CONTROLLING ROUGHNESS

Exploring the influence of 3D printing on the roughness of a bio mixture to design controlled acoustic properties

MAY 2025

MASTER THESIS
Integrated Product Design | Industrial Design Engineering | Delft University of Technology

AUTHOR
Carmen Enríquez Comendador

CHAIR
Dr. ir. E.L. (Zjenja) Doubrovski |
Department of Sustainable Design Engineering

MENTOR
Ir. E.J.L. Noordhoek |
Department of Human Centered Design

IN COLLABORATION WITH
Omlab

ACKNOWLEDGEMENTS

This graduation project would not have been possible without the invaluable support, guidance, and collaboration of many individuals. I am sincerely grateful for the encouragement, expertise, and generosity that helped shape this work.

I would like to thank my supervisory team, Eliza Noordhoek and Zjenja Doubrovski, whose critical insights and support have been essential throughout this project. Their questions challenged me to make meaningful decisions and maintain a reflective, critical approach to my work. Beyond academic mentorship, their encouragement during moments of uncertainty helped me regain clarity and confidence, ultimately enabling me to bring forth a project that I am proud of.

This project would not have been possible without the trust and support from Omlab. I would like to thank Huub Looze for the enthusiasm, encouragement, and experience he shared. His insightful feedback and expertise consistently challenged my approach. Guiding the outcomes of this work to his vision and commitment to letting the potential of bio-material truly shine.

I would also like to thank the staff from the Lama LAB. For their patience and support in sharing their space with what became an almost daily, hands-on, and messy material project. Their help in finding the right tools to mix, store, and dry my prototypes was essential. Most of all, I truly appreciated their curiosity, encouragement, and kind words.

Ela Fasllija I would like to thank for so generously answering my questions and guiding me in the field of architectural acoustics. Her willingness to share knowledge and point me toward valuable references greatly deepened my understanding of the field. I am especially grateful for her help with discussing my findings and providing constructive feedback that helped shape the direction of this project.

I would also like to thank Martin Tenpierik for introducing me and granting access to the equipment used for sound absorption testing. His guidance was key in helping me understand how to conduct the tests and interpret the results. His support made it possible for me to carry out the experiments I had envisioned.

Last, I would like to thank Luka Suurmond, Emilie Barrow, Elena Dagg, and Silvia Teisanu, my friends, who stood by me throughout this journey with constant emotional support, encouragement, and care. Whether it was listening when things felt overwhelming, offering feedback, or simply reminding me to take a break, their support was invaluable. Their kindness, patience, and belief in me helped me stay motivated. I couldn't have made it through this process without them.

Sincere thanks to everyone who contributed to this work through feedback or support. Your involvement, whether technical, academic, or personal, has been crucial to the development and completion of this project.

ABSTRACT

This project explores the potential of Omlab's bio-circular material BM-1 for architectural applications, focusing on its use in fabricating indoor walls. The project investigates how 3D printing can be leveraged to actively design and control BM-1´s material properties, to enhance its unique opportunities.

By varying 3D printing toolpaths, the project aims to exploit the relationship between 3D printing parameters and material roughness as a design opportunity. Through an experimental methodology, the project demonstrates that surface roughness is highly dependent on toolpath design. Using the impedance tube method for absorption coefficient measurement, the project reveals the influence of 3D printing parameter variations on the acoustic absorption properties of BM-1 specimens.

The findings of the project show that additive manufacturing enables the design of multi-scale surface roughness that influences acoustic performance. This opens new pathways for 3D printing with bio-based materials in architectural contexts. Positioning roughness not as a limitation, but as an asset controlled to meet architectural needs.

TABLE OF CONTENT

GLOSSARY

3DP – 3D printing

LH – Layer height, vertical distance between 3D-printed layers

Wall thickness – Horizontal thickness of 3D-printed walls

Infill – Internal structure that fills a 3D-printed object

Deposition height – Height at which the material is deposited influenced by printing path variations

Toolpath – Translation of a 3D digital model into a layered extrusion

Printing path – Path followed by the 3D-printing machine to produce 3D objects

Feed rate – Speed of the 3D-printing machine

Flow rate – Amount of material extruded by the 3D-printing machine

Offset – Horizontal variation in the printing path target positions

Sound absorption – Measure of the amount of energy removed from a sound wave upon incidence on a material

Absorption coefficient – Quantity of the incident sound intensity that is not reflected by the material

CHAPTER 1: INTRODUCTION

With a startling 37% of worldwide emissions, the building and construction sector is by far the largest emitter of greenhouse gases (UN Environment Programme, 2023). Materials like cement, steel, and aluminum have a large carbon footprint during manufacturing and use.

The architectural field has seen a growing interest in sustainable construction practices, particularly through the use of bio-based materials and digital fabrication techniques. 3D printing has emerged as a transformative tool, enabling control over form and material performance. This technology has opened new perceptions for rethinking how materials behave and perform in architectural contexts.

This project is conducted through experiments using BM-1, a bio-circular material developed by Omlab.

Production with bio-circular materials provides a smaller embodied carbon footprint, and allows 3D printing production without the use of heat. Nevertheless, these materials come with increased handling complexity since they are anisotropic and heterogeneous when compared to standard industrialized materials (Rossi, 2023). Studying their behavior, characteristics, performance, and 3D printability can push for bio-circular material adoption.

The material properties of BM-1 when 3D printed are limited compared to conventional building materials. The main challenge, then, is to explore how such material can be manufactured in a way that shows its competence and proves its place in the architectural context. Not only showing it can do what other materials can, but also identifying its unique advantages.

This project aims to identify a material property of BM-1 that can be controlled through the 3D printing process, to develop it underlining the advantages of the material in the architectural context. This way, this project reframes materials defined as “poor” to unwrapping new design opportunities, offering a new perspective on the architectural use of bio-based 3D printed materials.

1.1 BM-1

BM-1

A fundamental aspect of the process was collaborating with Omlab, who provided access to a fully bio-based material alongside expert input.

The material provided by Omlab and used in this project is composed of 98% waste and 2% biobased organic matter. The raw materials are by-products and residual flows from sewage treatment. The source for the reinforcement in Omlab's printing material is cellulose. This material has the strength of gypsum concrete, but is lighter and locally produced.

