# Optimization of Vertical Greenery Systems for Noise Mitigation in Urban Environments

MSc Master Thesis Final Presentation
Building Technology Graduation Studio
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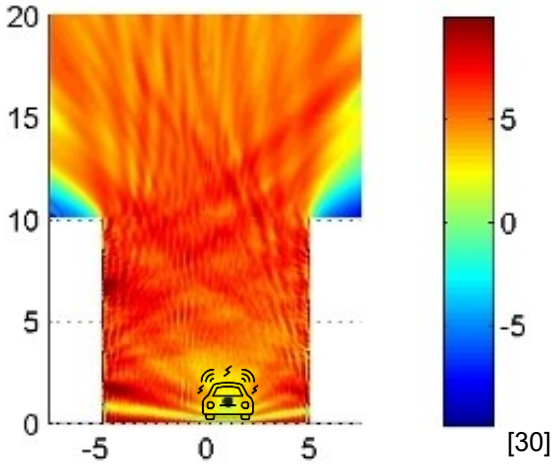
# Problem Statement

- Prolonged exposure to environmental noise is associated with a higher risk of both short- and long-term **health issues**. (WHO)
- **Road transport** is the most significant contributor to environmental noise pollution in EU. (European Environment Agency)

SPL (dB) 500 Hz



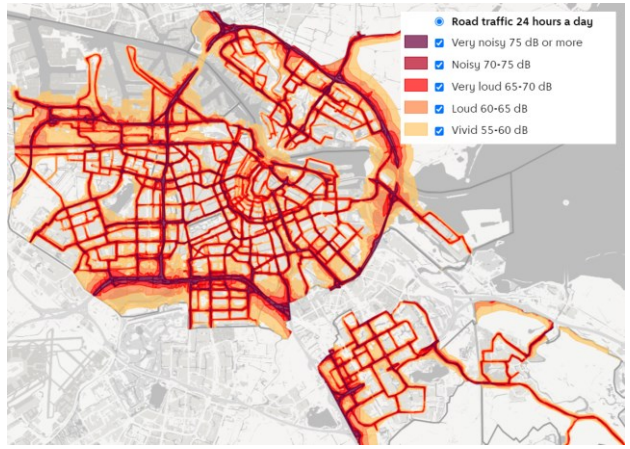

[30]

2D-Radiation pattern of a street canyon

Acoustically rigid facades →
- multiplicity of the re-reflected noise paths

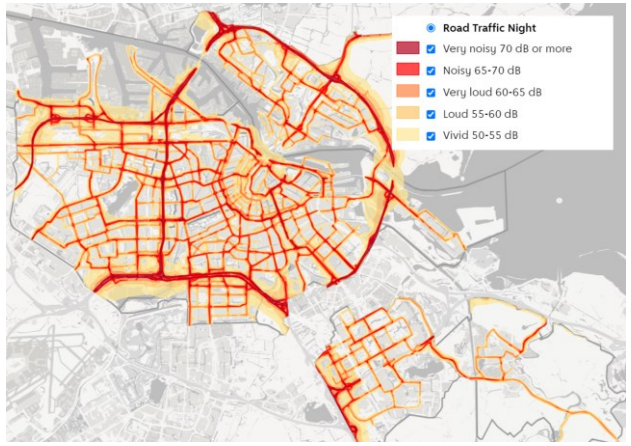
- **CNOSSOS-EU** – standardized assessment method for noise mapping across EU Member Countries

Amsterdam Noise Maps 2021




[1]

Day-evening-night exposure ($L_{den}$): < 55dB




[1]

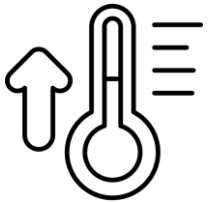
Nighttime exposure ($L_{night}$): < 50dB

# Ecosystem services provision by VGSs

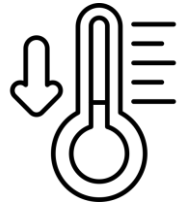
[2]

The Rubens at the Palace Hotel in Victoria, London
Main goal of the VGS to reduce flooding in the streets

## Private benefits



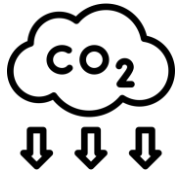
- Thermal buffering / thermal insulation
- Wind sheltering



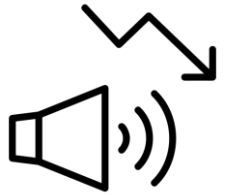
- Evaporative cooling
- Shading
- Increased surface albedo
- Improved emissivity

## Social benefits

- Urban Heat Island effect mitigation




- $CO_2$ uptake
- Air pollution reduction

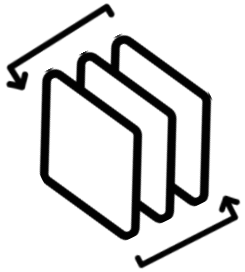


- Urban noise mitigation

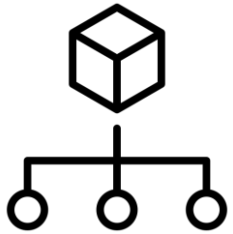
- Well-being
- Biodiversity

Challenges in early-stage design phase

**Limited Quantitative Data**



**Complex Multilayer Structures**



**Lack of Generic Models**

Approach proposed by Attal, Dubus, Leblois, and Cretin (2021)

**Transfer Matrix Method (TMM)**

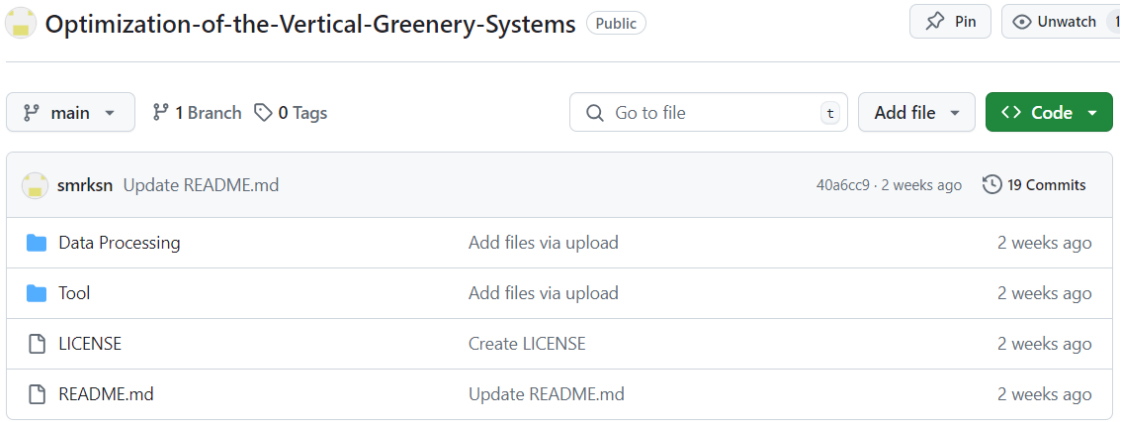
# Research Objectives and Deliverable

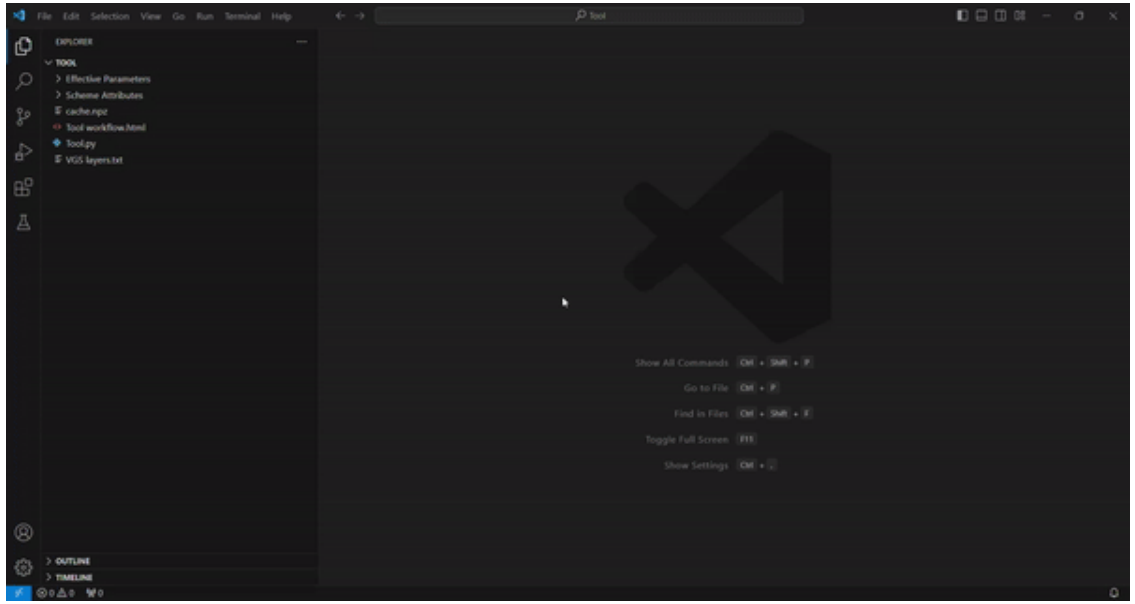
To develop a decision-support tool for stakeholders to assess the acoustical performance of arbitrary VGS designs using a multi-layered approach.

- Preparing a framework for quantifying the broader environmental and monetary impacts of VGSs.
- Developing a material library containing information about the acoustic properties of various VGS components.
- Leveraging the power of TMM to accelerate the implementation and enhance the effectiveness of VGS designs.

Click

Scan

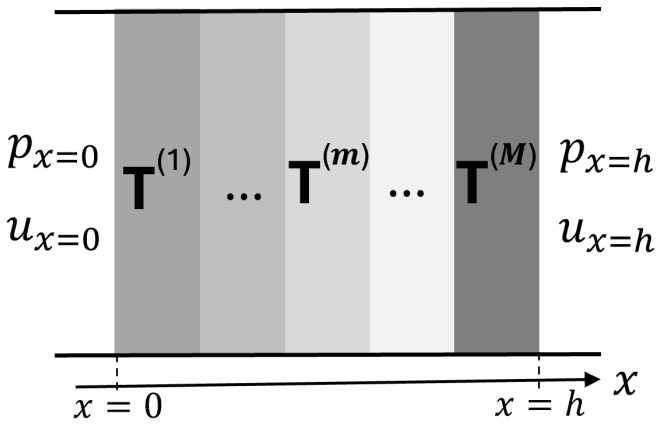


# Main Research Question

How does the TMM facilitate the quantification of the acoustic performance of VGSs?

*Facilitate – to make something possible or easier (Cambridge Dictionary)*



# Sub-Questions and the framework

**Sub-Question 1**

How are VGSs classified, and which factors shape the selection of their components?

**Sub-Question 2**

What are the key sustainability challenges in the widespread adoption of VGSs, and how can these challenges be addressed?

**Sub-Question 3**

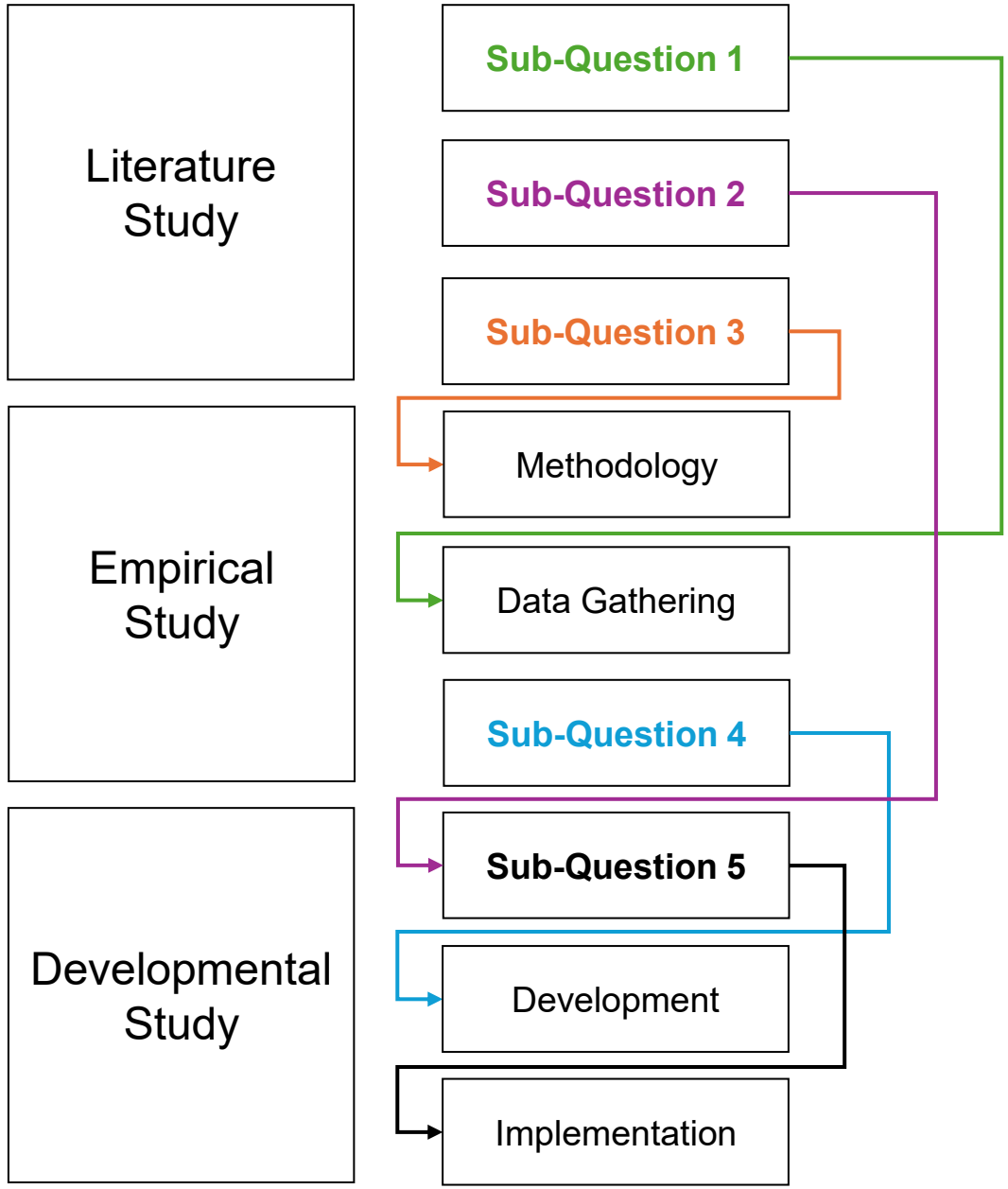
What mechanisms define the acoustic performance of VGSs?

