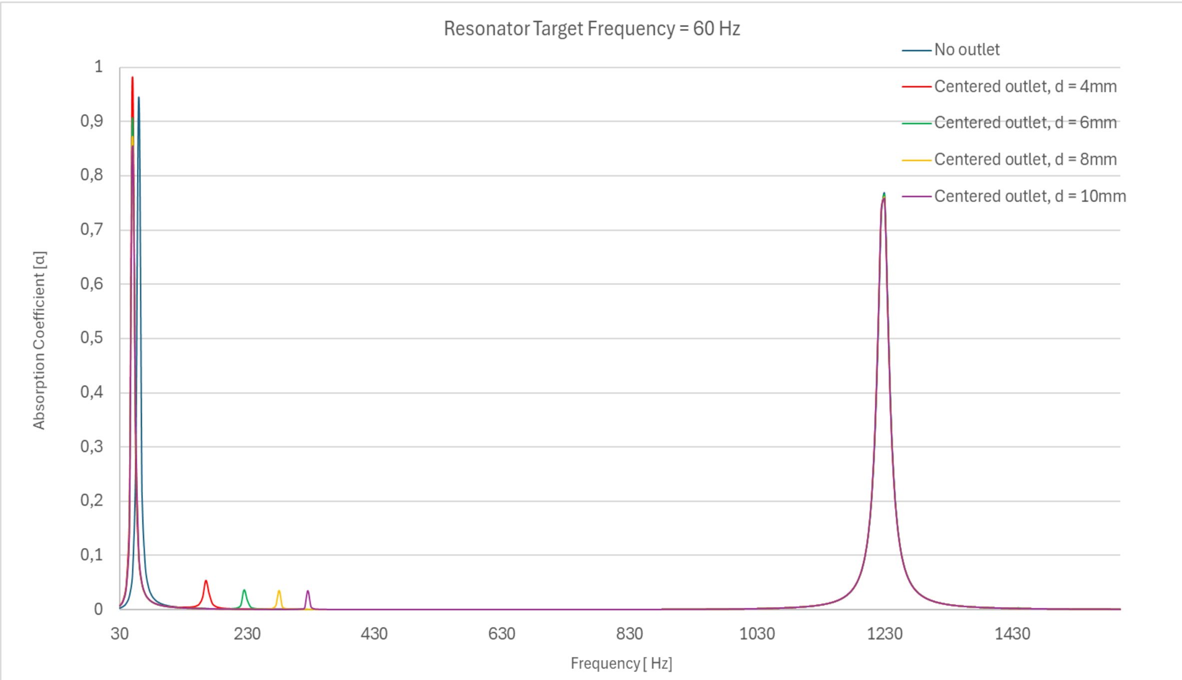


Figure 7.8: The introduction of secondary absorption peaks at higher frequencies.

The diagram of Figure 7.8 demonstrates that the introduction of the secondary absorption peaks occurs at higher frequencies, specifically around 1300 Hz, when outlets of varying diameters are added to the resonator system. The higher-frequency location of the secondary peaks is primarily a result of the significantly smaller geometric dimensions of the secondary resonator, which collectively alter its resonant characteristics compared to the primary resonator.

7.4 Results and Optimization

This paragraph aims to answer the last sub-research question of the study, particularly: *What level of sound absorption can be achieved through the use of alternative solutions implemented into green roof systems?*

The graph of Figure 7.9 illustrates the absorption coefficient (α) of the examined system, with one curve obtained from the impedance tube measurement test and the other one from the COMSOL simulation. This simulation is performed in order to validate the simulation model of the green roof system.

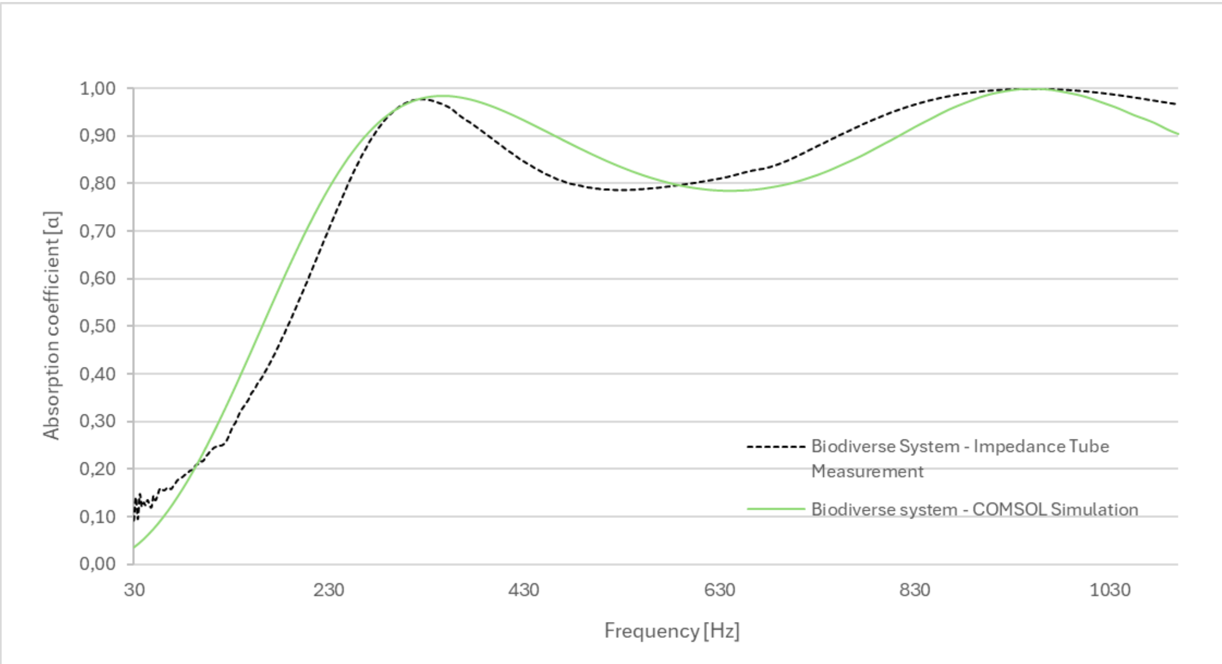


Figure 7.9: Graphic representation of the sound absorption coefficient as a function of frequency for the biodiverse system as occurred form the impedance tube measurement (black-colored line) and the simulation (green-colored line).