Omlab develops material recipes for different applications, varying the components in the mixture. To refer to the material provided by Omlab for this research, the recipe will be referred to as Bio-Mixture 1 (BM-1). The main ingredients for this material recipe are calcium carbonate, alginate cellulose, and water. Resulting in a paste suitable for extrusion-based additive manufacturing.

Omlab´s projects

Omlab's circular, constructive print material is part of the National Emission-Free Construction program. Their prototype of a toilet wall (Figure 1) shows the implementation of biomaterials in building infrastructure.

In the context of 3D printing with bio-based materials, significant effort is often required to formulate pastes that are extrudable and to understand the material's behavior during and after the printing process. The challenges Omlab faces are not only concerning the printability of the material, but also pushing the limits of what is considered a "poor" material, and elevating its performance to meet high construction standards.

Omlab´s prototype "Stroncq" (Fig. 4) designed by Lilian van Daal is a stool that showcases the material´s strength. Further, Omlab shows applications of its material in nature with "Vespers" (Fig. 2), a bat house. Additionally, "Bio-slope tile" (Fig. 3) shows the opportunity for bio-receptiveness of the material as organisms can nurture from the material and grow biodiversity.

Figure 1 : Toilet wall (Omlab, 2024)

v

^

Figure 2 : Vespers (Omlab, 2024)

^

Figure 3 : Bio-slope tile (Omlab, 2024)

^

Figure 4 : Stroncq (Omlab, 2024)

Knowledge gap

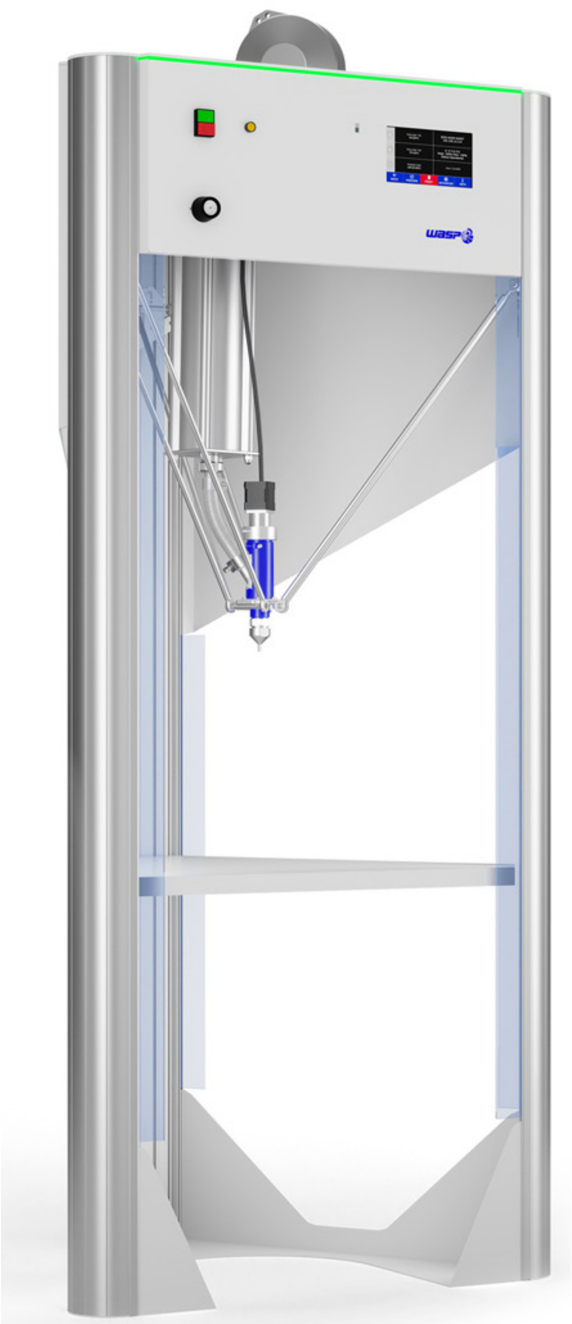
So far, Omlab has showcased the applications of their material in furniture, bio-receptiveness, and interior walls for separation. In terms of bio-receptiveness, Omlab´s material holds promise as it can enhance biodiversity growth. In the architectural context, its strength and the possibility of replacing others have been proven. However, these examples lack the emphasis of its opportunities in the building context. A knowledge gap still remains in terms of what unique advantages of this material are, and why it should be 3D printed.

In order to adopt a new material in the building infrastructure context, its place in the architectural context should be proven. Therefore, this project addresses the knowledge gap in presenting unique material properties controlled by a 3D printing process. With Omlab´s material recipe as a focal point, this project explores and presents valuable opportunities for implementing 3D-printed bio-circular materials in architecture.

1.2 WASP 40100 LDM

To be able to identify the properties and opportunities of BM-1 when 3D printed, 3D printing experiments with the material had to be conducted.

To get access to a machine that allows cold extrusion with BM-1, a collaboration with the TU Delft Architecture Faculty LAMA Lab was established. Within the lab facilities, the WASP 40100 LDM (Fig. 5) was used. This machine is a ceramic 3D printer designed to print any fluid-dense material.



^

Figure 5 : WASP 40100 LDM (WASP, 2025)

Material preparation

A key factor affecting 3D printed outcomes with BM-1 is the material preparation. Being the material used for this project quite fibrous, the ingredients must be mixed and blended as homogeneously as possible. To ensure a proper material mixture, the following steps must be followed:

First, the dry ingredients should be mixed. Then, water is added, and the paste is mixed manually thoroughly. When done mixing, the material consistency is tested. When the consistency is satisfactory, the material is divided into balls so the material can be easily put into the tank. Afterwards, the material balls are pushed into the tank to avoid air bubbles. Lastly, the machine pressure is set to 4-5 bar, and the material should flow into the extruder.

Syringe test

The syringe extruding test (WASP, 2024) can help assess if the material is ready to print with. The syringe test consists of filling a syringe with the material, pushing it out and checking the angle at which the material falls off the syringe. The falling angle is measured according to the horizontal.

For BM-1, a 45-degree fall is perfect for extruding. With this falling inclination, the material should flow into the extruder between 4 and 5 bar.