**Sub-Question 4**

How do the proposed VGS components perform acoustically?

**Sub-Question 5**

What key metrics are essential for stakeholders to effectively assess VGS design effectiveness and make informed implementation decisions?

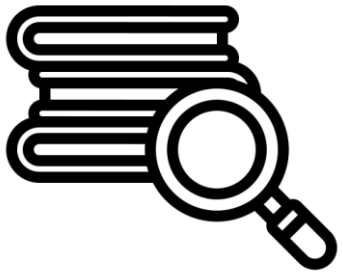


## Methodology : Linearly Applied Research

**Induction**

Exisitng knowledge and theory

Literature study

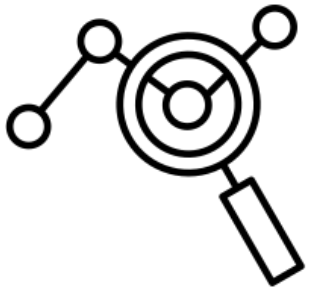


**Deduction**

Qualitative content analysis

Quantative research

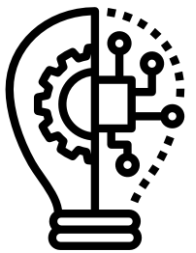
Empirical study



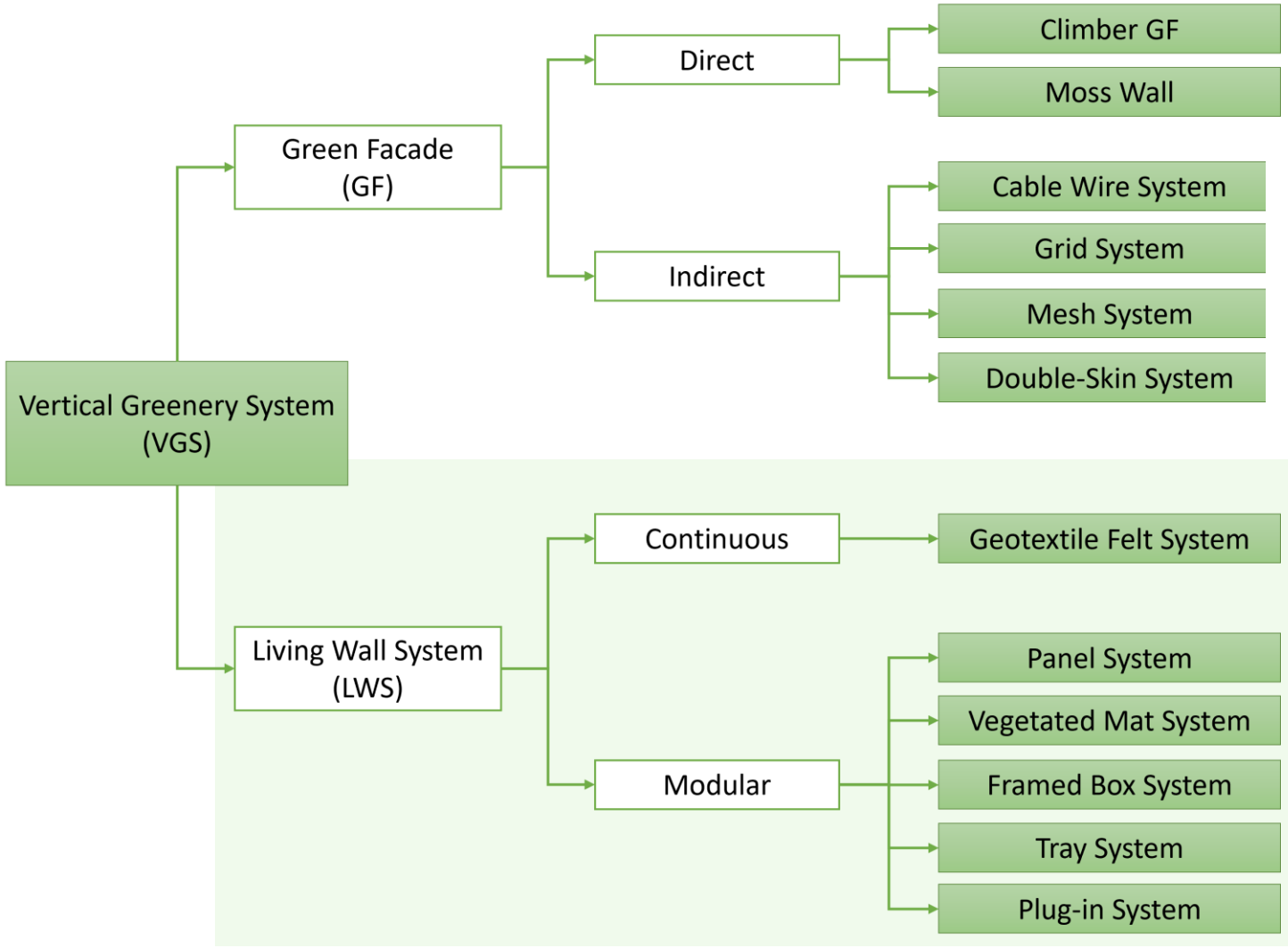
**Abduction**

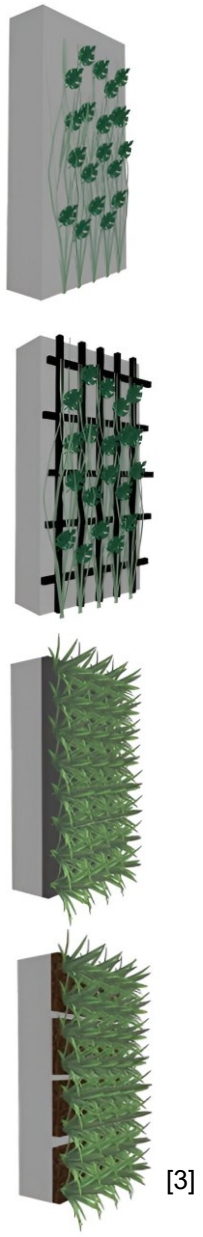
Practical application

Developmental Study



# Vertical Greenery Systems



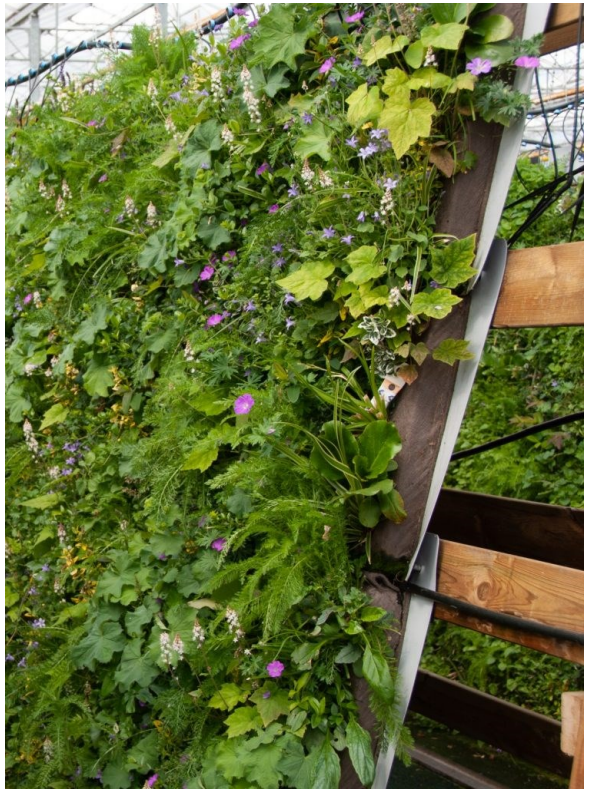
[3]

# LWSs (Continuous: Geotextile Felt System)


[4]

*prod. F+P System by SingularGreen*

# LWSs (Modular: Panel System)



[5]

*prod. Flexipanel by SemperGreen*

# LWSs (Modular: Vegetated Mat System)

[6]

*prod. Vertipockets by Living Green Walls*

# LWSs (Modular: Framed Box System)

[7]

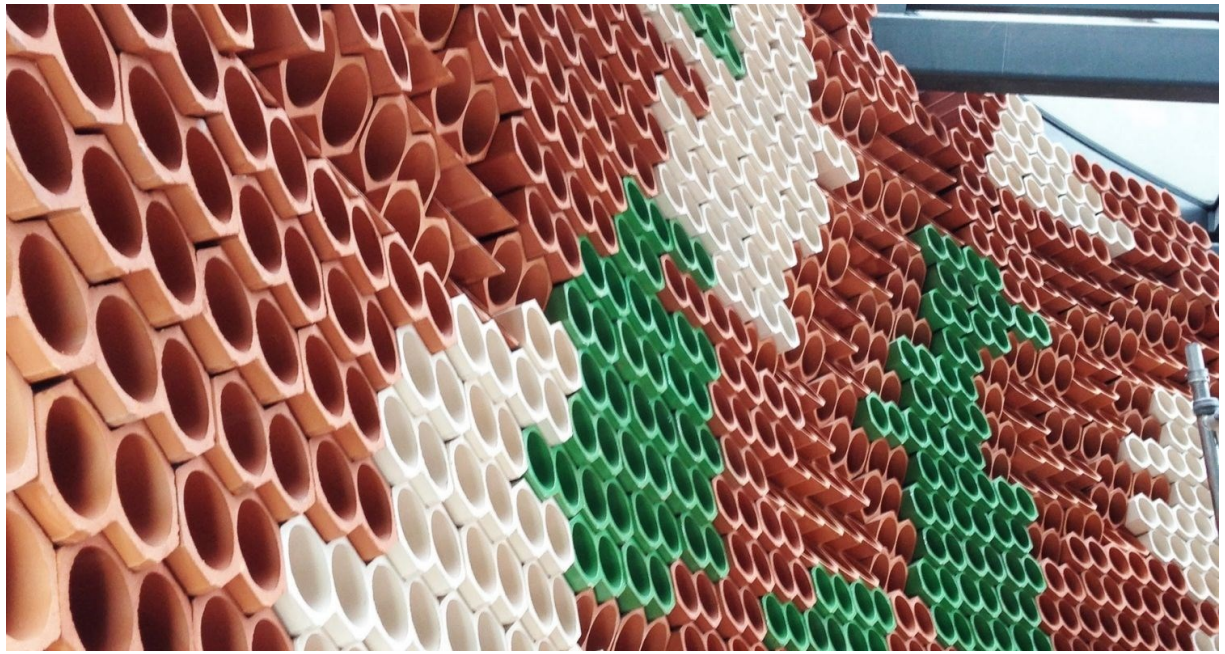
*prod. VersiWall GM by Elmich*

# LWSs (Modular: Tray System)

[8]

*prod. Vertiss by Novintiss*

# LWSs (Modular: Plug-in System)




[9]

*prod. EcoBin by SingularGreen*

## Flexible LWS types for design modifications


[7]

*prod. VersiWall GM by Elmich*


[4]

*prod. F+P System by SingularGreen*


[5]

*prod. Flexipanel by SemperGreen*

## Suitable subtrates

Perlite [10]

Vermiculite [11]

Clay balls [12]

Coco coir [13]

Coco husk [14]

Sphagnum moss [15]

Mineral wool [16]

# Suitable plants for Dutch climate

## Ajuga reptans

[17]

## Festuca glauca

[18]

## Bergenia cordifolia

[19]

## Waldestania ternata

[20]

## Heuchera

[21]