Both curves present an overall similar pattern, particularly in the low to mid frequency range, up to around 350 Hz, where an increase in absorption is observed, leading to a peak near this frequency. While the two curves present some differences, these seem reasonable, as achieving complete compatibility between the experimental measurement and the simulation is inherently challenging, considering differences in modeling assumptions, boundary conditions, and experimental setup. Despite these differences, the overall behavior of the system is captured by both methods, confirming the reliability of the simulation in representing the acoustic behavior of the system.

The effect of adding resonators to the system

To enhance the system's low-frequency absorption performance, the integration of Helmholtz resonators is being explored. Figure 7.10 represents the effect of adding resonators on the system's acoustic performance, comparing the absorption coefficient (α) of the system with and without the resonators, as obtained through COMSOL simulation. As can be seen, the general absorption pattern is broadly consistent between the two conditions, with peaks and troughs occurring at similar frequencies. When resonators are introduced into the system, the absorption coefficient decreases modestly across the frequency spectrum. This decrease in absorption coefficient can be attributed to the resonators occupying a portion of the substrate volume (about 13%), lowering the amount of acoustically active substrate material. Because the substrate is required for sound absorption, its partial replacement to accommodate resonators marginally reduces the system's overall acoustic capacity, with the reduction being more noticeable at low frequencies than at mid and high frequencies. This difference can be explained by the interaction of the resonators with the substrate layer. At the low frequency range, the resonators primarily take over the function of sound absorption, since they are designed and tuned to target particular low frequencies. However, as explained, accommodation of resonators requires reduction of the acoustically active material amount that is available for broad range absorption. Since the substrate contributes significantly to sound absorption at the lower frequencies, its partial removal results in a slight but noticeable drop in acoustic performance within this range.

On the other hand, in the mid and high frequency range, the characteristics of the substrate that are mainly responsible for and control the sound absorption process are porosity and flow resistivity. As the resonators are less effective at this frequency range, the system's performance remains mostly determined by the substrate layer. This could explain the less pronounced impact on the absorption at higher frequencies.

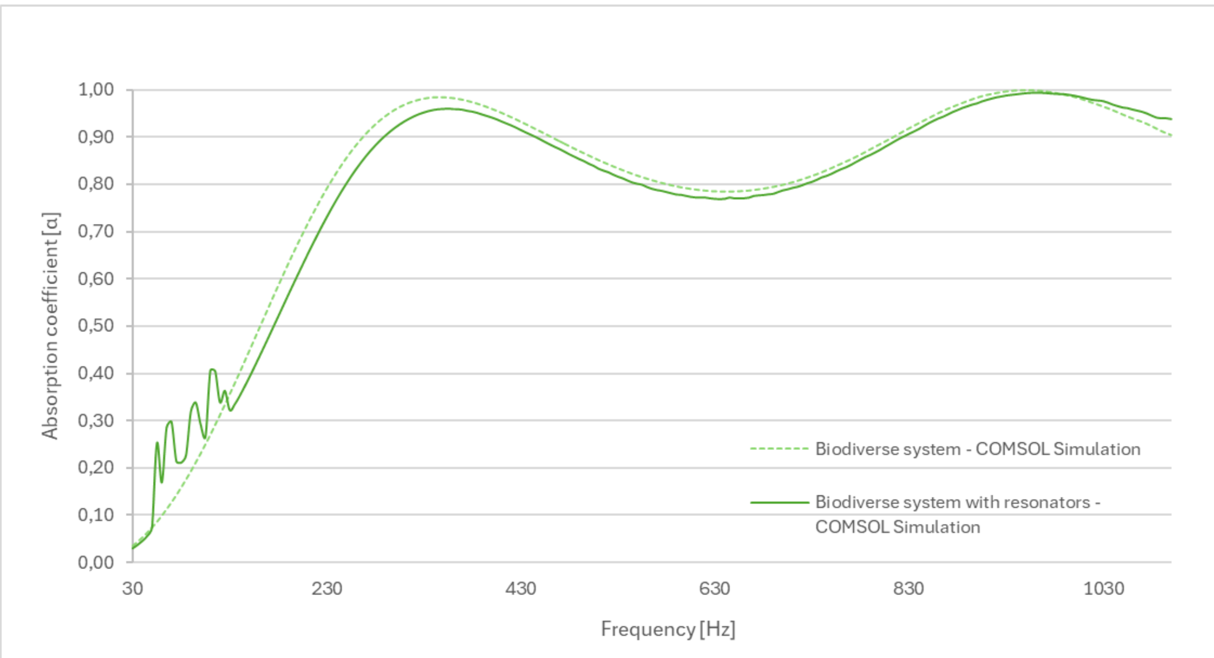


Figure 7.10: The influence of adding resonators on the Biodiverse system's acoustic performance.

Nevertheless, the integration of resonators introduces targeted improvements at specific frequencies, enhancing the system's ability to address particular acoustic challenges. This trade-off highlights the fact that depending on the particular frequency range and absorption requirements of the application, substrate removal and the benefits provided by the resonators integration should be carefully balanced.