^

Figure 6 : Material preparation

1.3 MATERIALS USED FOR INTERIOR WALLS

In order to adopt a new material in the building infrastructure context, its place in the architectural context should be proven. Omlab´s current aim is to build interior walls for houses using their material. Thus, before exploring the characteristics of Omlab´s material, the currently implemented materials should be reviewed.

Interior wall materials significantly influence a building's aesthetics, functionality, and occupant well-being. Durability, maintenance, light reflectance, fire resistance, sound absorption, and cost are the main characteristics designers and architects consider when selecting an inner wall finish (Binggeli, 2008). Assembly and finishing are also important for the designer to consider how and what the material will be attached to.

Plaster and gypsum boards are commonly used to finish the interior wall and ceiling surfaces of buildings. These materials are resistant to wear and easy to clean, with additional surface treatments enhancing both their resilience and aesthetic appeal (Binggeli, 2008).

Plaster

There are many types of plaster that are used for different applications. Gypsum plaster is strong, lightweight, and fire-resistant, making it good for walls and ceilings that are not subject to moisture (Binggeli, 2008). Acoustical plaster (Fig. 10) has a rough texture, is applied by spraying, and is a porous variation of plaster that helps absorb sound (Binggeli, 2008).

Gypsum

Gypsum board, also known as drywall, is a natural insulator, highly fire-resistant and has a low thermal conductivity which makes it a good insulating material (Binggeli, 2008). A variation of the material for further sound insulation is sound-dampening gypsum board, which is used to reduce sound transmission (Binggeli, 2008).

Gypsum board contains more embodied energy than plaster. It is estimated that 10-25% of gypsum board is wasted on-site (Binggeli, 2008). Gypsum has the potential to produce toxic hydrogen sulfide in a landfill, which is why some landfills do not accept drywall waste (Binggeli, 2008). Furthermore, gypsum board may contain additives including fungicides, adhesives, or vinyl that limit its recycling and disposal options (Binggeli, 2008).

Since Omlab´s material has the strength of gypsum concrete, and knowing the environmental impact of gypsum board, Omlab´s vision of replacing this material with a more sustainable practice meets architecture´s urgent call for sustainable action. Nevertheless, further research needs to be conducted to ensure that this biomaterial can provide the same advantages as gypsum board. As well as provide new advantages inherent to the material properties of BM-1.

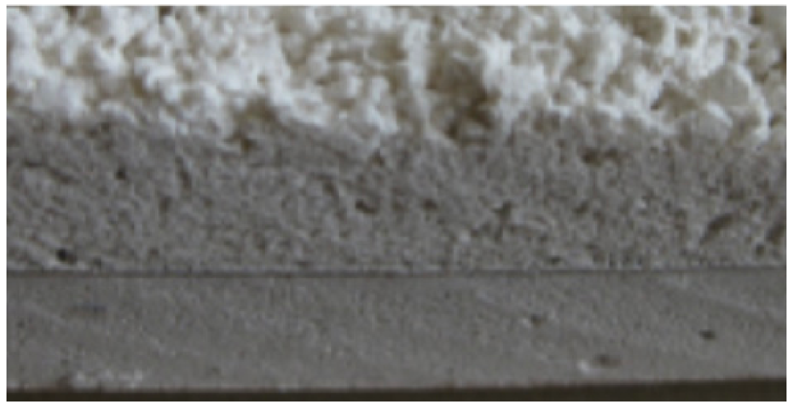
In this chapter, the characteristics of materials implemented for indoor walls have been discussed. These are important as to adopt a new material, these characteristics must be equal or superior.

^

Figure 7 : Veneer plaster on gypsum base (Binggeli, 2008)

^

Figure 8 : Gypsum board on metal stud (Binggeli, 2008)



^

Figure 9 : Acoustical plaster on gypsum base (Binggeli, 2008)

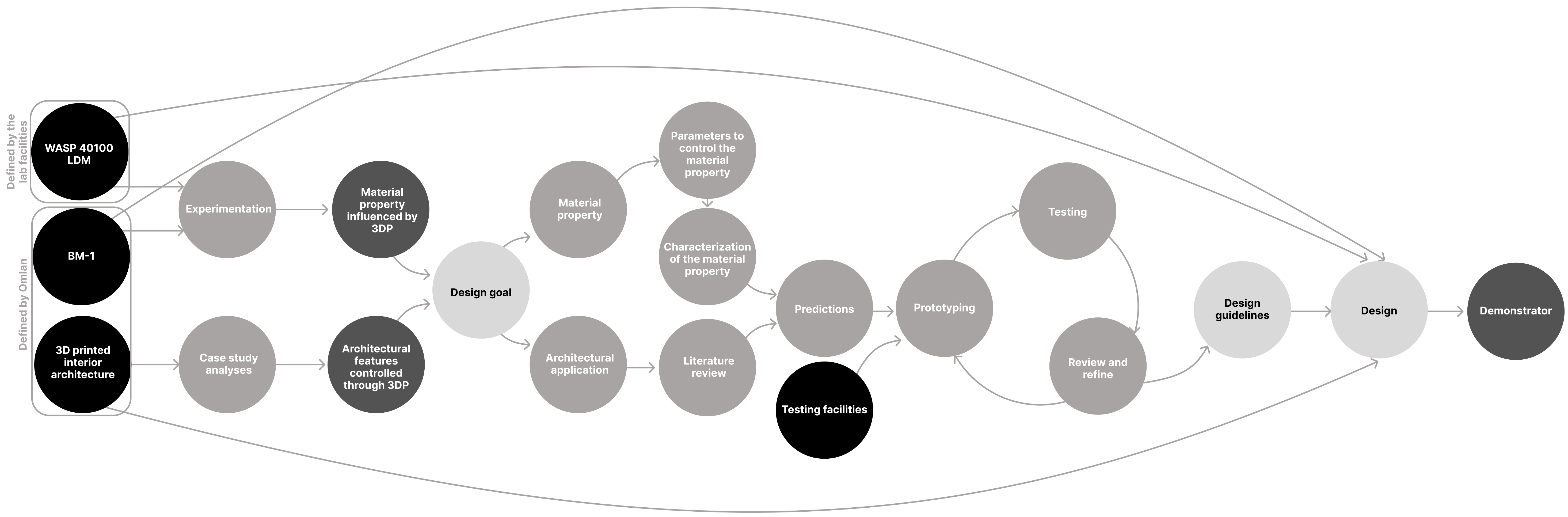
^

Figure 10 : Gypsum board perforated panels (Binggeli, 2008)

1.4 PROJECT GOAL

Given that the strength and ability of BM-1 to replace other materials have been proven, but its unique opportunities and why it should be 3D printed remain unexplored, this project should broaden BM-1´s 3D printed advantages. Therefore, this project must explore how BM-1 can be manufactured in a way that shows its unique properties and proves its place in the architectural context. With this context in mind, the following project goal was formulated.