## Test samples

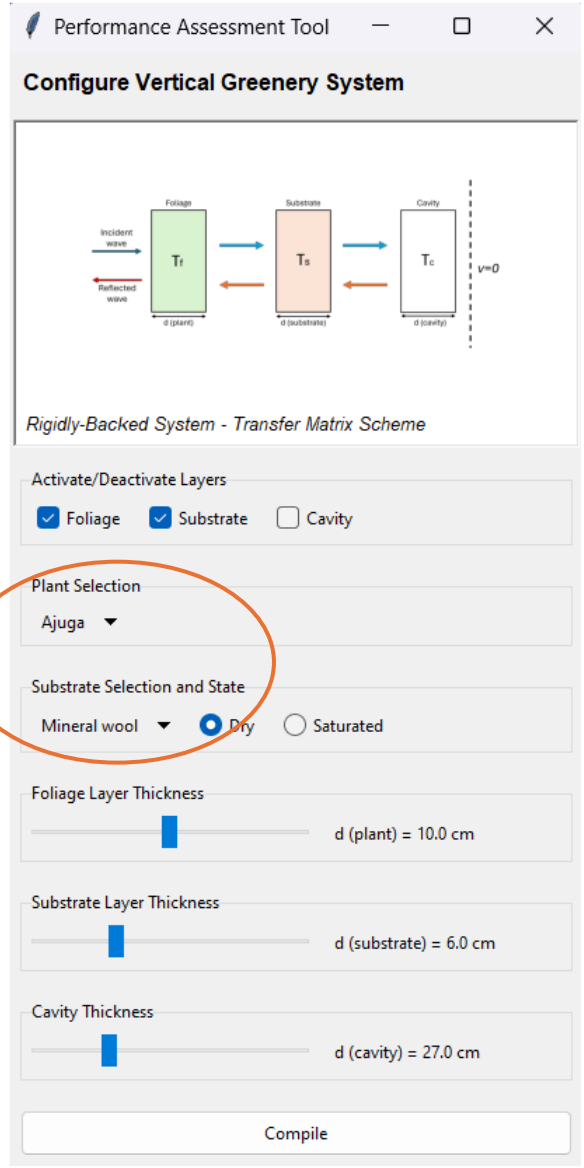
Ajuga

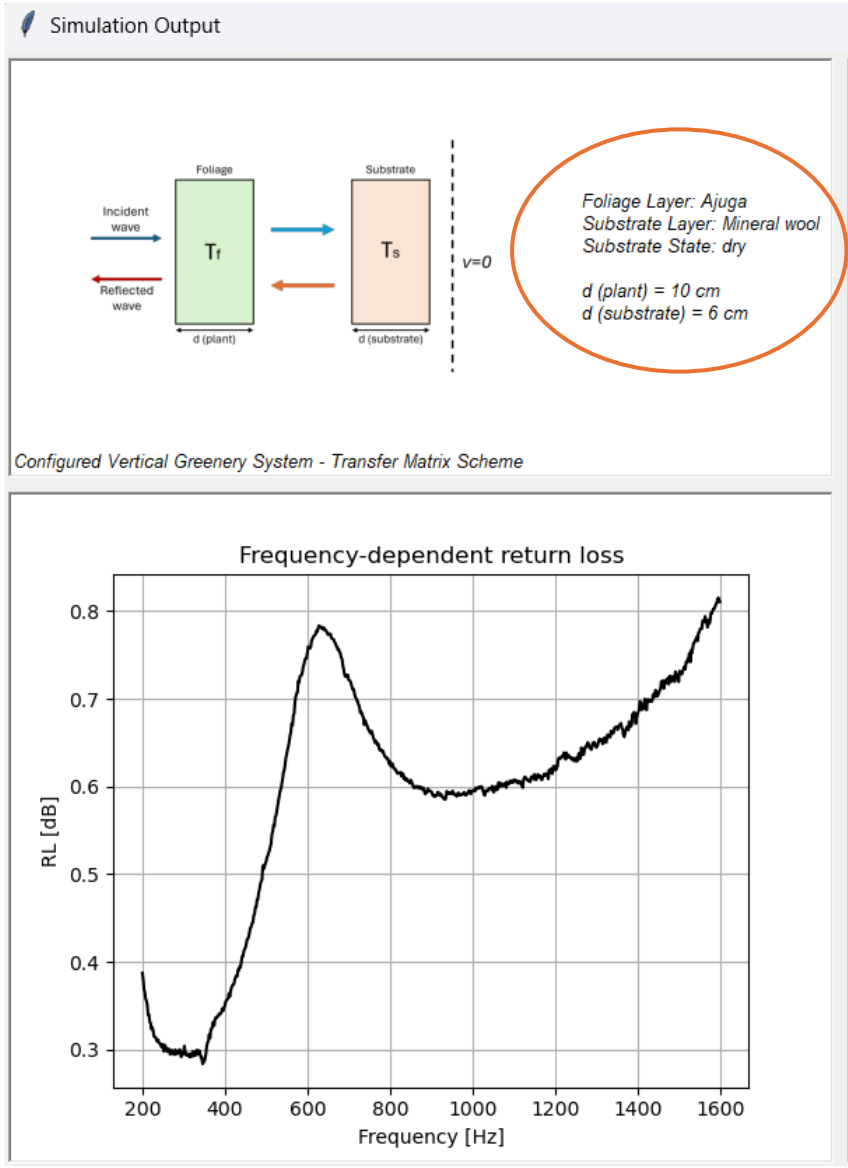
Grass

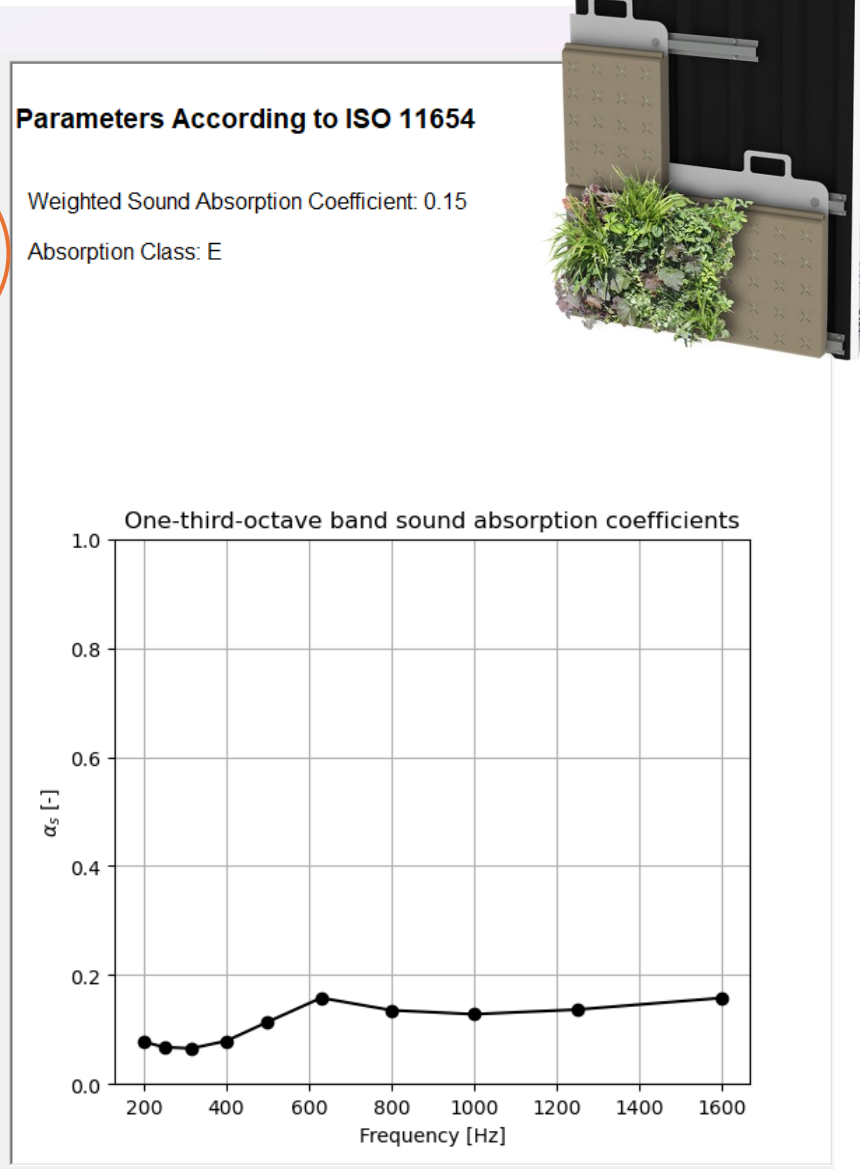
Bergenia

Waldestania

Heuchera



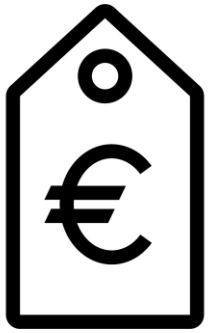



Example: *prod. Flexipanel by SemperGreen*

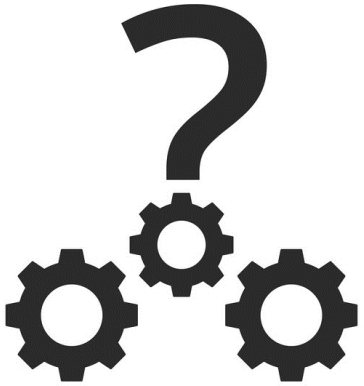
## Environmental and Economic Performance

Main criticism to widespread adaption of LWSs

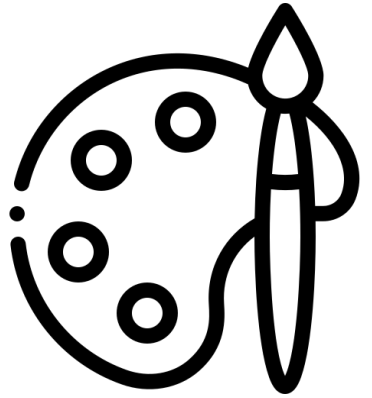
LWSs being perceived as too expensive and unsustainable.



Concerns about the complexity of LWSs and their susceptibility to failure.



Criticisms regarding the decorative nature of LWSs.



# Economic factors

**Problem**
- Stakeholders are scared by high initial investment and ongoing life-cycle costs.
- Important to assess the long-term economic value of LWSs.

**Cost-Benefit Analysis (CBA)**
- Compares life-cycle costs and benefits in monetary terms to determine viability.

**Complication**
- The provision of ecosystem services by LWSs varies depending on the scale of the project.
- Limited established knowledge about LWSs lifespan due to their novelty.

**Challenge**
- Quantifying urban-scale benefits from ecosystem services in monetary terms is challenging.

# Environmental factors

**Problem**
- ‘Greenwashing’ claims
- Important to assess the long-term environmental value of LWSs.

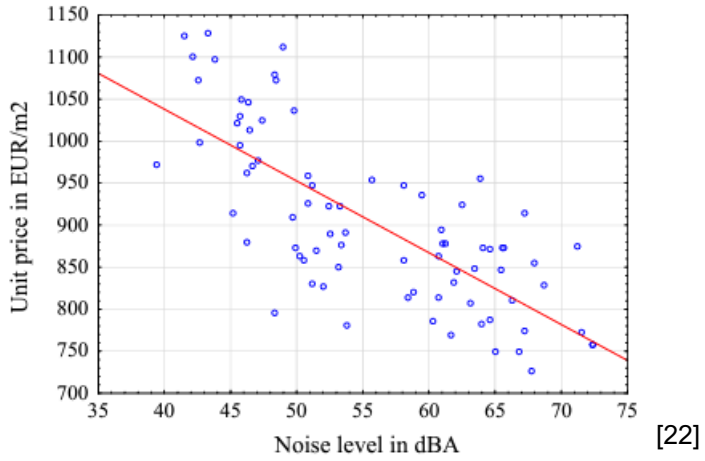
**Life-Cycle Assessment (LCA)**
- Measures emissions, resource consumption, and associated environmental and health impacts throughout the product life cycle.

**Complication**
- The provision of ecosystem services by LWSs varies depending on the scale of the project.
- Limited established knowledge about LWSs lifespan due to their novelty.

**Challenge**
- Quantifying urban-scale benefits from ecosystem services in terms of environmental/health impact is challenging.

# LWS performance integration into CBA

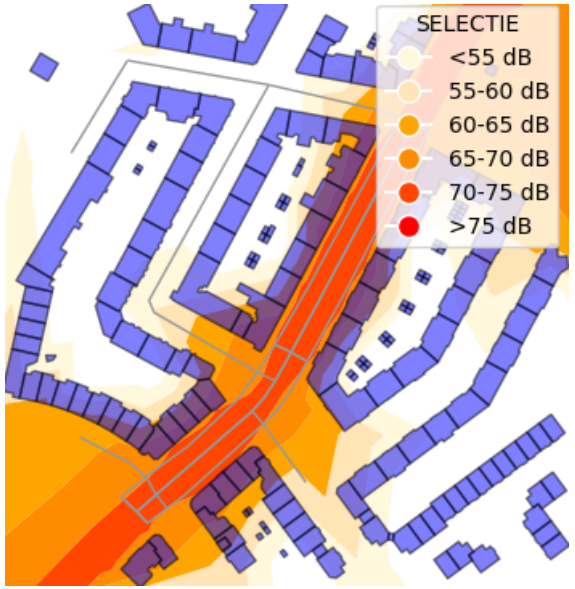
- What scale is considered for the noise assessment? (street, neighborhood, district)?
- What is the hedonic value of the real estate as a function of noise level?
- What is the total hedonic price of dwellings in the considered area?
- What is the total hedonic benefit when comparing the "before" and "after" scenarios?
- Are the monetary benefits higher than the investment costs?




[22]

Unit price of apartments in (EUR/m2) in Poland

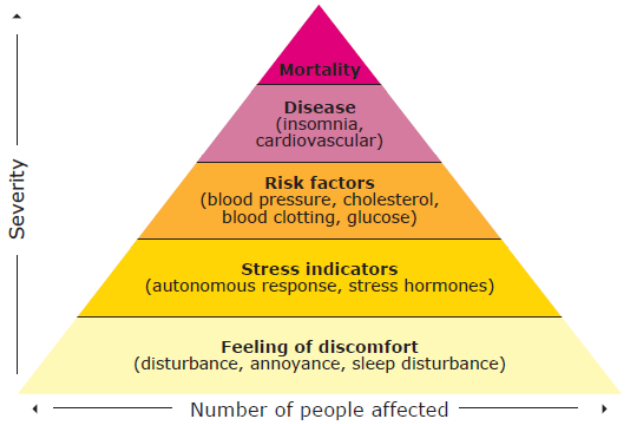
Before




After

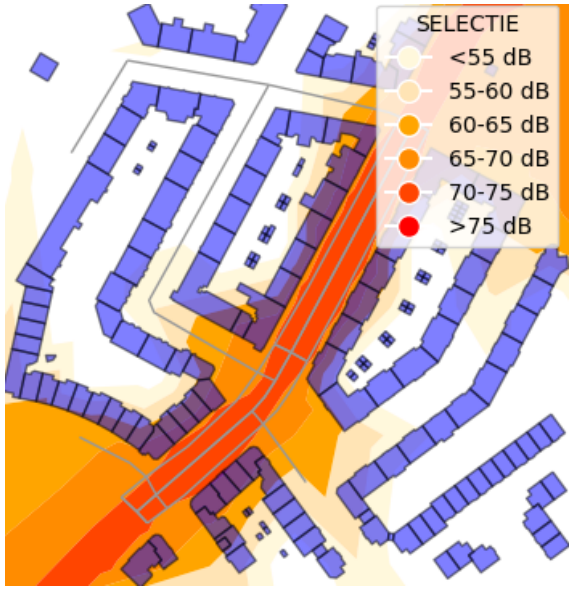
# LWS performance integration into LCA

- What scale is considered for the noise assessment? (street, neighborhood, district)
- How is the population distributed across different noise levels?
- What noise exposure categories are defined based on noise levels?
- What proportion of the population falls within each noise exposure category?
- What are the disability weighting factors for each defined noise exposure category?
- What are the DALYs (Disability-Adjusted Life Years) calculated per population segment?
- What is the magnitude of impacts to human health in LCA?
- Is the magnitude significantly different between the "before" and "after" scenarios?