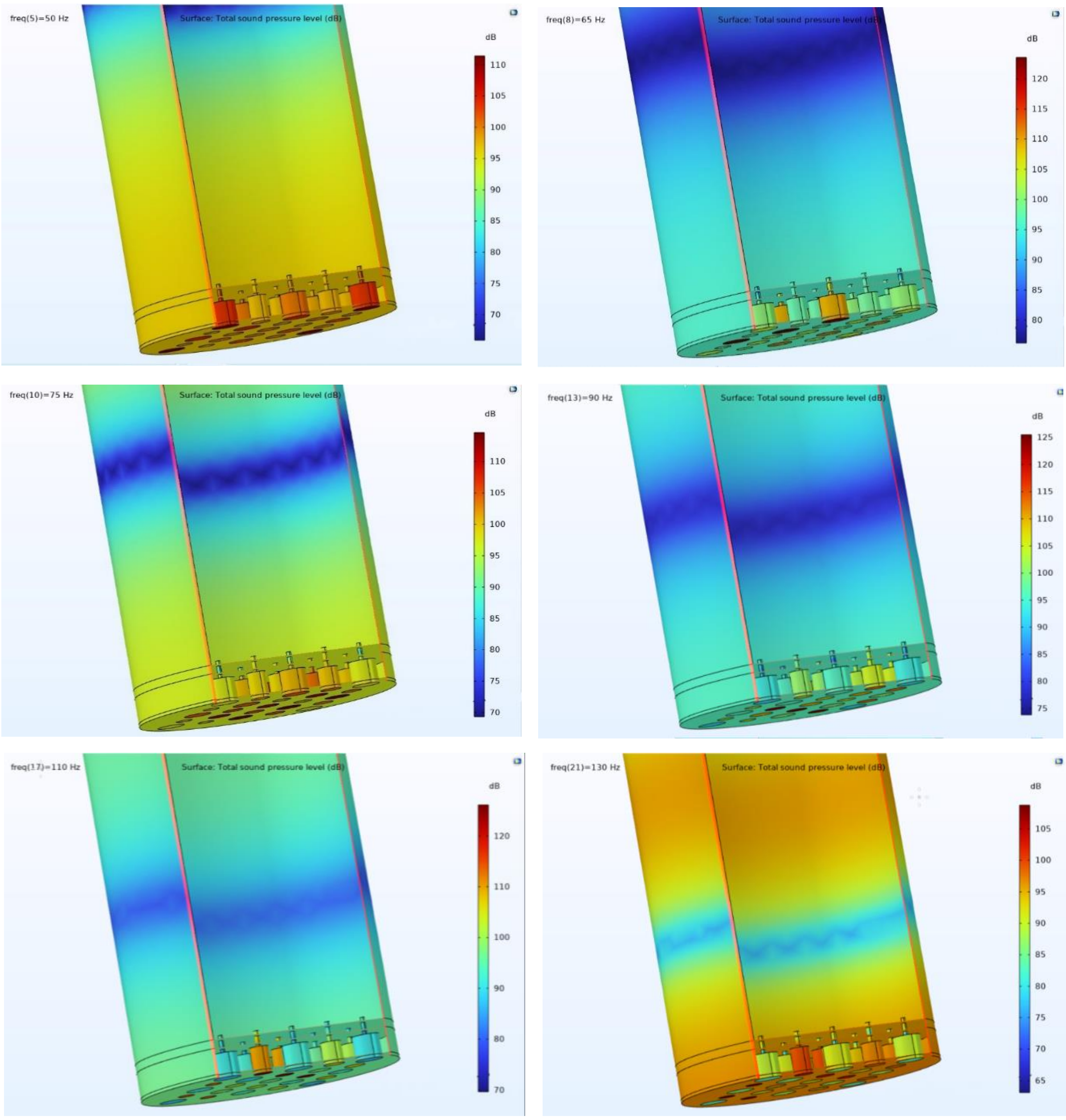


Figure 7.11: Total sound pressure level distribution at various frequencies (50, 65, 75, 90, 110 and 130 Hz) in the green roof-resonators system (Results extracted from concept E).

Table 7.1: Number of resonators for each target frequency in the different tested concepts.

Concept / Target Frequency	A	B	C	D	E
60 Hz	8	9	7	4	4
70 Hz	-	-	-	-	3
75 Hz	-	-	-	3	-
80 Hz	-	7	6	-	3
90 Hz	9	-	-	3	3
100 Hz	-	5	5	-	3
105 Hz	-	-	-	3	-
110 Hz	-	-	-	-	3
120 Hz	3	4	3	3	3
130 Hz	-	-	-	-	3
135 Hz	-	-	-	3	-
140 Hz	-	-	4	-	-

Table 7.1 provides a clear overview of the concepts that were developed and tested during the analysis. The results that occurred from the simulations for these concepts are presented in Figure 7.12. Based on the absorption coefficient graphs of the different concepts, there are some major observations that should be mentioned:

- It is clear that adding more resonators targeting a wider range of frequencies, while keeping the total number of resonators constant, results in a slight drop in the absorption coefficient. This is to be expected, as dispersing the resonators across more frequencies spreads the acoustic absorption over a wider frequency range, lowering absorption concentration at certain frequencies. At the same time, this greater distribution leads to a more uniform absorption curve, which provides more consistent absorption performance over a wide frequency range. While the decrease in absorption cannot be neglected, covering a wider spectrum of sound may be useful in practical applications.

- Although the resonators are initially designed and tuned to target specific frequencies, a shift in their initially intended peak is observed. This shift can be attributed to the addition of water outlet perforations at the cavity's base, as well as the presence of an air gap beneath the resonators, which represents the drainage layer. These perforations, while vital for the drainage system, may affect the impedance characteristics of the resonators and the entire system, affecting resonance frequencies. Appendix B provides a detailed analysis of the impact of adding these small water outlets to the cavity base of a resonator.

- **Concept E (8 target frequencies**): While in concepts A, B, C and D the simulation results provided the expected, slightly shifted frequency peaks, in concept E, where eight different frequencies are targeted, the expected eight peaks in the absorption coefficient curve are not present. Instead, the graph exhibits fewer peaks, indicating that the effects of the resonators may overlap. As in this concept, a smaller frequency step of 10 Hz is adopted, this may cause the resonators' effect to overlap. This overlap could cause some of the resonators to operate in the same frequency range, limiting the number of distinct peaks and leading to a more blended absorption curve.