*The project goal is to identify a **material property of BM-1** that can be **controlled through the 3D printing process**. To then develop the 3D printing parameter and material property correlation in an **application that underlines the advantages** of controlling that material property **in the architectural context**.*



^
Figure 11 : Methodology

1.5 METHODOLOGY

For the specified project goal, a methodology was defined.

To be able to identify a material property of BM-1 that can be controlled and develop it in the architectural context, the project was structured into different process steps that go from exploring and researching broadly the topic of 3D printing with BM-1, to delivering a demonstrator of a controlled material property in an applied context.

Given the context of interior architecture to develop the opportunities of BM-1 in, case studies were conducted. These case studies provided an understanding of how 3D-printing processes are developed towards meeting architectural needs.

In parallel, an experimental phase was conducted to find a correlation between 3D printing settings and material properties. With the aim to identify a material property influenced by the 3D printing process.

A collaboration was established with Omlab to get access to a bio-mixture and with the TU Delft Architecture Faculty to get access to a 3D-printing machine. Therefore, the characteristics form BM-1, the material, and the WASP 40100 LDM, the 3D-printing machine, constrained the experimental phase.

From the material property derived from experimentation and architectural needs met through 3DP from the case study analyses, a design goal was defined.

Then, the material property was then characterized according to the relevant parameter types that influence it. Based on this characterization and a review of literature, a prediction was made regarding how the controlled material property would perform in the application defined by the design goal. Subsequently, available testing facilities were reviewed to assess what aspects of the material property could be tested and how.

Next, specimens presenting the identified parameter variations contributing to a material property are tested in the context defined by the design goal. This process featured an experimentation loop where specimens were produced, tested, evaluated, and re-produced. This loop was repeated until the implications of the material property in the application were fully understood.

Finally, design guidelines for controlling the material property in an applied context were defined. These guidelines, together with the context of interior architecture, the prototyping constraints of BM-1, and the printing machine, feed the design of the final demonstrator. The demonstrator is a means to showcase the controlled identified material property in an applied context.

CHAPTER 2: 3D-PRINTED ARCHITECTURE CASE STUDIES

2.1 GOAL AND APPROACH

To underline how 3D printing BM-1 can enhance characteristics of the material that help meet architectural needs, it is important to understand how architects make use of additive manufacturing processes further than as a production technique, as a means to achieve architectural features.

In this project, case studies were analyzed to identify how 3D printing parameter variation is implemented to achieve architectural features. The aim of these case studies is to understand how architectural needs are met through controlled 3D printing processes. To later find an application for BM-1 that shows the advantages of 3D printing this material.

The chosen case studies were selected to show the advantages of using additive manufacturing in architecture. The case studies were analyzed in terms of technology, material, and geometry, to analyze how additive manufacturing processes can help achieve architectural features. This helps to understand what key parameters helped achieve specific architectural needs.

Technology

Different additive manufacturing processes offer unique advantages and constraints, making it essential to match the technology to the project's goals. Here, the type of printing machine caters to different scales and material requirements. For the scope of this project, the production technologies should use a cold extrusion deposition method, similar to BM-1. As well as showing a clear correlation between technology and architectural goals.

Material

The material selection of the projects also defines the aesthetic and functional properties of the project. Not only to meet an alignment between material selection and architectural vision, but the material properties also constrain the project´s scope with what the material can or can not do. The projects analyzed show various materials that, through additively manufacturing their properties contribute to architectural needs.

Geometry

Additive manufacturing allows architects to explore complex geometries that are otherwise difficult or impossible to achieve with conventional methods. In the chosen projects, it is not just about generating a geometry that is printed but how architects use a geometry to achieve a certain architectural trait. The chosen geometries enhance how design for 3D printing can help achieve architectural features.

2.2 CONCLUSIONS FROM CASE STUDIES

The case studies gathered multiple interesting features that were achieved through additive manufacturing, and underline the added value of using this technology for building infrastructure.

The individual case studies can be found in Appendix 1. This chapter will go through the main takeaways from the case studies to understand how architectural needs are met through controlled 3D printing processes. To later find an application for BM-1 that shows the advantages of 3D printing this material.

Summary of findings

Ten projects showing how different architectural features are achieved through a 3D printing process were analyzed.

The projects TOVA by IAAC and Tecla by Mario Cucinella architects, show examples of manufacturing with local materials to build houses. In these two projects, through 3D printing a complex infill geometry, indoor wall features such as light filtration, airflow, and heat insulation are achieved. Further, Tecla introduces the distinction between geometry for outer and inner walls to achieve different insulation, ventilation, and shading properties.

The projects TOVA by IAAC and Tecla by Mario Cucinella architects, show examples of manufacturing with local materials to build houses. In these two projects, through 3D printing a complex infill geometry, indoor wall features such as light filtration, airflow, and heat insulation are achieved. Further, Tecla introduces the distinction between geometry for outer and inner walls to achieve different insulation, ventilation, and shading properties.

The project TerraMound showcases a system of porous networks to build architectural pieces, which is beneficial for ventilation, bio-receptivity, and acoustic control. Alternatively, a different project by Urban Reef, also targets porosity for bio-receptivity but instead of through infill, through printpath variations and the use of biomaterials, creating a livable condition for plants or fungi. Moreover, a research project about Termite Structures presents how this bio receptiveness and nature-integration can be achieved not only by material recipe but by defining a geometry that meets the living material´s needs.

Impact Printing and Ceramic Tesselation are two projects analysed that, though they are not 3D printed, underline the importance of technology choice and geometrical formulation of complex surfaces. These two projects show how additive manufacturing can allow to build tall walls without any formwork.