Exposure categories and health endpoints [23]

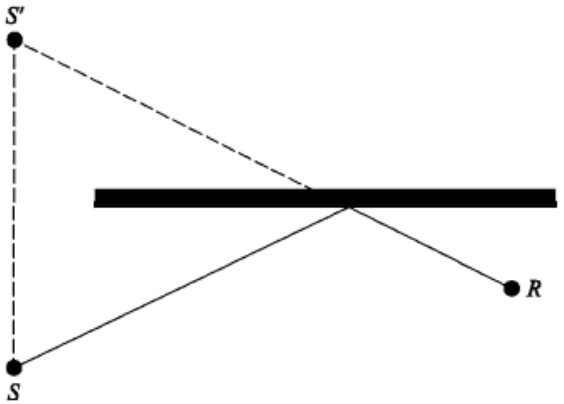
Before




After

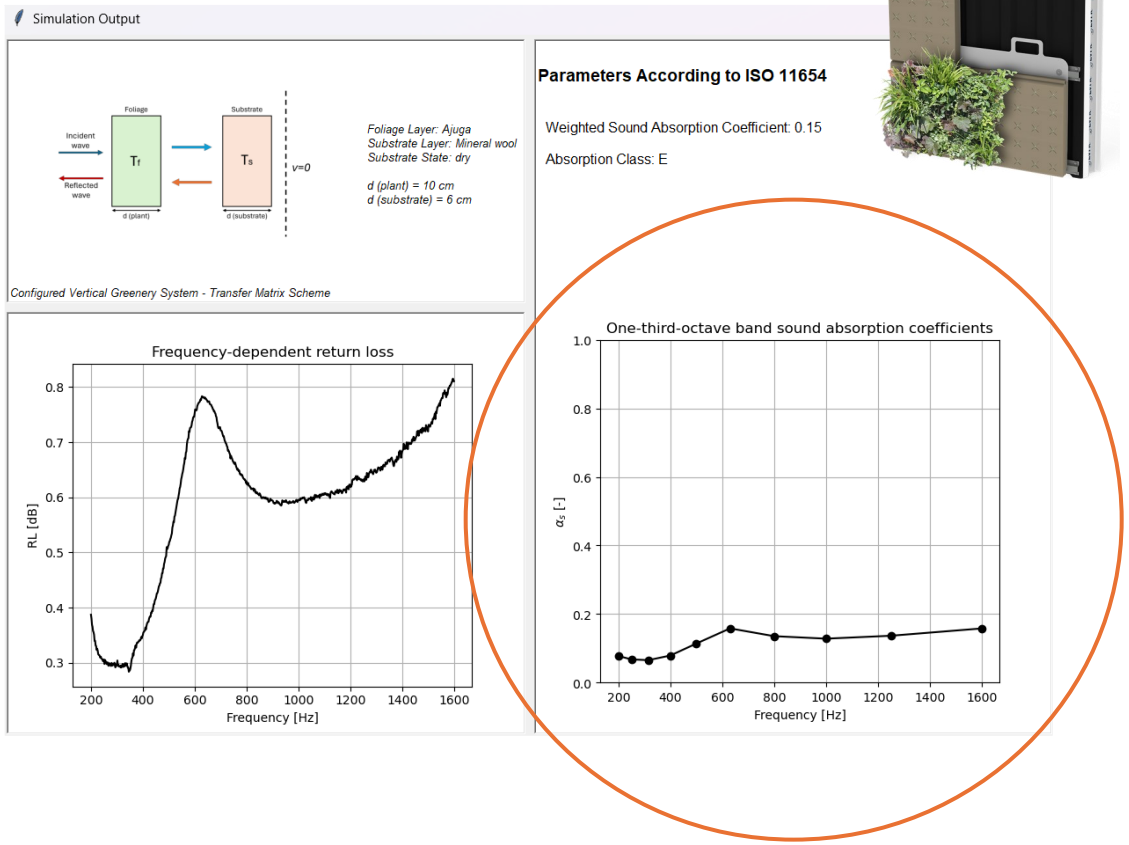
# Urban simulation procedure according to CNOSSOS-EU

- Inputs to calculation are expressed in 1/3 octave bands within the range of 100 Hz to 5 kHz.
- Reflections on building façades and noise barriers are simulated using image sources.
- Power levels of image sources are determined using frequency-dependent absorption coefficients.



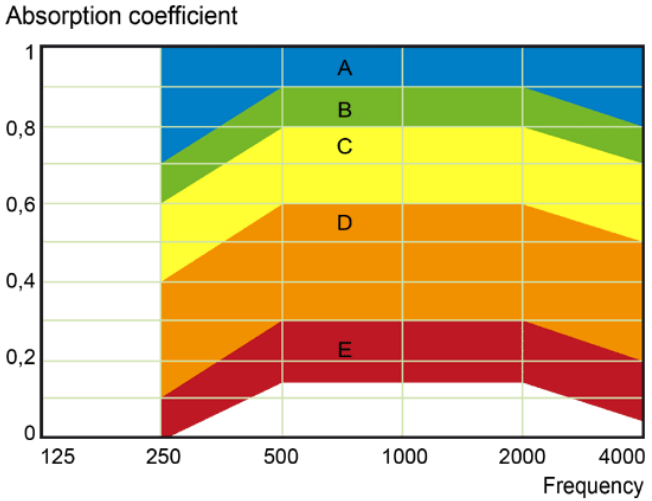

[24]

Image source scheme

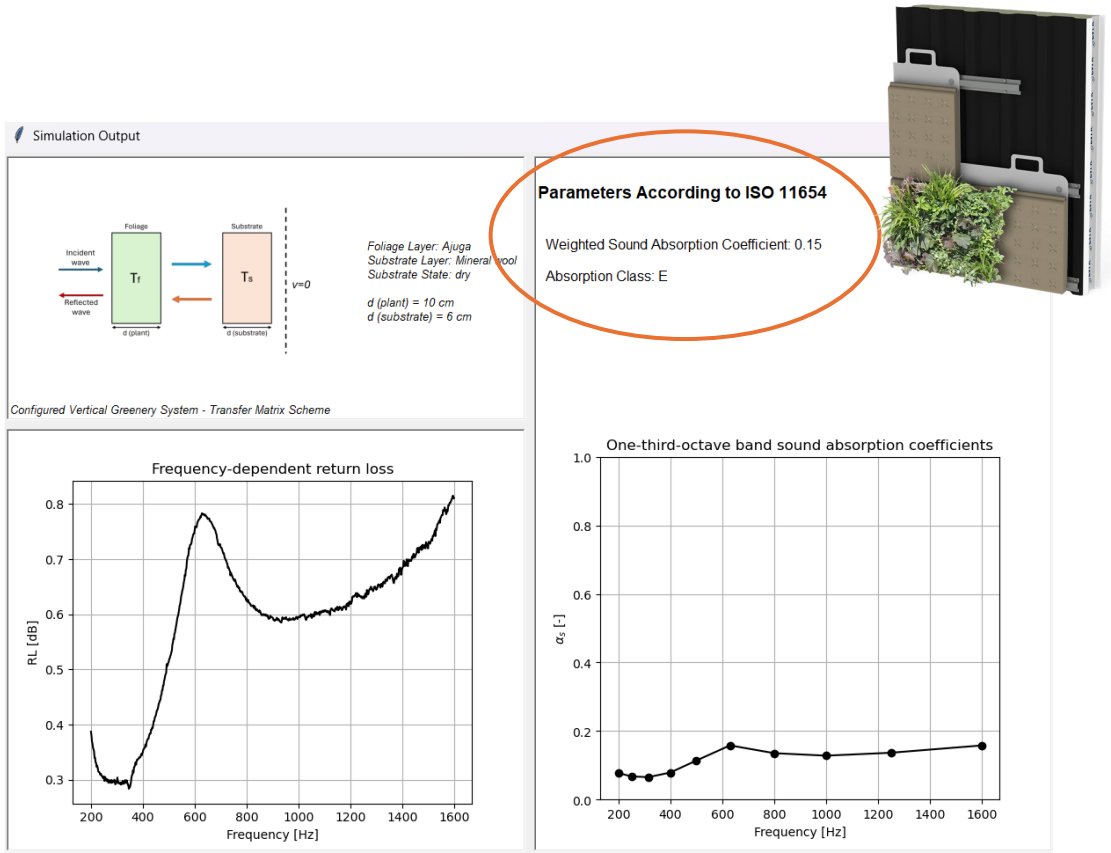


# Weighted Sound Absorption Coefficient and absorption class

- Practical absorption coefficients are compared with a reference curve.
- The reference curve is designed to represent the acoustic performance of most products on the market.
- The weighted absorption coefficient is determined by the reference curve absorption at 500 Hz.
- Stakeholders can easily navigate different products by referring to sound classes A–E.

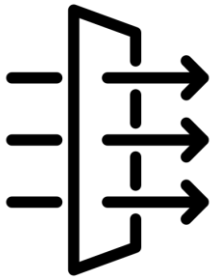



Absorption classes [25]

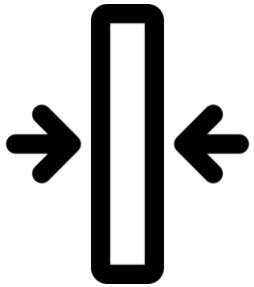


# Acoustic Mechanisms

- Foliage and substrate layers induce visco-thermal losses mechanisms.
- Visco-thermal losses depend on the porosity, pore size and tortuosity of the layer.
- Overall absorption performance of the layer depends on its flow-resistivity and thickness.

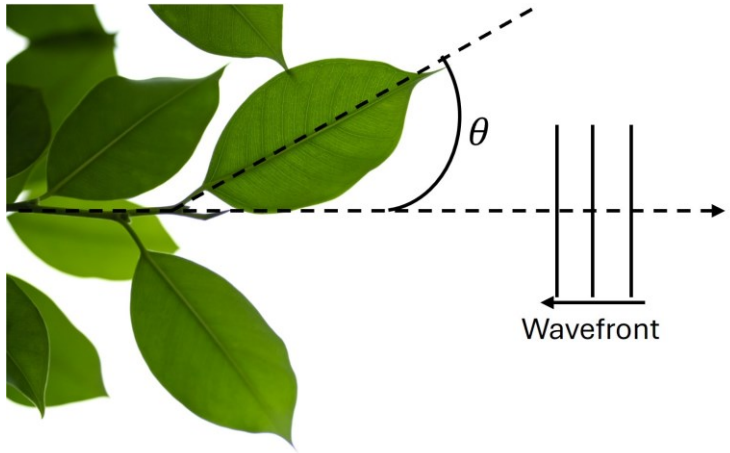


Optimal flow resistivity →
- decreased impedance mismatch
- increased visco-thermal losses.



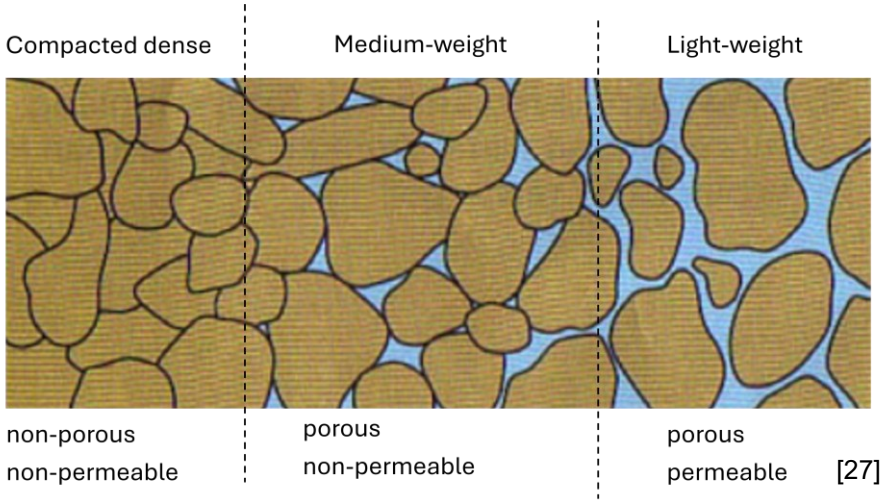
Optimal thickness →
- decreased impedance mismatch
- increased visco-thermal losses.

- Higher leaf area density and larger dominant leaf orientation angles $\theta$ result in increased tortuosity, leading to enhanced acoustic absorption.




[26]

- Lightweight substrates are preferable because their increased porosity enhances acoustic absorption.




[27]

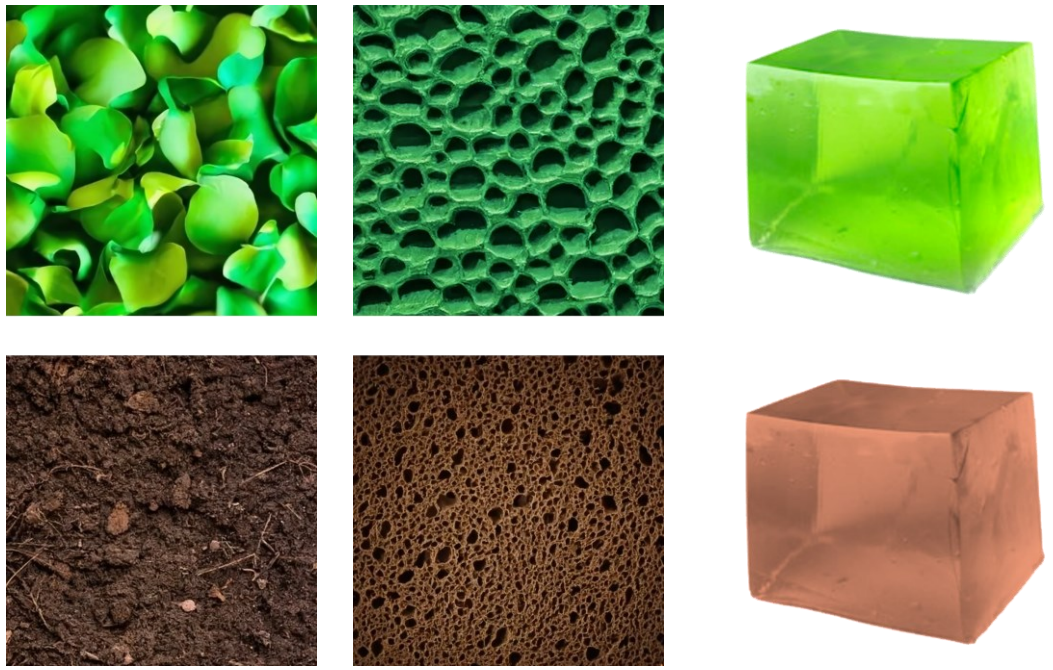
# Equivalent Fluid Model

How to model complex structures?