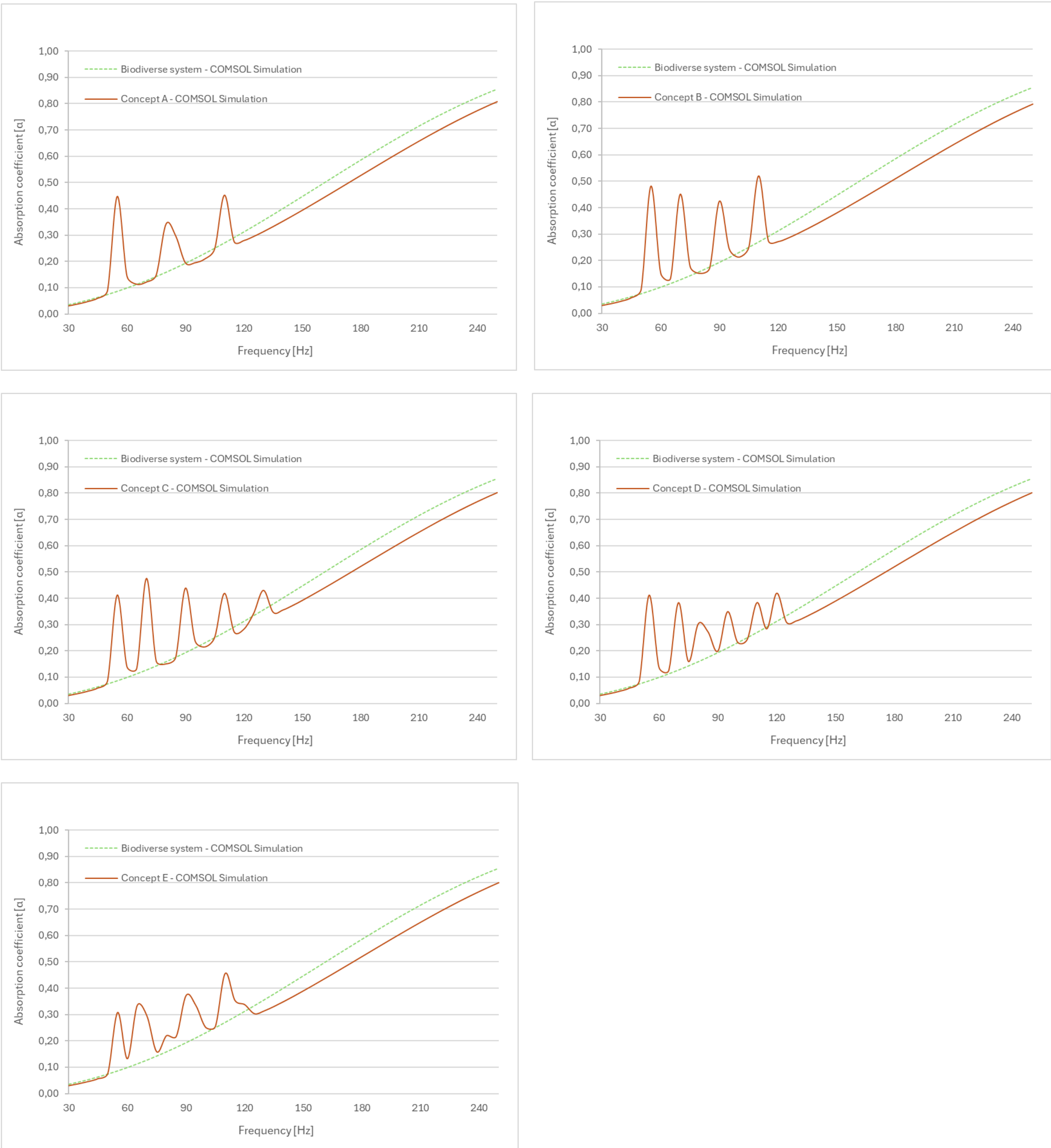


Figure 7.12: Comparison of the system's acoustic performance among the different concepts developed.

Optimization

In an attempt to examine if the results can be further optimized, two different optimization strategies are explored. In particular, these attempts are tested on concept E, which is based on the simulation of 8 target frequencies.

(a) Cross-structure fins along the neck of the resonator

The primary purpose of adding cross-structure fins into the resonator necks is to increase airflow resistance across the length of the neck. This increase in resistance can be used to modify the resonator to operate more effectively across a wider range of frequencies. The mechanism behind the idea of cross-structure fins, that are stiff parts of the necks, is that they can potentially interrupt the airflow and result in increased flow resistance. As a result, the higher resistance can affect the resonator's capacity to absorb sound waves, especially at the desired frequencies. On the other hand, these structures occupy physical space inside the neck, reducing the effective available air volume inside the neck. As the resonator's performance at the desired frequency is dependent on the interaction of waves within this air volume, a smaller available air volume can potentially reduce the absorption coefficient.

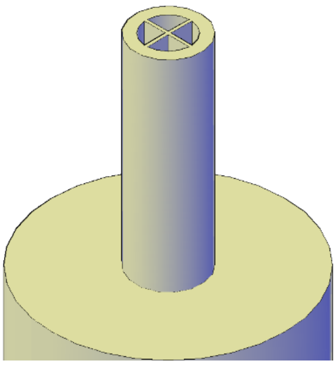


Figure 7.13: *Introduction of cross- structure fins inside the resonator's neck.*

(b) Smaller-diameter second neck

A different optimization proposal involves the introduction of a smaller-diameter second neck to the resonator in order to increase the overall resistance of the neck system. The second neck is placed alongside the existing neck and has a smaller diameter to increase the resistance to airflow. The idea behind this mechanism is that adding a second neck automatically creates a parallel airflow route with its own resonance characteristics, this may lead to a broader absorption peak. Hence, the second neck can introduce a slightly different resonant frequency, resulting in shifting peaks or overlapping that can increase the system's bandwidth. However, similarly to the cross-structure fins, adding a second neck may also have an impact on the absorption coefficient value. As the effective air volume passing through the primary neck, which is critical for resonance, may be diminished, this redistribution of airflow may reduce the resonator's ability to absorb sound effectively. Finally, adding a second neck can cause a shift in the system's resonance frequency. In case this shift moves the resonance away from the desired frequency, the system's peak in absorption coefficient may decrease.