Further, a project on Mineral Foam Insulation targets heat insulation through a toolpath that creates a contour-perpendicular zigzag shell.

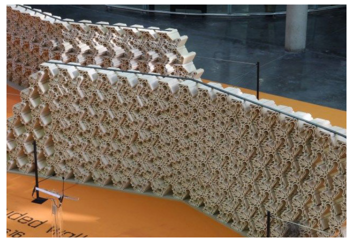
A research project conducted in TU Delft about 3D Printed Sound Absorbers presents a workflow for architects to build a geometry based on sound absorption theory to achieve predictable acoustic behaviors.

Lastly, Grading light showcases an in-depth study on toolpath variation to modify the perception of depth and alter illumination.

TOVA
IAAC

Impact Printing
ETH Zürich

Tecla
Mario Cucinella architects



Ceramic Tesellation
Harvard University

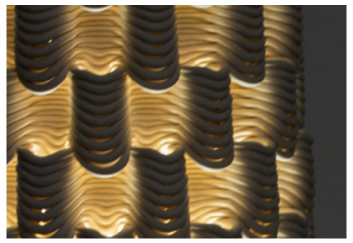
TerraMound
Rameshwari Jonnalagadda

Mineral Foam Insulation
ETH Zürich

Urban Reef
Urban Reef

3D printed Sound Absorvers
Foteini Setaki

Termite Structures
Vanessa Costalonga



Grading Light
James Clarke-Hicks

^

Figure 12 : Features achieved through a 3D printing process from case studies

Paremeter manipulation

The individual analysis of each case study, underlined architectural features that were achieved through parameter manipulation in a 3D printing process.

Figure 12 displays the connections between the identified features from the case studies, and which parameter categories were manipulated to achieve the different identified features. The variables affecting 3D printing processes were divided into slicing parameters, machine-specific parameters, material-specific parameters, and geometry-specific parameters. This division is made to understand which parameters of a 3D printing process were modified to achieve a specific architectural need.

The outcomes are displayed in a 2D space between the four 3D printing parameters, connecting to the parameters that helped achieve that feature. For example, the feature "geometry for sound absorption" was achieved through geometry design, but it is also close to material-specific parameters as the material deformation can influence the coefficient of sound absorption.

From this visualization, it is clear that toolpath variation is a key approach for designing 3D-printed architecture.

These toolpath variations generate different topologies that achieve certain features for an architectural application. The applications addressed in the case studies include bio-receptiveness, material bonding, thermal conduction, grading light, and acoustic treatment. The feature of bioreceptiveness was achieved through toolpath-generated porosity

using biomaterials. High material bonding was achieved through printing techniques with a high material overlap, allowing to build tall walls without any formwork. Thermal insulation can be achieved through toolpath variations that generate different surface topologies beneficial for thermal insulation. Light grading is highly influenced by toolpath variation to modify the perception of depth and alter illumination. And, lastly, generating systems of porous networks can allow the achievement of acoustic control.

Opportunities for BM-1

Through the case studies, toolpath variation as a means to add functional architectural features such as bio-receptiveness, material bonding, thermal conduction, grading light, and acoustic treatment were identified.

These findings serve as possible architectural applications for 3D printing with BM-1.

Omlab has already showcased in products the strength and bio-receptiveness of their material. Nevertheless, as previously discussed, a knowledge gap still remains in terms of what the unique advantages of this material are, and why it should be 3D printed. Therefore, the application chosen to develop a 3D printing process for BM-1 should showcase why BM-1 should be 3D printed and underline the advantages of adopting this material.

Designing a process that implements geometry at the forefront to achieve light scattering, for example, would not define why BM-1 should be 3D printed. The chosen application should answer why BM-1 should be implemented, why it should be 3D printed, and what its place in the architectural context is.

To know what architectural needs BM-1 could help achieve, it is necessary to first identify what influence toolpath variation has on BM-1.

With this in mind, the experimentation phase was conducted with the aim of finding a material property of BM-1 that is influenced by the 3D printing process. To later correlate this with the found architectural needs from the case studies.

CHAPTER 3: EXPERIMENTATION

3.1 FOUNDATIONS FOR EXPERIMENTATION

The goal of the experimentation is to find a material property of BM-1 that is influenced by the 3D printing process. Experiments concerning different 3D printing parameters were formulated to find a correlation between 3D printing settings and BM-1 properties.

Identifying the right parameters for a certain 3D printing process is essential to achieve predictable outcomes. When the correlation between parameter variation and printed outcome is unclear, unpredictable results occur. Understanding the relationships between process parameters and final part properties will be critical in facilitating predictable outcomes and controlling material properties.

To fully understand what aspects of the 3DP process affect the behavior of BM-1, the different parameters influencing the 3DP process must be defined.

Multiple variables affect 3D printing processes. When conducting research in the 3D printing field, some parameters are defined as variables to achieve a certain goal, and the rest are set as constants (Takahashi & Miyashita, 2017). The variables affecting 3D printing processes can be divided into slicing parameters, machine-specific parameters, material-specific parameters, and geometry-specific parameters (Agarwala et al., 1996).

WASP LDM 40100 parameters

The machine-specific parameters include nozzle diameter, tank capacity and print volume.

The print volume and tank capacity are defined by the WASP 40100 LDM clay 3D printer. Furthermore, the nozzle diameter was set to 8mm as it is the nozzle diameter currently used by Omlab.

For the comparability of different experiments, the machine-specific parameters were set as constant.

BM-1 parameters

The material-specific parameters refer to the viscosity, density, stiffness, and flexibility of the material.

Some production days after the material was prepared for printing, it was not possible to conduct testing due to problems with the extruder motor. This led to having to store already mixed with water material, in a sealed environment, to later use. This process of adding water, storing, and adding water again influenced the material properties highly and so has to be considered in the result analysis.