- Both foliage and substrate can be considered porous absorbers.
- Porous absorbers are typically composed of a solid frame filled with a fluid (air).
- The behavior of a porous absorbers can be described using *effective parameters:*

- *Complex characteristic impedance* – describes the resistance of a lossy medium to propagating sound waves.
- *Complex wavenumber* – describes the rate of decay of the sound wave's amplitude in a lossy medium.

- If inhomogeneities are much smaller than the wavelength → sound wave propagates as if the medium is homogeneous.

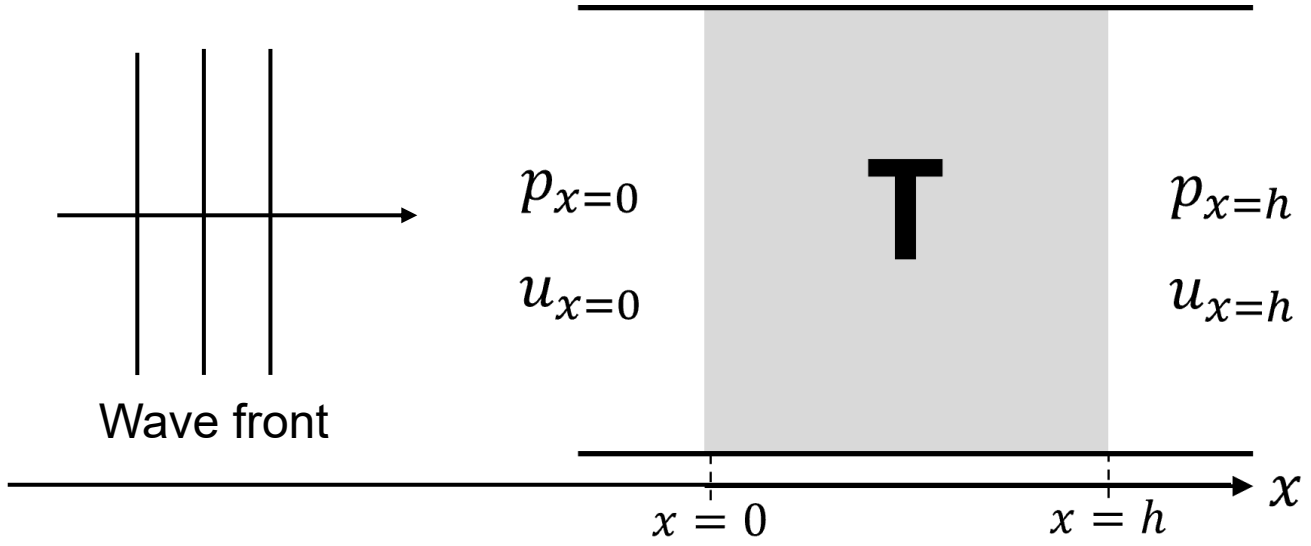


[28]

Original structure | Equivalent porous structure | Equivalent fluid model

# Transfer Matrix Method (TMM)

- TMM establishes a relationship between pressure and particle velocity across an equivalent fluid system.




- Transfer Matrix, **T** links the acoustic properties on either side of a one-dimensional fluid layer.

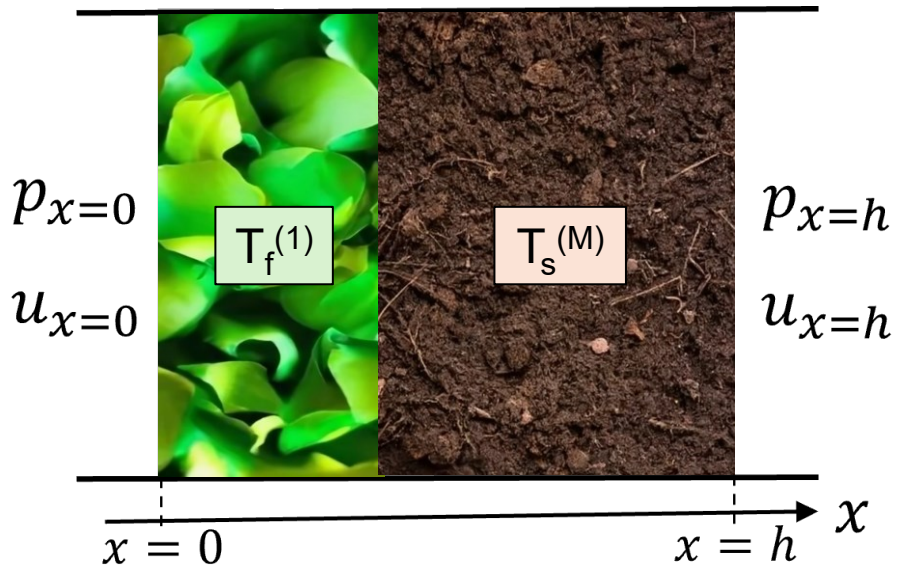
$$\mathbf{T} = \begin{bmatrix} \cos(kd) & jz_c \sin(kd) \\ j\frac{1}{z_c} \sin(kd) & \cos(kd) \end{bmatrix}$$

$z_c$ - complex characteristic impedance

$k$ - complex wavenumber

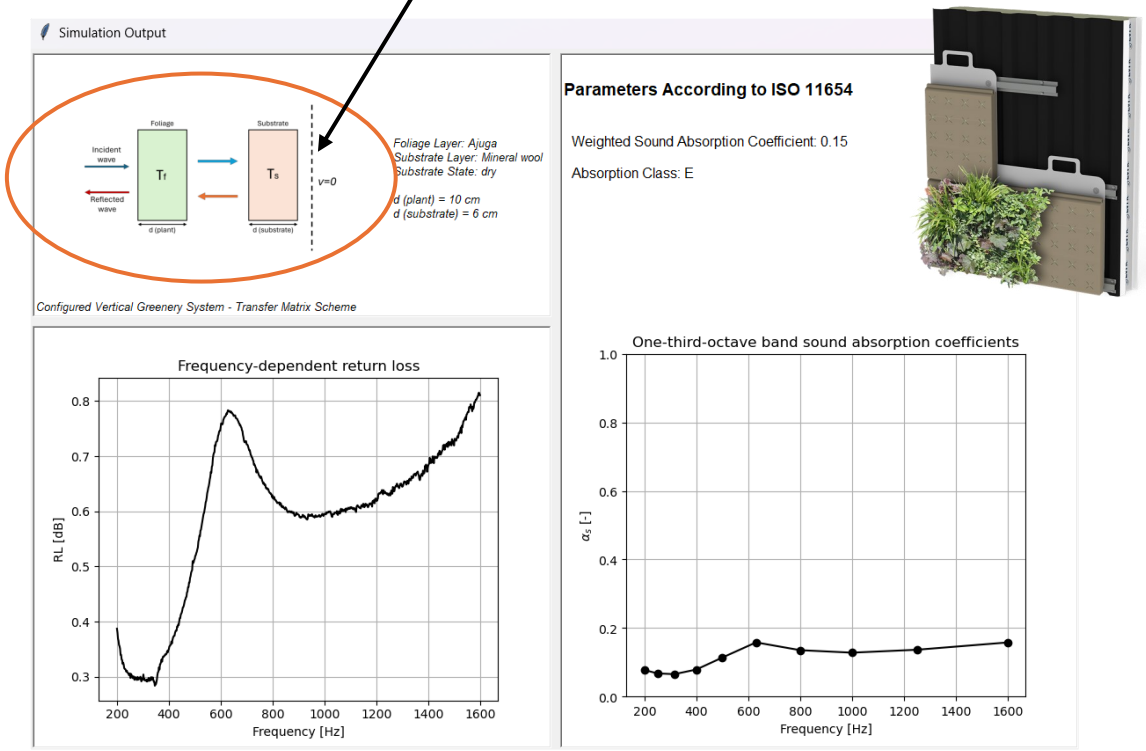
$d$ - thickness of the layer

# Multilayer system




$$\mathbf{T}_{\text{total}} = \prod_{m=1}^{M} \mathbf{T}^m$$

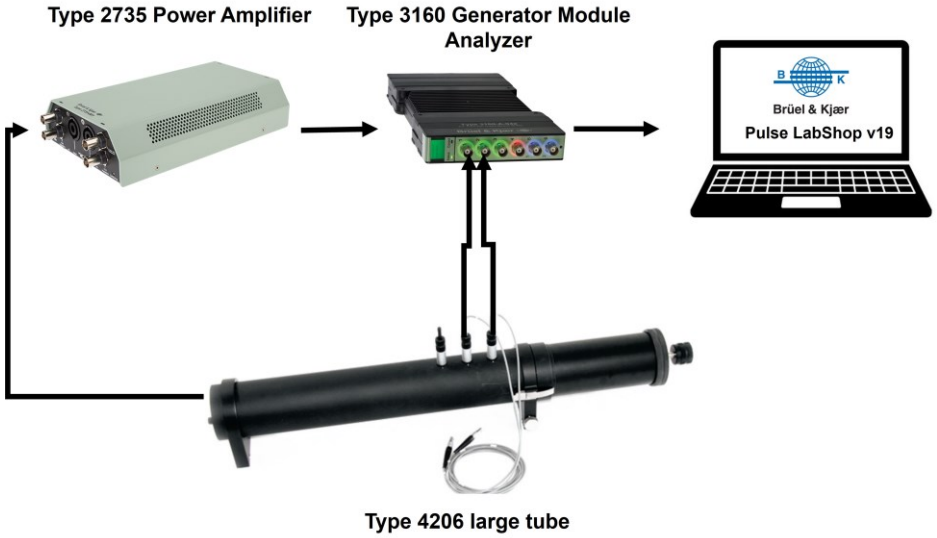
Rigid-backing condition (no transmission)




- Total transfer matrix allows to derive the system's reflection, (transmission) and absorption coefficients.

# Empirical Data Gathering

- Based on **ISO10534-2** two-microphone technique for **normal *surface* impedance**




Measurement setup (Brüel & Kjær)

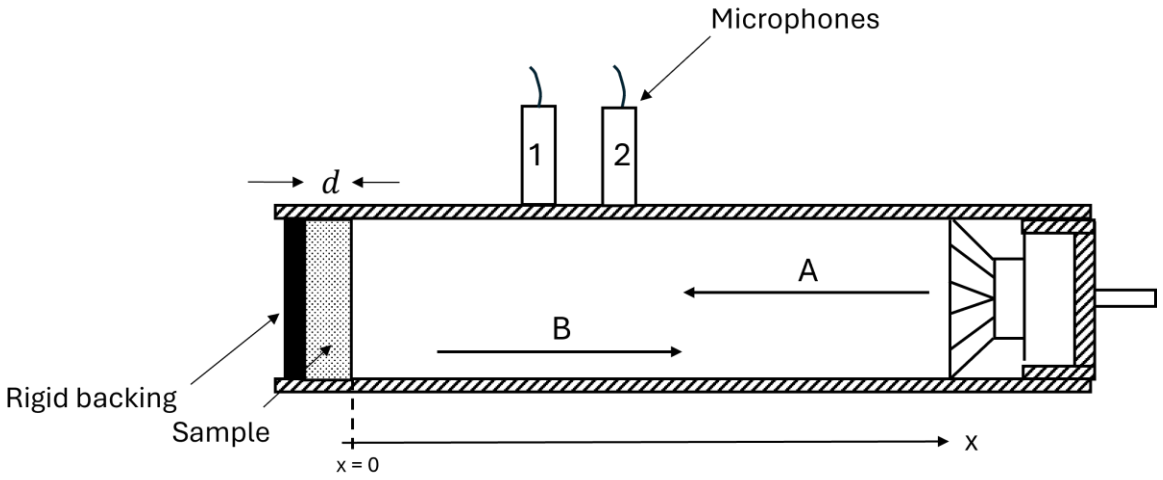
$z_c$ - complex characteristic impedance

$k$ - complex wavenumber

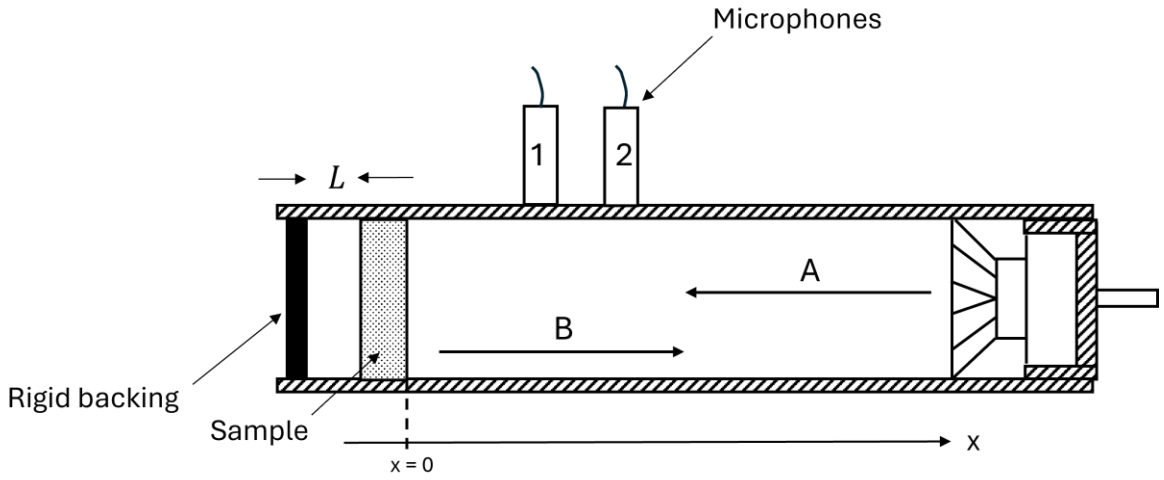
| | | | |
|---|---|---|---|
| kc_Pumice_saturated.npy | 20/06/2024 10:17 | NPY File | 12 KB |
| kc_Vermiculite_dry.npy | 20/06/2024 10:17 | NPY File | 12 KB |
| kc_Vermiculite_saturated.npy | 20/06/2024 10:17 | NPY File | 12 KB |
| kc_Waldestania.npy | 20/06/2024 10:16 | NPY File | 12 KB |
| zc_Ajuga.npy | 20/06/2024 10:16 | NPY File | 12 KB |
| zc_Bergenia.npy | 20/06/2024 10:16 | NPY File | 12 KB |
| zc_Clay balls_dry.npy | 20/06/2024 10:17 | NPY File | 12 KB |
| zc_Clay balls_saturated.npy | 20/06/2024 10:17 | NPY File | 12 KB |