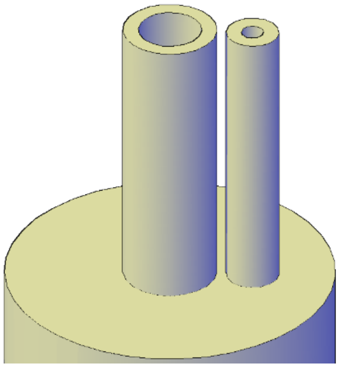
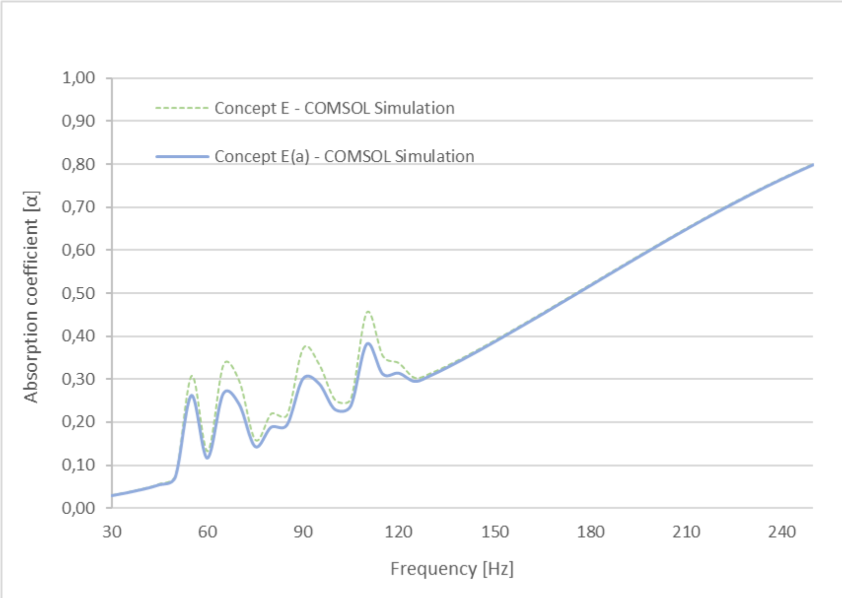
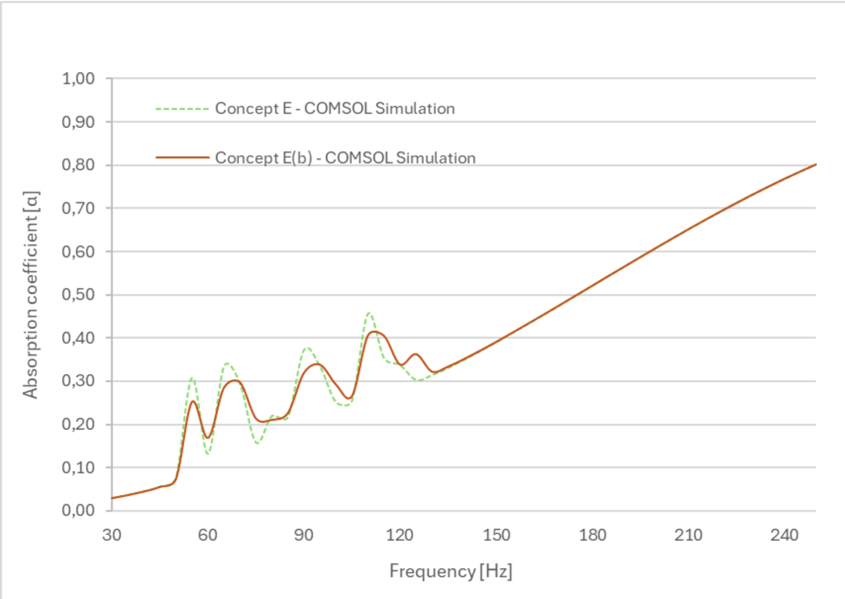


Figure 7.14: *Introduction of a second neck alongside the primary neck.*



(a)



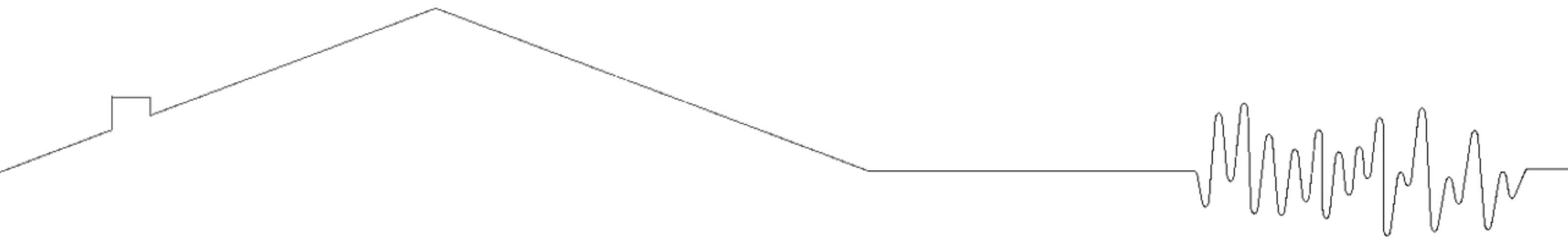
(b)

Figure 7.15: The effect of adding (a) cross-structure fins along the neck of the resonator and (b) secondary neck alongside the primary neck on the system's acoustic performance (concept E).

The results of the two optimization strategies show an impact on the system's acoustic performance. The first graph shows that the introduction of cross-structure fins in the neck provides a noticeable reduction in the maximum absorption coefficient values while not significantly broadening the frequency peaks.

On the other hand, the addition of a secondary neck alongside the primary neck (graph b) results in a slight reduction in the maximum absorption coefficient values. Additionally, in this strategy the overall absorption range appears more consistent, contributing to smoothing the frequency response.

It is also important to mention that in both cases the optimization technique is applied to the resonators selectively. In particular, not all resonators in the system are equipped with the optimization techniques, but only one resonator of each target frequency group is optimized. This selective approach was adopted when simulations demonstrated that applying the optimization to all resonators results in a dramatic reduction in the maximum absorption coefficient values.



REFLECTION

8
Discussion

8.1 Results and Validation

The aim of this chapter is to discuss and analyze the reliability of the methodology that is followed throughout the research, emphasizing its reliability and validity in analyzing the acoustic performance of the integrated green roof system. By assessing the strengths and limitations of the experimental and simulation procedures used, the discussion provides a comprehensive understanding of the methodology's effectiveness and ability to provide reliable results. Particular attention is given to the impedance tube model and COMSOL acoustic simulation, highlighting their contribution to the study while addressing inherent constraints such as scale, material assumptions, and boundary conditions. Finally, the chapter discusses additional steps that could increase the reliability and validity of the findings, providing valuable insight into future study areas.