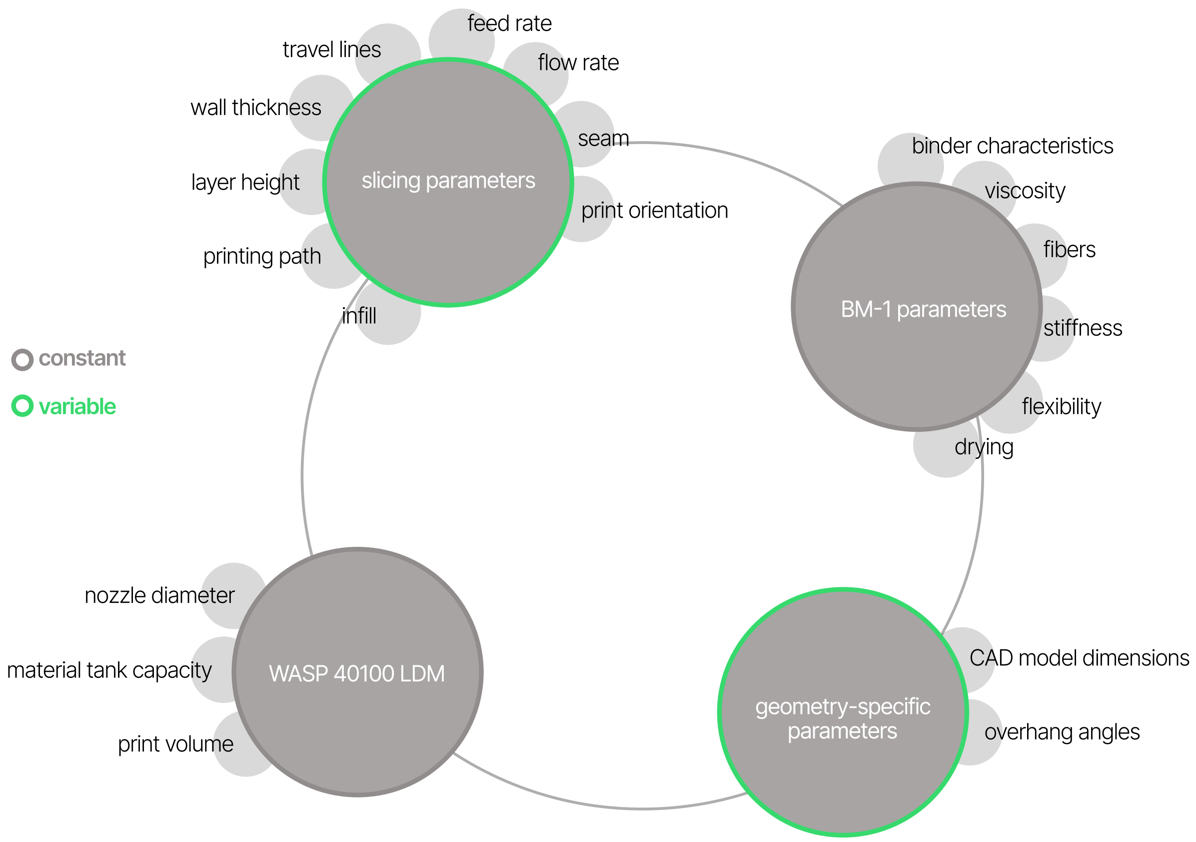
These material conditions determine whether a certain toolpath can be printed or if the print will collapse. Therefore, analyzing the test results alongside the syringe test outcomes helped identify the influence of the material consistency on the 3D printed material properties.

Accordingly, though only the BM-1 material recipe was implemented in the experimentation, the material-specific parameter slightly varied from one production day to another.

Slicing and geometry-specific parameters

The slicing parameters are the feed, flow, seam, orientation, infill, printing path, layer height, wall thickness and travel lines. The geometry-specific parameters are the CAD model dimensions and overhang angles. All these parameters are set as variables that are defined by the purpose of every experiment.

Figure 13 shows the parameters that remain constant and variable for the conducted experiments.



^

Figure 13 : Paramerts influencing the 3D printing process with BM-1, constant and variable parameters

To find a material property of BM-1 that is influenced by the 3D printing process, multiple questions were formulated to define experiments aiming to answer them. Four main experiment categories were defined.

Printing resolution

Testing the abilities of the material in terms of detail resolution, overhang, collapse without infill, and cleanness of material retraction. The aim of this experiment category is to understand the ability of BM-1 to achieve a clean model accurate piece. An important aspect of 3D-printed architecture is the model accuracy.

Experiment category questions

How well can BM-1 capture fine details and sharp edges in printed models?

What is the maximum overhang angle BM-1 can support without requiring infill?

How cleanly does BM-1 perform material retraction?

Layer height variation

Experimenting with different approaches to setting feed and flow rates to achieve a continuous wall thickness for prints varying layer heights. These tests define how to accurately keep a constant wall thickness, concerning the ability to achieve predictable outcomes.

Experiment category questions

Can a uniform wall thickness be maintained when printing with variable layer heights using BM-1?

What parameter combinations produce the best wall thickness consistency when varying layer heights?

Repetitive patterns

Testing whether material roughness can be achieved through pattern repetition. The aim of this category is to explore how the distinctive roughness of BM-1 varies utilizing patterns.

Experiment category question:

In what way do repetitive patterns affect material roughness in BM-1?

Print path noise

Exploring how added noise in the printing path, varying directions, can influence the material roughness. With this category, the roughness of BM-1 is achieved through random movements within the printing path.

Experiment category question:

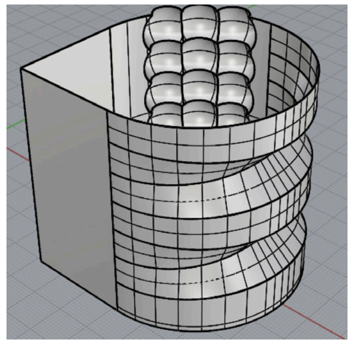
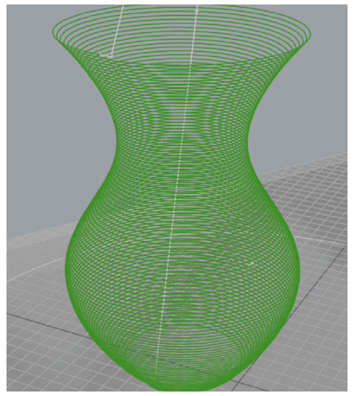
How does introducing directional variation (noise) into the printpath affect the surface texture of BM-1 prints?