Input binary files for the tool
Folder *Effective_Parameters/*

# Measurement protocol



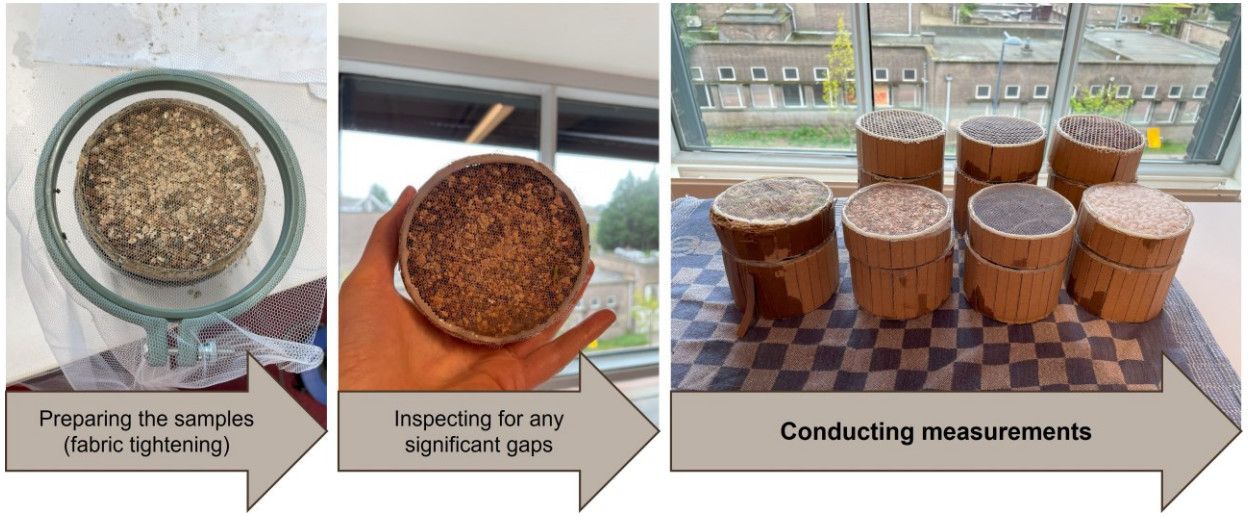

Two-thickness method




Modified two-cavity method

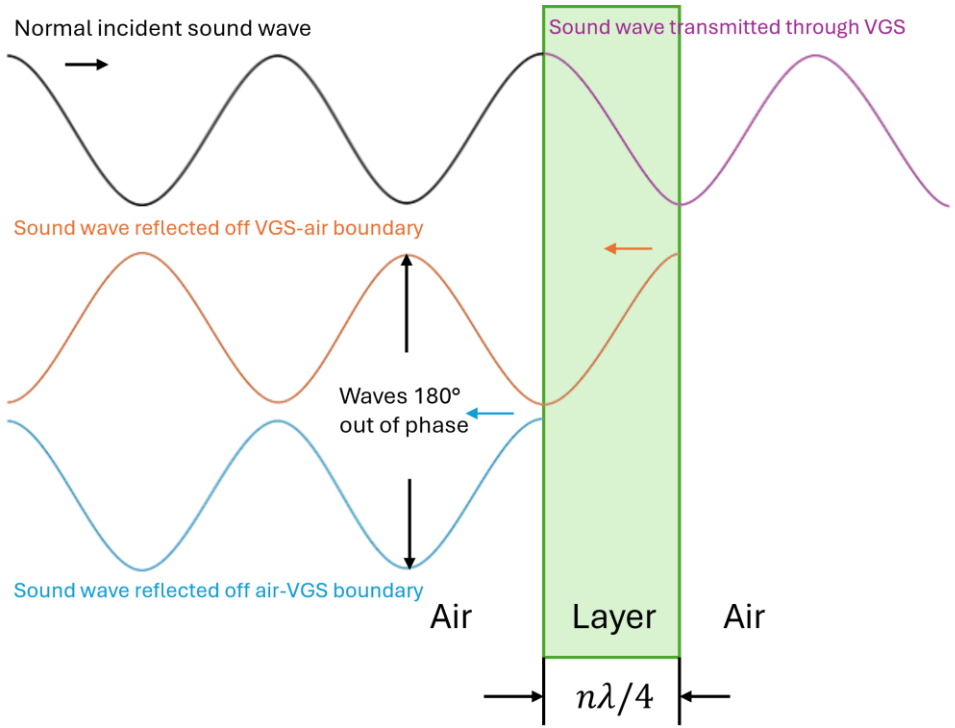
# Test sample preparation

- Plant test samples
- Dry substrate test samples
- Saturated substrate test samples