8.1.1 Reliability and Validity of the Method

The reliability and validity of the used methodology can be evaluated with regard to its strengths and limitations. Specifically, the approach demonstrates particular benefits:

- Both COMSOL simulations and impedance tube measurements provide a safe and controlled environment for analyzing acoustic behavior. This reduces external noise and interference while improving the ability to consistently reproduce the same results under the same experimental conditions when the method is repeated multiple times.
- The COMSOL model enables extensive analysis of different configurations, materials, and resonator designs, providing insight into the system's expected acoustic performance.
- The impedance tube method is a widely known method for testing acoustic characteristics in small specimens, adding legitimacy to the initial measurements.

However, the findings are based on controlled simulation conditions, which may not account for external factors that can affect the resonators' performance in practice. As the simulation is a process that can contain inaccuracies, assumptions, and simplifications, although it can provide a dependable framework for analyzing and optimizing the results, the need for further experimental validation in field conditions is critical and necessary.

8.2 Limitations of Impedance Tube Measurements

The impedance tube measurements that are used to assess the acoustic performance of the different green roof systems by Sempergreen and extensively described in paragraph 5.1, have certain limitations that should be acknowledged in order to get an accurate understanding of the results. The main limitation is that the impedance tube test is performed on a small-scale sample with a diameter of 10 cm, which may not fully reflect the behavior of the larger system. As in real-world applications, the system is much larger in scale, and considering the different boundary conditions, layer interactions, as well as material heterogeneity, the observed acoustic characteristics in a small sample might differ from those of the full-scale system.

Additionally, the boundary conditions in the impedance tube are significantly more restricted compared to those of a real-scale green roof system. These boundary conditions can affect wave propagation, especially in the low-frequency spectrum, where the acoustic behavior is highly affected by the system's geometry. Instead, the tube's small capacity may not adequately portray the realistic interactions of sound waves that can occur in an open environment.

Another limitation is that impedance tubes are designed to allow sound waves to propagate in a single direction along the tube's axis, measuring only normal incidence. In real-world scenarios, sound waves interact with the system at various angles, leading to complex acoustic phenomena that the tube cannot replicate. Additionally, this single-direction configuration assumes that the material under testing is homogeneous over the cross-section, since non-uniformities could result in diffraction or scattering effects that could not be properly captured by the simple plane wave model. However, the assumption of homogeneity may not be valid for a real-scale system, where material discrepancies, thickness variations, and uneven layering can occur. This could lead to inconsistencies between the actual and measured acoustic performance.

Furthermore, the impedance tube method is mainly effective within specific frequency ranges, hence the results might not capture the entire range of the system's acoustic behavior. Since the different systems tend to behave differently at various frequency ranges, this limitation may lead to an incomplete appreciation of their general acoustic performance.

Last but not least, the simplified cylindrical shape of the tube and specimens does not account for more complex, irregular shapes that may be present in the actual system. This simplification could result in neglecting important acoustic phenomena, such as diffraction, interference, and scattering effects that can occur in real-scale green roof systems.

In summary, while the impedance tube measurements provide useful information into the acoustic behavior in a controlled environment, they may not be able to fully capture the complicated behavior of the multilayered system.

8.3 Limitations of Acoustic Simulations

While the approach used provides a strong framework, the absence of real-scale experimentation to evaluate the final results can be considered a disadvantage or limitation. The simulation, even though valuable and reliable under controlled conditions, may contain inherent inaccuracies due to several factors. In COMSOL, a number of simplifications have been made to simulate the geometry of the system, which may not fully capture the behavior of the real system. These simplifications involve assumptions on the material properties, boundary conditions, and simplified, idealized geometries that are used to reduce computational demand; however, they might accurately represent the real-world setup. Additionally, the COMSOL model includes discretization and numerical solving techniques, which is sources of errors and inaccuracies, something that was particularly noticed when coarse mesh resolutions were used or whenever inappropriate boundary effects were modeled.

8.4 Research and Potential

This research can contribute to the expanding information on green roof acoustic optimization and the use of resonators as a possible solution for low-frequency sound absorption. The findings demonstrate that it is possible to increase the acoustic performance of green roof systems within a range, thereby filling a knowledge gap in the current solutions for low-frequency noise management. However, as mentioned, without a representative physical prototype, with which real-scale experiments can be conducted for comparison of the simulation results, there is no definite way of verifying the accuracy of the simulated results. As a real-scale test in the field could indicate inaccuracies that may not have been anticipated in the simulation model, this is particularly critical for complex systems like the examined, where parameters such as moisture, temperature, and material degradation could affect the overall performance.

To enhance the results' reliability and validity, it would be important to consider a real-scale validation step. This could involve the development and acoustic testing of a larger-scale prototype for a green roof biodiverse system with integrated Helmholtz resonators, ensuring that it reflects the representative properties and acoustic characteristics of the real system. By comparing the real-measured data to the simulation findings, any discrepancies can be identified, and the simulation model can be updated to reflect more refined material property assumptions.

To summarize, the absence of a large-scale experimental validation is a reasonable concern. A real-scale experimental comparison could provide clearer results on how well the simulation models can reflect the real acoustic behavior of the system. In this case, without validation, while the method followed remains a reliable and valid approach, the final results should be considered as approximations that might have to be refined through physical testing. Finally, the results of this research can serve as a valuable reference for future researchers, focusing on further optimizing resonator designs or investigating the impact of vegetation on acoustic performance.

9
Conclusion

The aim of this research was to answer the following question:

" How can the acoustic absorption of green roofs be improved, focusing on the low-frequency spectrum, and considering the importance of sustainability and environmental footprint/impact ? "

In order to answer this question, the research approach used both qualitative and quantitative methodologies to provide a comprehensive analysis of the main topic. The research involved three main stages. The study began with a thorough literature review to establish a theoretical insight into green roof technology, the acoustic performance of green roofs, as well as the role of Helmholtz resonators. This initial phase provided useful information on the current situation of green roof performance, the limitations of existing solutions, as well as the potential benefits of integrating resonators into the system. It also emphasized the importance of considering sustainability and environmental impact during designing. This helped to situate the research within a broader context of urban noise pollution and the need for ecologically responsible design practices.