3.2 SUMMARY OF EXPERIMENTS

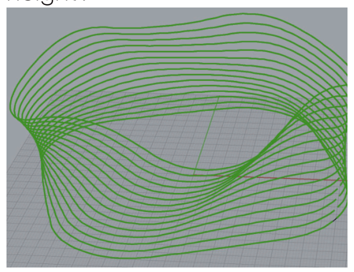
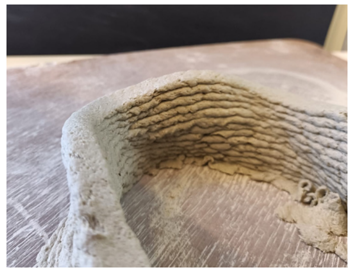
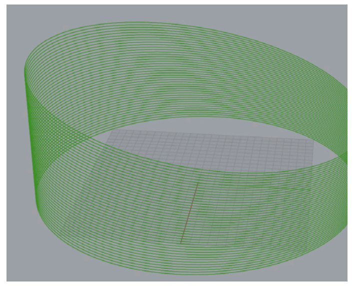
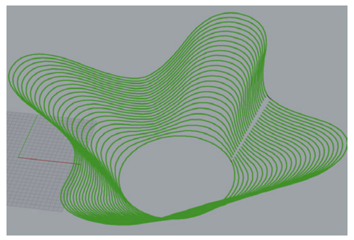
The following pages display an overview of the experiment questions, approaches, and conclusions.

To view the full experiment production sheets, visit Appendix 2.

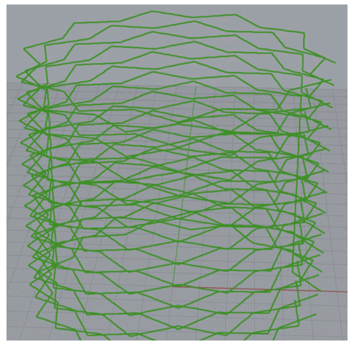
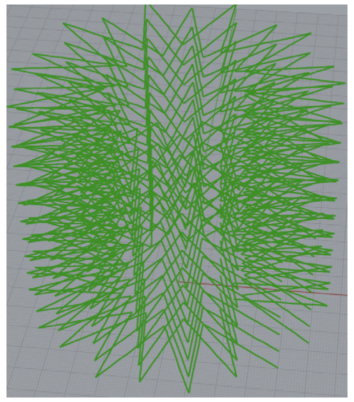
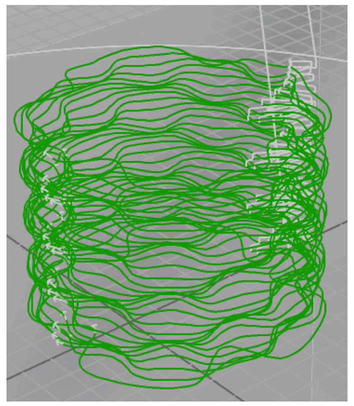
Printing resolution

Experiment	Approach	Hypothesis	Testing	Findings
DETAIL RESOLUTION AND OVERHANG –What is the detailing accuracy and overhang limit of the material?  	Test piece defined for "Formulating and Testing a Clay Body for Extrusion Clay 3D Printing" (J. Keep, 2020)	The material can withstand a maximum of 30 degree overhang and the details are rather rough	3D print geometry horizontally sliced	The material can withstand a maximum of 30 degree overhang and the details are rather rough
COLLAPSE WITHOUT INFILL –When does the material collapse when doing a single wall with wall angles?  	Creating a printing path single wall spiralized path with wall angles of up to 50 degrees	50 degrees is very demanding and it will deform from the beginning	3D print custom polyline	The print deforms as the wall builds higher. 50 degrees with no infill is too demanding
CLEANNESS OF MATERIAL RETRACTION –How clean is the travelling retraction? 	File of multiple single lines separated from each other	The retraction is clean	3D print geometry horizontally sliced	The retraction is quite sharp. The fibres of the material become more visible

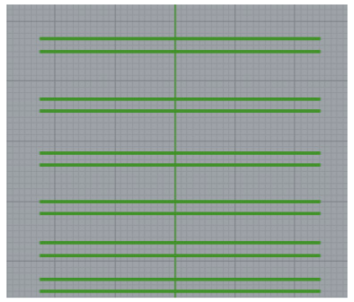
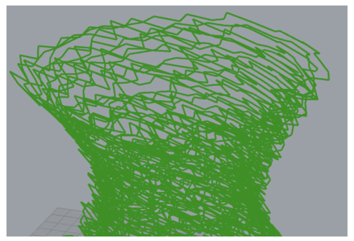
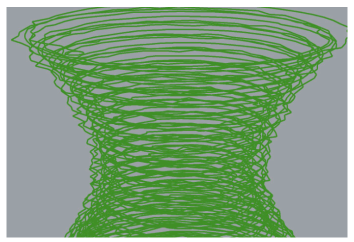
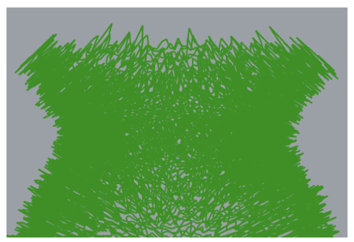
Layer height variation

Experiment	Approach	Hypothesis	Testing	Findings
EXTRUSION RATE –Does the wall thickness stay constant when setting the flow rate by a percentage according to the layer height?  	In the slicer the vector lengths are remapped into 0.5 to 1. The number assigned from this defined range refers to the distance between layers	The wall thickness should be constant	3D print non planar polyline sliced with a custom made slicer	The wall thickness does not stay the same and goes from 6mm to 11mm
FEED RATE –Does defining the speed rate value domain through the flow values help achieve a constant wall thickness?  	Defining the max and min speed as: Feed=Extr/ LW*LH	The wall thickness should be constant	3D print non planar polyline sliced with a custom made slicer.	The wall thickness was between 9 and 11 mm, almost constant. Though the WT was set as 8mm
FEED RATE WITH OVERHANG –Does defined speed rate help construct diagonal walls?  	Defining the max and min speed as: Feed=Extr/ LW*LH for a geometry with 50% overhang	The feed rate should help build up at a demanding overhang	3D print non planar polyline sliced with a custom made slicer	The layer heigh increases as it builds up since the material can not withstand the 50 degree overhang