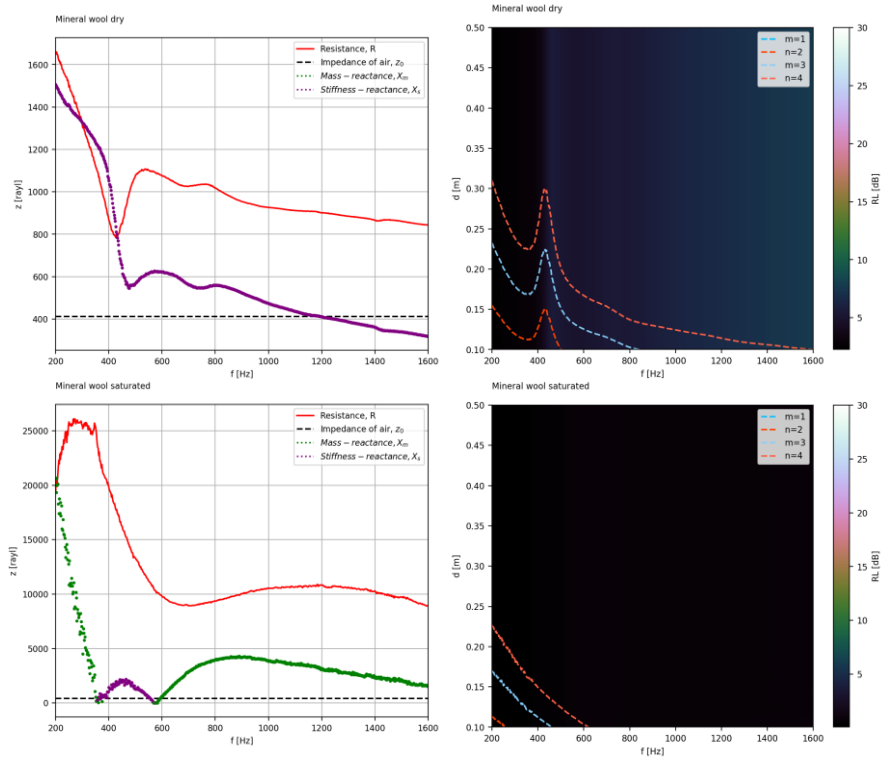

# Data interpretation

- Higher Return Loss (RL) performance is favourable for urban noise mitigation

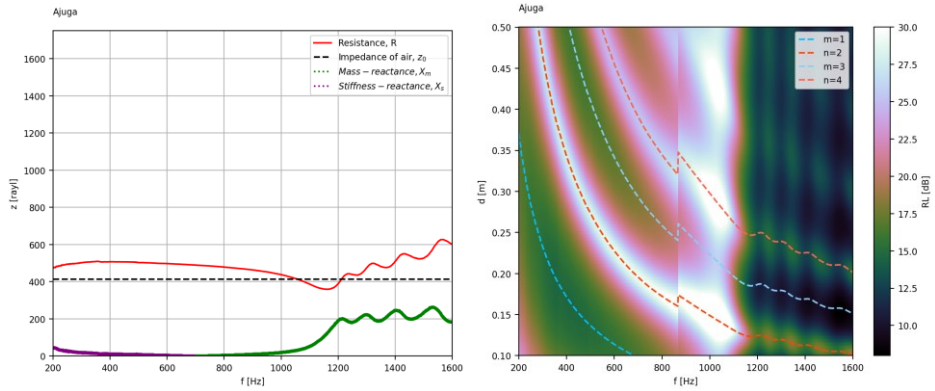



Destructive interference scheme

*n = 2, 4, 6 ...*

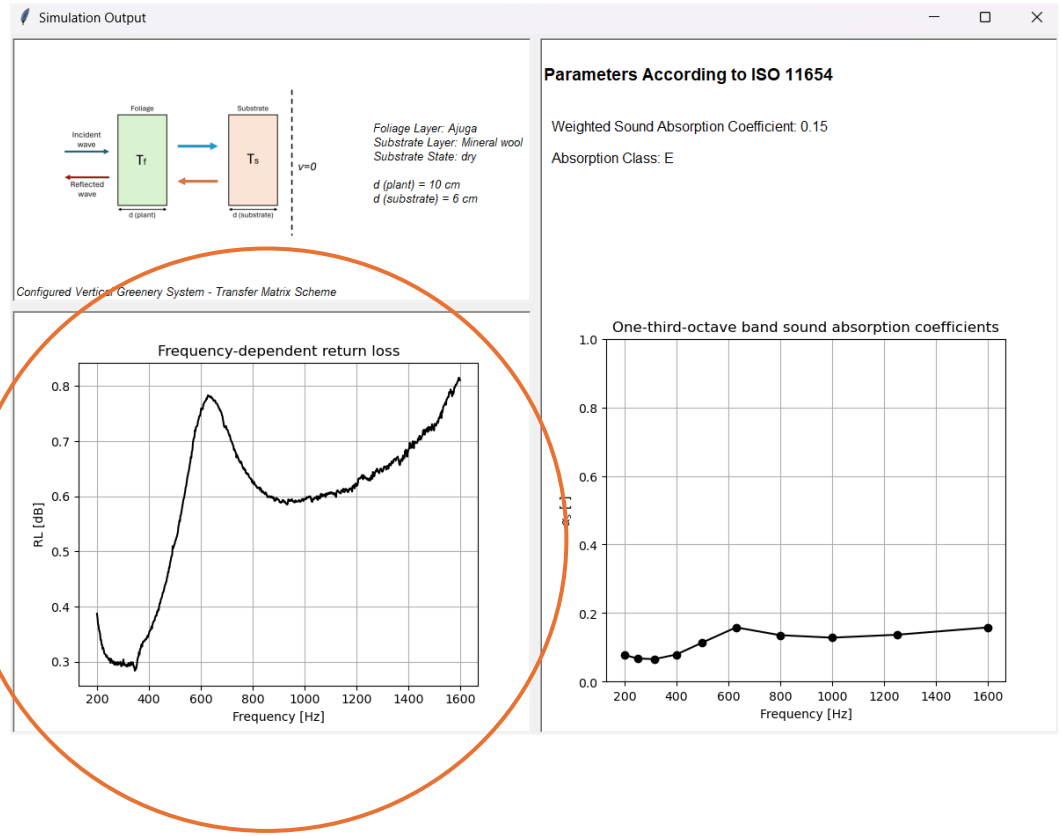



RL performance of the mineral wool



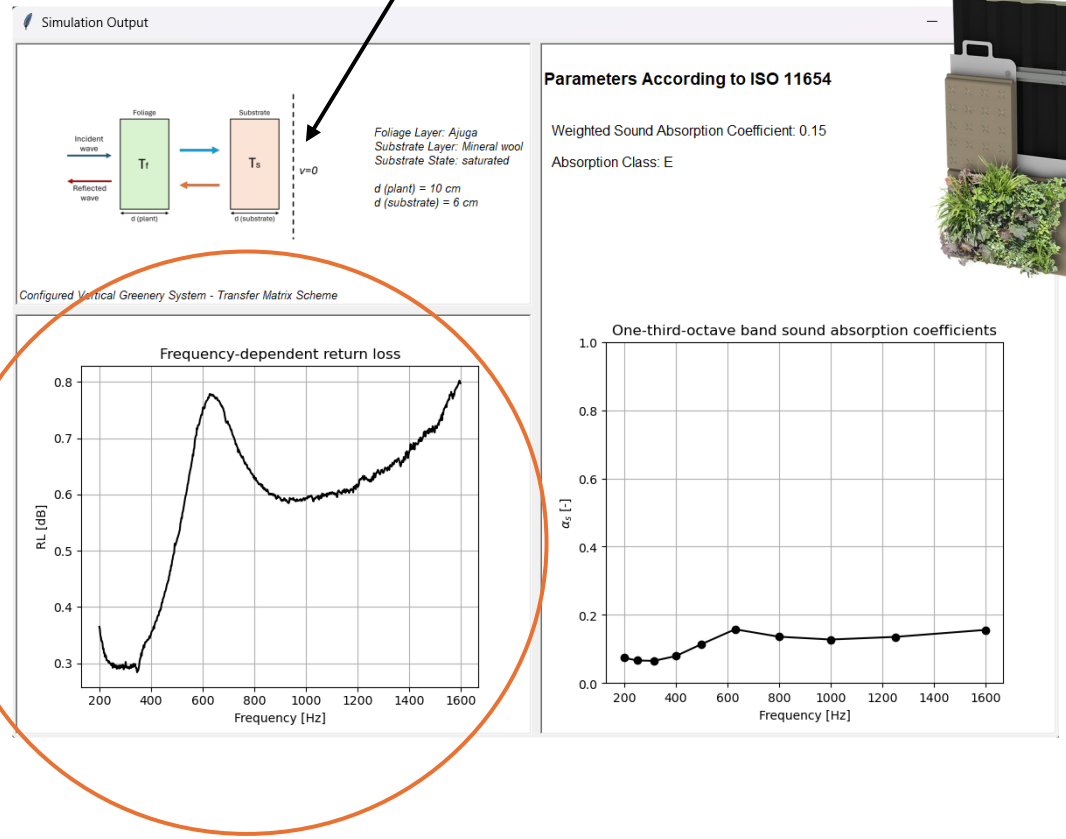

RL performance of the Ajuga plant

# Data interpretation




Ajuga + Mineral wool dry

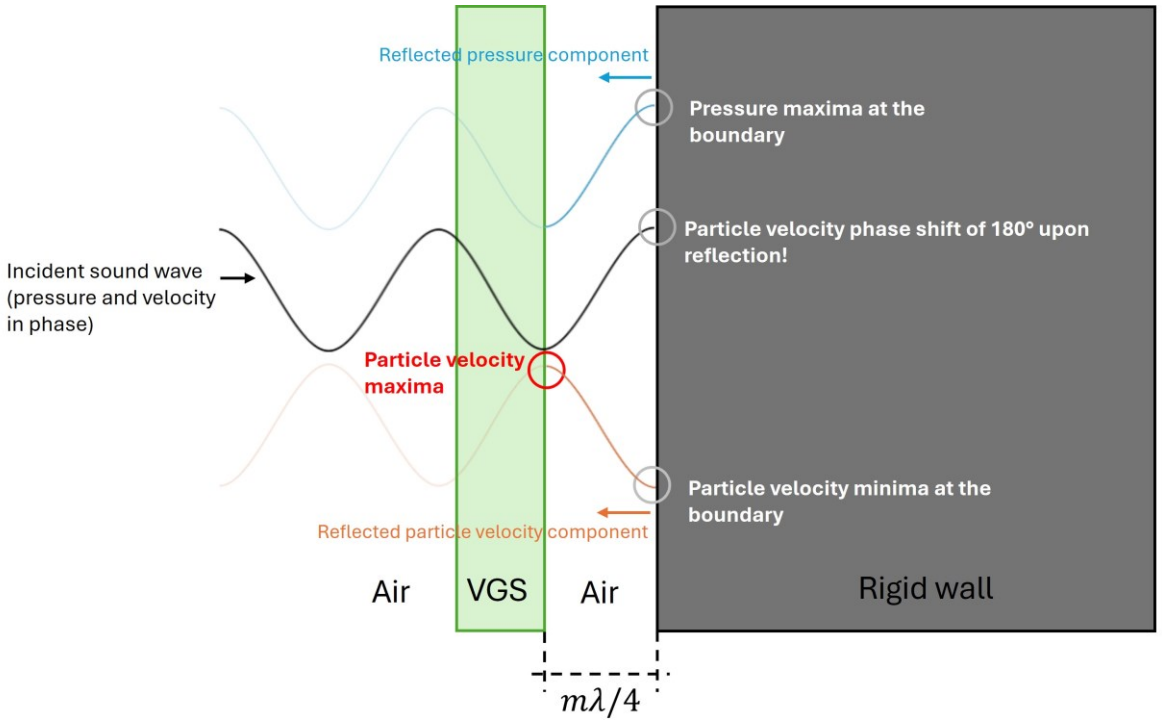
Rigid-backing condition (no transmission)





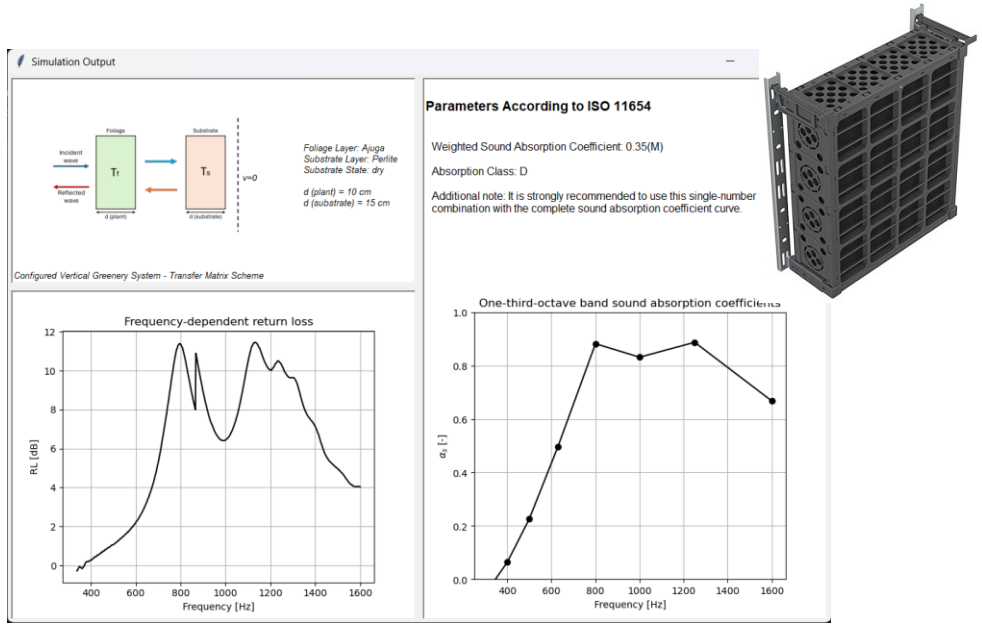

Ajuga + Mineral wool saturated

# Cavity Mechanism



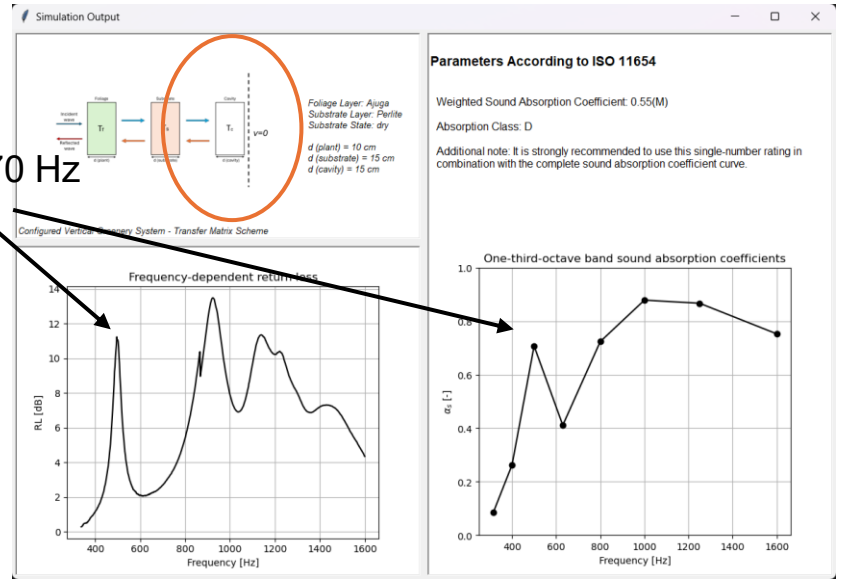

Cavity influence on the wave attenuation

*m = 1, 2, 3 ...*




Dry module (perlite)

0.15 m cavity → 570 Hz




Dry module (perlite) + cavity

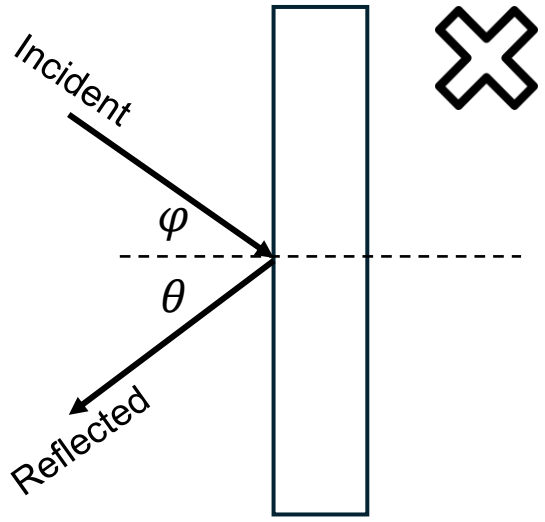
## Current Limitations of the Tool

- The trial-and-error approach to optimization can be both labor-intensive and time-consuming.

→ need for an automation algorithm based on input project requirements.

- Normal incident data alone is not be representative for urban simulations.

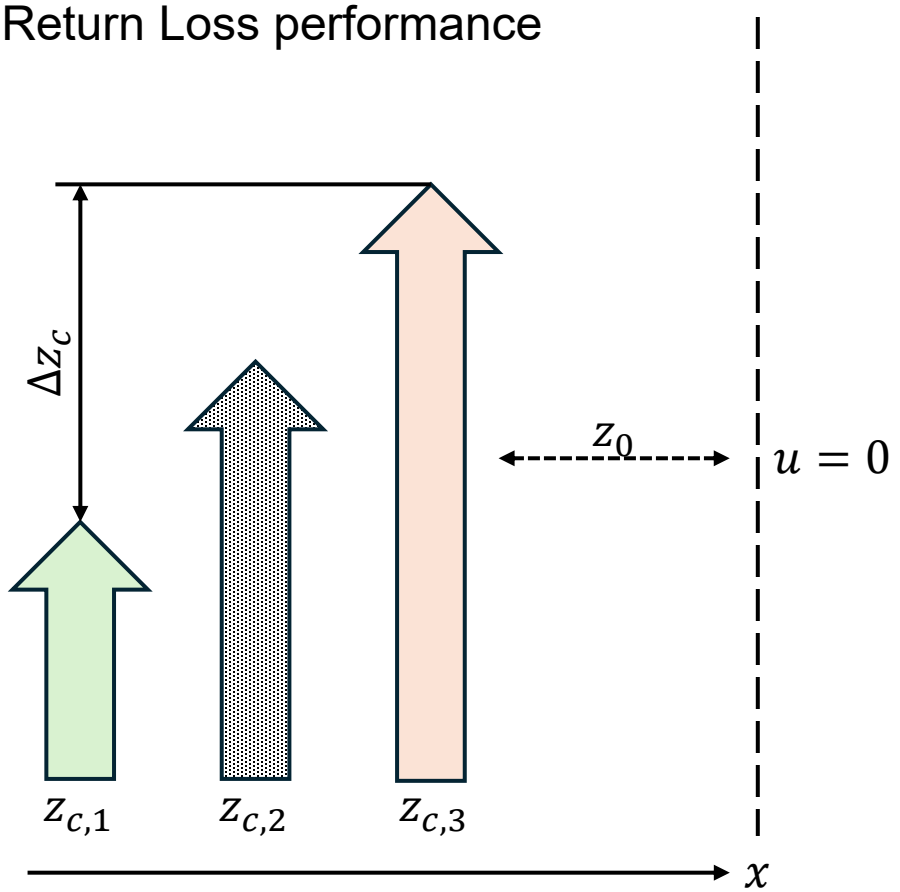
→ need for oblique incidence data.



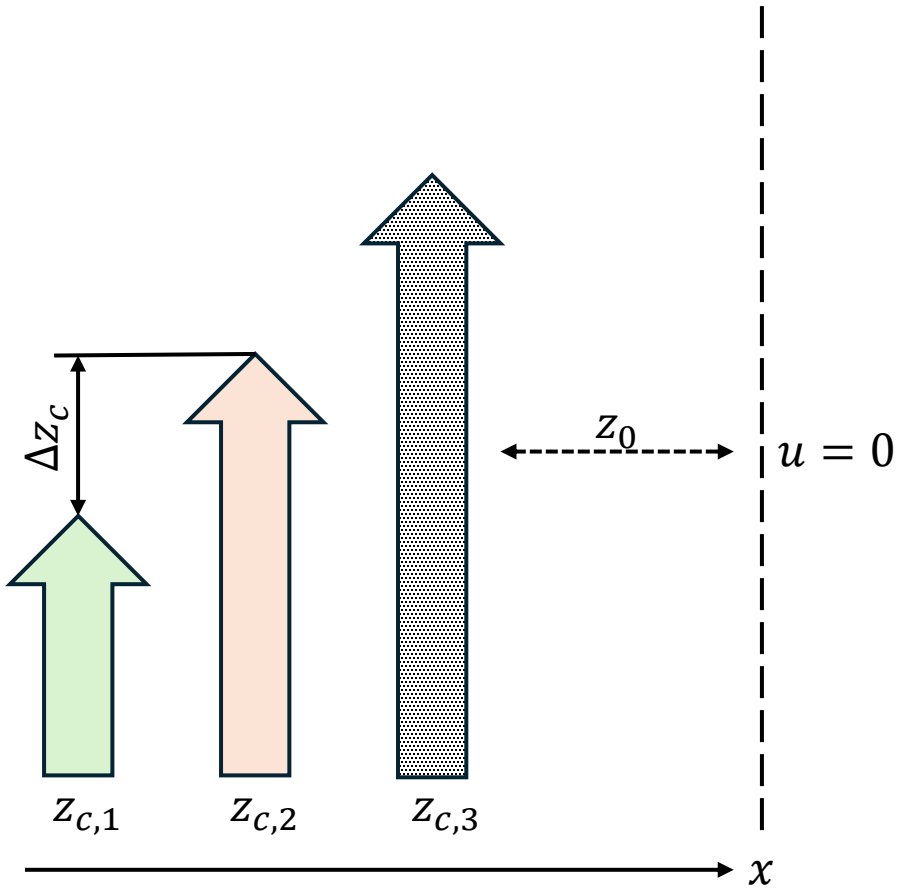
# Recommendations

- Too abrubt or too soft impedance gradient between LWS layers results in lower Return Loss performance

– Layer for smoothing impedance transition gradient (e.g. perforated panel, resonant absorber)