Based on the literature research, a simulation model was developed to assess the integration of Helmholtz resonators embedded into the substrate of the green roof system. Before creating the simulation model, impedance tube measurements were performed to gather experimental data and validate the different systems' acoustic properties, providing a foundation for the subsequent stages. These measurements were critical in understanding the baseline acoustic performance of green roof systems. Following this, a concept design with integrated resonators was developed and refined to serve as a basis for the simulations. The simulation stage required not only expertise in acoustics but also technical knowledge of material properties and their interaction with sound waves. The developed model provided quantitative data that allowed examination of the system's acoustic performance across various frequencies and combinations. This approach yielded key insights into the design and tuning of the resonators, as well as their interaction with the porous substrate layer, enabling a comprehensive assessment of the system's potential for low-frequency sound absorption.

Another essential aspect of the research was the environmental impact of the proposed solution. As the main goal was to develop a solution that increases acoustic performance while at the same time supporting sustainability, sustainable and long-lasting materials were chosen in order to guarantee that the system could remain effective without causing additional waste.

Key Findings

The primary objective of this research was to explore methods for enhancing the low-frequency sound absorption of green roofs, with a specific focus on the integration of acoustic resonators.

- The study demonstrated that, compared to the other tested systems, the intensive green roof system emerged as the most promising for resonator integration, offering the significant advantage of substrate depth. Its thicker substrate layer allowed for more flexible integration of Helmholtz resonators without compromising essential functions.

- The integration of Helmholtz resonators into the substrate of the system can enhance acoustic absorption in the low-frequency range, achieving absorption coefficients ranging from 0.3 to 0.5 depending on the frequency and concept used. While this enhancement seems to be lower than the standalone performance of the single resonators, it represents a substantial improvement compared to the baseline green roof system without resonators. Additionally, while the results show improvements, the obtained absorption values do not perfectly align with the original aim of achieving consistently high values of absorption coefficient at lower frequencies with the given number of resonators. However, further increasing the number of resonators could potentially achieve this target. The significance of these improvements still depends on the intended application of the green roof. For scenarios prioritizing low-frequency noise mitigation, such as urban environments with prevalent low-frequency sound, resonators offer a measurable benefit. However, the associated effort to adapt the system, such as the reduction of substrate material volume and considerations for water drainage, must be carefully evaluated against the potential acoustic gains.

- The final concept design incorporated the following key elements: Cylindrical Helmholtz resonators were determined to be the most effective, owing to their acoustic efficiency and ability to target low-frequency noise. Additionally, rigid materials, such as FRP (Fiber-Reinforced Plastic) or stainless steel, were identified as the most effective for resonator fabrication due to their durability, lightweight properties, water resistance, and favorable acoustic performance.

- Among the tested concepts, concept E, which targeted eight different frequencies, demonstrated the most balanced performance. While this approach resulted in a drop in the absorption coefficient values of approximately 0.2 compared to concepts targeting fewer frequencies, such as the ones developed for three and four target frequencies, it provided a significant advantage in producing a smoother absorption curve. This curve effectively covered a broader range of frequencies within the range of 50 to 125 Hz, addressing a wider spectrum of noise.

- The inclusion of water outlet perforations at the base of the resonators' cavity introduced a noticeable **shift in the resonant frequencies** ranging from 5 to 10 Hz. While this design adjustment slightly altered the system's frequency response, it ensured better drainage functionality without significantly compromising the overall acoustic performance.

What are the lessons learned?

In conclusion, the integration of Helmholtz resonators into green roof systems presents a promising strategy for improving low-frequency absorption while maintaining acceptable performance at higher frequencies. However, practical implementation requires a careful balance of acoustic benefits, substrate performance, and maintenance considerations. For urban environments grappling with low-frequency noise pollution, this study demonstrates that resonator integration can be a valuable addition to green roof systems, provided the design and material selection are carefully optimized.

Reflecting on the difficulties encountered during this research, one of the most significant challenges was reconciling acoustic performance with the practical requirements and geometrical restrictions that the green roof system design provided. Keeping the resonators operational while avoiding any interference with the roof's drainage and vegetation growth presented various design issues. The simulations were useful; however, being able to perfectly reproduce all the factors of real-world conditions, which could affect the system's performance over time, remains a challenge.

To summarize, this research provides a deeper understanding of the main complexities and limitations involved when designing acoustically optimized and, at the same time, sustainable green roof systems. It highlights the importance of interdisciplinary techniques in which acoustic performance and sustainable design are properly combined. Finally, with regard to the contribution of this study to the field of building physics, the research showed that incorporation of acoustic optimization methodologies into green roof systems can be promising for addressing environmental noise concerns within a certain range.

In any case, a comprehensive cost-benefit analysis is required to determine whether the acoustic advantages offered by the integration of resonators can outweigh the associated trade-offs, such as the reduction in substrate volume, potential challenges to water drainage functionality, and the additional costs related to materials and installation. Conducting such an analysis is crucial to ensure that the green roof system can achieve its intended performance objectives while maintaining sustainability and practicality.

10

Recommendations

This study has demonstrated the potential of integrating Helmholtz resonators into green roof systems to enhance their acoustic performance, particularly at low frequencies. However, there are several aspects that warrant further exploration and development of this concept.

- First, future research should focus on refining the design of the resonators to achieve greater efficiency while maintaining compatibility with green roof requirements. Alternative geometries and configurations should be explored to optimize the system's acoustic performance without interfering with drainage or vegetation growth. Adjustable or tunable resonators could also be investigated to adapt the system to varying noise conditions in urban environments.

- Additionally, simulation models could be improved to better represent real-world conditions, such as temperature fluctuations, moisture variations, and material degradation over time. Validating the simulation results through experimental testing on physical prototypes is essential to ensure their accuracy and reliability, particularly in dynamic environmental conditions.

- Furthermore, long-term monitoring of integrated systems under real-world conditions is recommended to assess their acoustic performance, structural integrity, and interaction with the vegetation layer over time. Environmental factors such as pollution and debris accumulation should also be studied to understand their impact on the system's performance.