If too abrupt impedance transition between LWS components



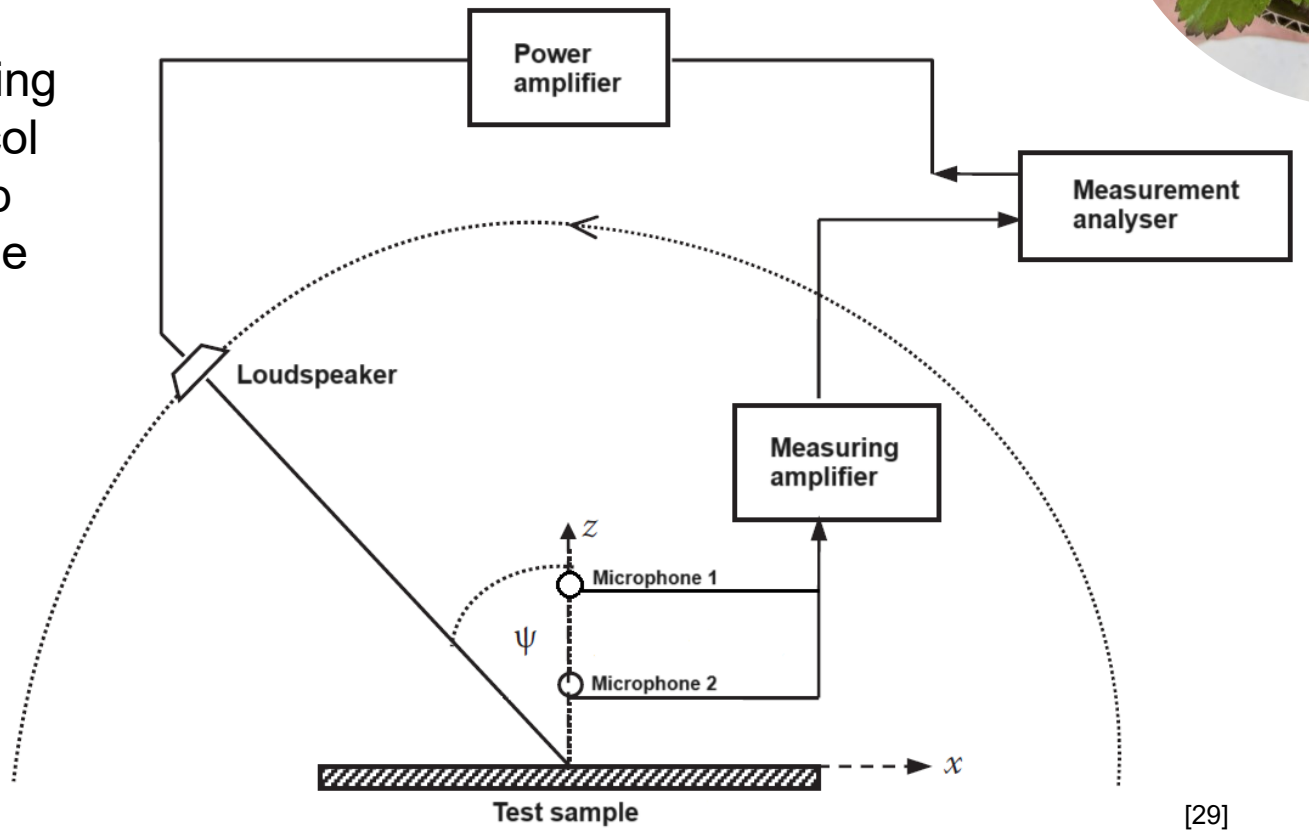

If too soft impedance transition between LWS components

# Recommendations

It is recommended to use two-microphone free-field measurement setup instead of impedance tube measurement setup:

- **Oblique incidence data**
- No test sample shape altering
- Same measurement protocol
- More freedom for setting up the working frequency range

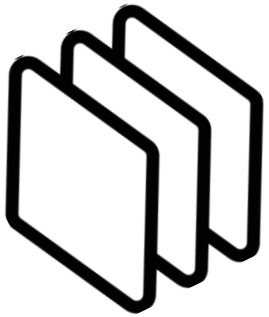
... Requires more resources



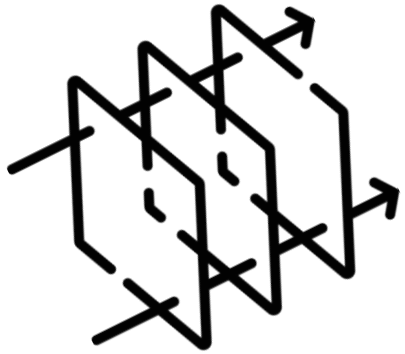

[29]

## Conclusion

How does the TMM facilitate the quantification of the acoustic performance of VGSs?



- Breaks down complex LWSs into homogeneous layers.



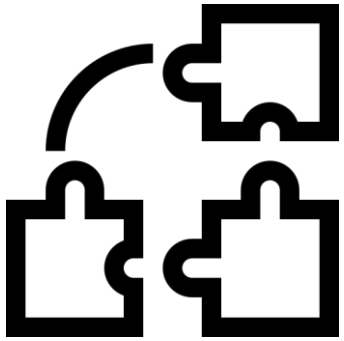
- Enables accounting for complex impedance transitions between the layers.

- Determines the performance of the superposition of layers under specific boundary conditions.

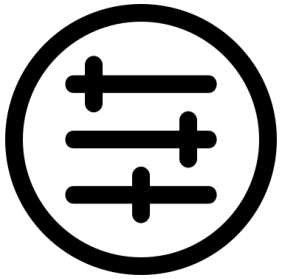
## Conclusion

The primary objective of this study was to develop a decision-support tool for stakeholders to assess the acoustical performance of arbitrary VGS designs using a multi-layered approach.

- Design LWS by focusing on the combined performance of components, not on their isolated performance.



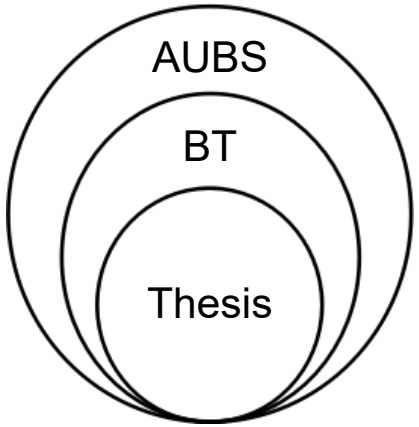
- Utilize the material library to experiment with various component combinations.



- Adjust extrinsic variables of the components to identify acoustic performance improvements of the LWS.

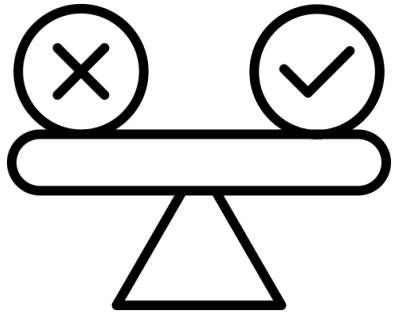
# Reflection

## Relevance of the project



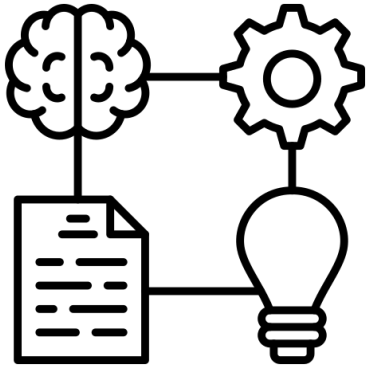

- Thesis – Focuses on acoustic engineering principles
- BT – Emphasizes advanced technological solutions based on building physics
- AUBS – Supports interdisciplinary approaches to tackle built environment challenges

## Feasibility of the project



- Facilitates comparison of VGS with top synthetic facade materials
- Promotes widespread integration of VGSs in line with the European Climate Pact goals
- Potential enhancement of the urban soundscape (human-prespective)

## Learning process



- Developed a structured method for breaking down complex problems
- Sharpened ability to interpret and evaluate data critically
- Enhanced proficiency in using various analytical tools

# Figures references


1. Spatial Planning and Sustainability Department, Municipality of Amsterdam. (2024). *Amsterdam Sound Map 2021.* Retrieved from https://maps.amsterdam.nl/geluid/
2. Andrews, K. (2013). *London's largest living wall designed to reduce urban flooding.* https://www.dezeen.com/2013/08/21/londons-largest-living-wall-will-combat-flooding/
3. Cortês, A., Tadeu, A., Santos, M. I., de Brito, J., & Almeida, J. (2021). Innovative module of expanded cork agglomerate for green vertical systems. *Building and Environment*, *188*, 107461. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360132320308283
4. SingularGreen. (2021). *Vertical gardens for interior and exterior; F+P System. Retrieved from* https://www.singulargreen.com/en/fp-system/
5. SemperGreenwall. (2024). *Flexipanel. Retrieved from* https://sempergreenwall.com/nl/flexipanel/
6. Living Green Walls. (2020). *Living Green Walls. Retrieved from* https://livinggreenwalls.co.za/2017/08/09/living-green-walls-vertipockets-going-green-just-became-even-easier/
7. Elmich. (2016). *National Gallery Singapore. Retrieved from* https://elmich.com/asia/?portfolio=national-gallery-singapore/
8. Novintiss Society. (2019). *Living wall maintenance and set-up: Mounting, watering and maintenance.* Retrieved from https://www.vertiss.net/mur-vegetal-entretien-mise-en-oeuvr?lang=en
9. SingularGreen. (2015). *Ecobin vertical garden.* Retrieved from https://www.singulargreen.com/en/ecobin-system/
10. Gathera. (2024). *Hydroponic perlite stones.* Webshop. Retrieved from https://gathera.com/products/perlite
11. Gathera. (2024). *Hydroponic vermiculite.* Webshop. Retrieved from https://gathera.com/products/vermiculite
12. Gathera. (2024). *Expanded clay balls.* Webshop. Retrieved from https://gathera.com/products/expanded-clay-balls
13. Rainbow Mealworms. (2024). *Coconut coir blocks.* Webshop. Retrieved from https://www.rainbowmealworms.net/coconut-coir-blocks-11-lb/
14. De Kammieshop. (2024). *GiganTerra Coco Husk 10 Liter.* Webshop. Retrieved from https://www.dekammieshop.nl/giganterra-coco-husk-10-liter/
15. The Garden Belle. (2024). *Live sphagnum moss fresh cuttings.* Webshop. Retrieved from https://thegardenbelle.com/products/live-sphagnum-moss-fresh-cuttings
16. Service Partners. (2024). *Mineral wool batt insulation.* Webshop. Retrieved from https://www.service-partners.com/insulation-supplies/mineral-wool-insulation/batt/
17. Wikimedia Commons. (2023). *File: Ajuga reptans 20070429 132711 1.jpg - Wikimedia Commons, the free media repository*. Retrieved from https://commons.wikimedia.org/w/index.php?title=File:Ajuga_reptans_20070429_132711_1.jpg&oldid=787219051
18. Wikimedia Commons. (2022). *File: Festuca glauca 001 Tehran Botanical garden 2016.jpg - Wikimedia Commons, the free media repository*. Retrieved from https://commons.wikimedia.org/w/index.php?title=File:Festuca_glauca_001_Tehran_Botanical_garden_2016.jpg&oldid=718373290
19. Wikimedia Commons. (2023). *File: Bergenia crassifolia a1.jpg - Wikimedia Commons, the free media repository*. Retrieved from https://commons.wikimedia.org/w/index.php?title=File:Bergenia_crassifolia_a1.jpg&oldid=821530485
20. Wikimedia Commons. (2020). *File: Waldsteinia ternata A.jpg - Wikimedia Commons, the free media repository*. Retrieved July 1, 2024, from https://commons.wikimedia.org/w/index.php?title=File:Waldsteinia_ternata_A.jpg&oldid=451274614
21. Wikimedia Commons. (2020). *File: Heuchera americana Green spice.jpg - Wikimedia Commons, the free media repository*. Retrieved from https://commons.wikimedia.org/w/index.php?title=File:Heuchera_americana_Green_spice.jpg&oldid=512379142
22. Szczepańska, A., Senetra, A., & Wasilewicz-Pszczółkowska, M. (2015). The effect of road traffic noise on the prices of residential property – A case study of the Polish city of Olsztyn. *Transportation Research Part D: Transport and Environment, 36*, 167-177.
23. Babisch W. (2002). The Noise/Stress Concept, Risk Assessment and Research Needs. *Noise & health*, 4(16), 1–11.
24. Kephalopoulos, S., Paviotti, M., & Anfosso-Lédée, F. (2012). *Common Noise Assessment Methods in Europe (CNOSSOS-EU)* (EUR 25379 EN; JRC72550). Luxembourg: Publications Office of the European Union.
25. Fellert Acoustical Ceilings AB. (2012). *Sound class and weighted alpha*. Retrieved from https://www.fellert.com/blog/interestingfacts/sound-class-and-weighted-alpha/
26. Thipsorn, M. (2022). Close up of nature view green leaf on white isolated background under sunlight with copy space using as background natural plants landscape, ecology cover concept. Retrieved from https://www.vecteezy.com/photo/7360323-close-up-of-nature-view-green-leaf-on-white-isolated-background-under-sunlight-with-copy-space-using-as-background-natural-plants-landscape-ecology-cover-concept
27. Cilaird. (2023). *Different sized pore spaces in soil*. Retrieved from https://soil.evs.buffalo.edu/index.php/File:9FDE2B38-94FC-495B-A12B-F57898660EFC.png
28. Craiyon. (2024). Craiyon - ai model drawing images from any prompt. Retrieved from https://www.craiyon.com/
29. Cox, T. J., & D'Antonio, P. (2017). Acoustic absorbers and diffusers : theory, design and application [third edition]. *CRC Press*.
30. Van Renterghem, T. (2016). *2D-Radiation pattern of a street canyon.* Retrieved from https://users.ugent.be/~tvrenter/Stadsgeluid.htm

- *Designed by freepik.* (2024). **(Note: All icons are *designed by freepik).*** Retrieved from https://www.freepik.com/

*Thank You!*

Martijn
Marc
Alvaro
Martin
Mom
Dad

*Dedicated to my beloved grandmothers*