- Finally, the findings of this study could be extended to broader applications. Helmholtz resonators could be used in other noise-sensitive environments, such as indoor spaces or building facades. The scalability of this concept for larger urban projects, such as noise barriers or green walls, should also be explored. Collaboration with policymakers, architects, and urban planners could promote the adoption of acoustically optimized green roofs as part of sustainable urban noise management strategies.

Given the evolving needs of urban environments, by addressing these recommendations, future research and development can further improve the acoustic and environmental performance of green roof systems, contributing to more livable and sustainable urban environments.

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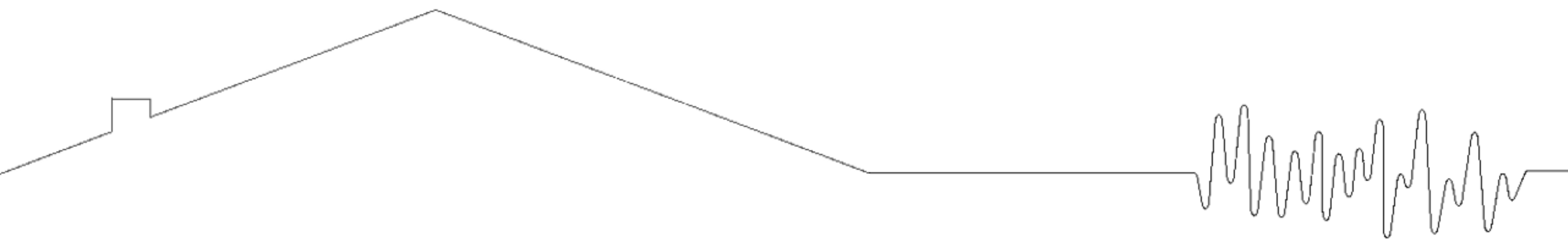

APPENDIX - MATLAB

Calculating the sound absorption of Helmholtz resonator

```
% model for calculating the sound absorption curve of a Helmholtz resonator sample
% copyright M.J. Tenpierik, TU Delft -- Edit by Jesse Bakker
% January 23, 2021

close all
clear all

%----------------- INPUT -----------------

%Resonator geometry
L = [90,90,110,100,90,100,80,80]/1000; %[mm] Neck length
a = [6.5,7.5,7.5,8,8,8.5,8.5,8]/1000; %[mm] Orifice radius
num = [4,3,3,3,3,3,3,3]; %[-] Amount of resonators

tp = [0]/1000; %[mm] Thickness of porous layer
sigma = 4000; %[] Flow resistivity of porous layer

cr = [60,60,55,50,45,45,40,35]/1000; %[mm] Helmholtz cavity radius
ch = [105,105,85,95,105,95,115,115]/1000; %[mm] Helmholtz cavity height

sw = [1100]/1000; %[mm] Sample width
sh = [1100]/1000; %[mm] Sample height

%Additional input
c = 343; %[m/s] Speed of sound
rho = 1.21; %[kg/m3] Density of air
Z0 = c.*rho; %[] Specific acoustic impedance
viscosity = 15.1e-6; %[m2/s] Kinematic viscosity of air


%----------------- CALCULATION -----------------

Sa = pi.*a.^2; %[m2] Orifice area
Sb = pi.*cr.^2; %[m2] Helmholtz cavity cover plate area
b = pi.*cr.^2.*ch; %[m3] Helmholtz cavity volume
%Sr = sw.*sh; %[m2] Sample surface area
Sr=0.25*pi.*sw.^2;


f = [30:2:800]; %[Hz] Frequency spectrum
nf = length(f); %[-] Frequency list length
kair = 2.*pi.*f./c; %[] Normal wave number
w = 2.*pi.*f; %[] Angular frequency
j = sqrt(-1); %[] Imaginary number


%Loop over different open areas
eta = num.*Sa./Sr; %[%] Porosity of samples surface
zi = 0;
delta = (8./3./pi).*a.*(1-1.25.*zi); %[m} Neck end correction

for x = 1:length(f);
  for y = 1:length(num);
```

```
%Delany & Bazley equations
%Zp(x) = Z0.*((1+0.0497.*(f(x)./sigma).^-0.754)-(j.*0.0758.*(f(x)./sigma).^-0.732)); %Impedance of porous layer
%kp(x) = (w(x)./c).*((1+0.0858.*(f(x)./sigma).^-0.7)-(j.*0.169.*(f(x)./sigma).^-0.595)); %Complex wavenumber
%Zp2(x,y) = -j.*Zp(x).*cot(kp(x).*tp(y)); %impedance at top of porous layer

%Impedance at top of air cavity (Eq.8.56a)
z1(x,y) = -j.*Z0.*cot(kair(x).*ch(y)).*(Sa(y)./Sb(y));

%Impedance of resonator neck (Eq.8.57a)
z2(x,y) = rho.*(sqrt(8.*viscosity.*w(x)).*(1+L(y)./(2.*a(y)))+(2.*w(x).*a(y)).^2./16./c);

z3(x,y) = j.*((2.*delta(y)+L(y)).*w(x).*rho)+z1(x,y)+z2(x,y);
z4(x,y) = z3(x,y)./eta(y);

%impedance of individual resonant absorbers
R(x,y) = (z4(x,y)-Z0)./(z4(x,y)+Z0); %reflection factor
alpha(x,y) = 1-abs(R(x,y)).^2; %absorption coefficient

  end
end

%Total reflection and absorption coefficient
Ztotal = (sum((z4).^-1,2)).^-1;
Rtotal = (Ztotal-Z0)./(Ztotal+Z0); %reflection factor of total array
alphatotal = 1-abs(Rtotal).^2; %absorption coefficient of total array


%----------------- PLOT -----------------

subplot(1,1,1);
plot(f,alpha,':',f,alphatotal,'-k','Linewidth',2);
xlabel('f [Hz]','FontName','arial','FontSize',12);
ylabel('Absorption coefficient [-]','FontSize',12);
hold on

[pks,locs] = findpeaks(alphatotal,f);
findpeaks(alphatotal,f);
text(locs+1,pks,num2str(locs'));

axis([0,500,0,1]);
grid on
```