Repetitive patterns

		Approach	Hypothesis	Testing	Findings
SHORT ZIG ZAG – Is the material roughness modified when printing repetitive patterns?	 	Creating a zigzag print path	The roughness should become more pronounced from the nozzle movement	3D print custom polyline	The roughness is slightly increased by connecting the layers through the zig zag
LONG ZIG ZAG – Does the material roughness increase or decrease when patterns points are further appart?	 	Creating a zigzag print path where the zigzag points are further appart.	The roughness should increase	3D print custom polyline	The deposition height is higher and so the roughness is not increased by the layer on layer. Further, creases are created in the folding points of the zig zag
WAVE TEXTURE – Is the material roughness decreased with a bigger layer heigh and a uniform wave geometry?	 	Creating a repetitive print path with 4mm layer heigh and a curved-like texture	The roughness should not be influenced	3D print custom polyline	With the movement of the nozzle following the defined geometry, the material fibers becomes more visible

Printing path noise

		Approach	Hypothesis	Testing	Findings
INCREASING THE LAYER HEIGHT –How does the material roughness change at different layer heights?	 	Dispatch pattern for a cylinder with contours 1mm apart where for every two layers the layer height increases 1mm	The lower the layer height the rougher the result	3D print custom polyline	The material goes from very visible fibers making a rough finishing, to a smoother surface with cavities
PERPENDICULAR AND TANGENT NOISE –How does the roughness change when creating perpendicular and tangent noise in the printing path?	 	Printing path where the curve points are moved a different directions and distances every layer	The roughness should be increased	3D print custom polyline	Both noise directions increase the material roughness, and the fibers become more visible for long perpendicular noise
SHORT PERPENDICULAR NOISE –How does shorter perpendicular noise affect the roughness?	 	Printing path where the curve points are moved at a sorter distance range only in a perpendicular manner	The result should be rough	3D print custom polyline	The surface roughness is increased
NOISE WITH DIRECTION CHANGES –How does the material roughness vary when the points moved to add noise are moved not only horizontally outwards?	 	Creating a printing path where the curve points are moved varying in direction	The roughness should be increased	3D print custom polyline	The layers are pushed into each other in a way layers are no longer visible, and making fibers become very visible

3.3 RESULTS FROM EXPERIMENTATION

In this section, the analysis of the results will focus on 3D printing parameter manipulation and influenced material properties of BM-1.

Printing resolution

The print resolution tests led to several conclusions. The material can withstand a maximum overhang of 30 degrees, while its ability to achieve a certain level of detail accuracy is limited by the material consistency. Furthermore, it is possible to print geometries that are not constructed by a single line, as the retraction is relatively sharp. Though the material fibers become visible at the retraction points.

Layer height variation

The experiments targeting a continuous wall thickness for a print varying layer height underlined that the best wall thickness uniformity is achieved when setting the correlation: Maximum feed as: $F_{max}=E/W*H_{max}$ and minimum feed as $F_{min}=E/W*H_{min}$.

Where F = speed, E = extrusion, W = wall thickness, H = layer height, T=time, and L = layer length

With this relationship, we can relate the feed to the extrusion rate defined by the layer length, and achieve a continuous wall thickness when printing nonplanar layers.

Repetitive patterns

Through testing different repetitive patterns, it became clear that the roughness of BM-1 can be modified. Roughness can be created by using toolpaths that interconnect layers in different directions or by folding the material. The material fibers also become slightly visible when following small movements defined by a geometry.

Printing path noise

Noise added in the printing path affected the material roughness differently depending on the layer height and the direction in which the points are moved. As the layer height decreases, material roughness within the layer increases. And as the layer height increases cavities within the layer appear.

Both perpendicular and tangent noise contribute to roughness, though long perpendicular noise makes the fibers more visible as the material is pulled. Moreover, in areas where the previous layer is pushed and the extruded material is stretched, the material fibers become visible. Additionally, the continuous change in direction and pushing of the material enhances fiber visibility, while also making the layers less perceptible.

RESOLUTION

maximum overhang of 30°

clean retraction

REPETITIVE PATTERNS

roughness from connecting regions

roughness from folding

roughness from small movements

^

Figure 14 : Results from experimentation

LH VARIATION

correlation for a continius wall thickness

$$F=E/W*H$$

PRINT PATH NOISE

roughness from low layer height and high flow

cavities from high layer height

roughness from toolpath noise

roughness from direction changes

3.4 DISCUSSION

The experimentation results demonstrate that material behavior in 3D printing is significantly influenced by variations in printing parameters. The classification of results based on specific printing parameters, shows the impact of toolpath design on material roughness.

The discussion that follows examines this found relationship and discusses how these could be implemented towards developing a 3D printing process that enables the control of the roughness of BM-1. And what this controlled process could be applied to in the architectural context.

The experiment results underlined a correlation between parameter variation and BM-1 roughness.

Material property to control

To be sure to choose an adequate application of the material property, it is important to be precise about the material property that is being described. The achieved roughness creates cavities and makes the material fibers more visible. This is thanks to the cellulose in BM-1. This could be interpreted as parameter variation influencing the porosity of BM-1. As any solid material that contains cavities, channels or interstices may be regarded as porous. Therefore, in order to avoid ambiguity, the choice of terminology is important (Rouquerol et al., 1994). To discuss the opportunities of controlling the properties of BM-1, it is necessary to properly define what these cavities and fibrosity contribute to.

A rough surface is not porous unless it has irregularities that are deeper than they are wide (Rouquerol et al., 1994). While roughness is the ratio of the external surface area to the area of the geometrical envelope, porosity is the ratio of the total pore volume to the apparent volume (Rouquerol et al., 1994).

Given the definitions of roughness and porosity, we can conclude that the achieved material behavior from the experimentation refers to the material roughness. Though the presented results show an increase in cavities and fiber visibility, further testing needs to be conducted to conclude that the material is also achieving higher porosity.

As previously discussed in the case study analyses, toolpath variation has a great impact on material properties and thus can be developed as a means to meet architectural needs. From the experiments, it is clear that toolpath variation directly influences surface roughness, a distinctive property of BM-1. Given this correlation, it is important to further analyze the types of roughness that have been achieved. This way, the correlation between parameter manipulation and BM-1 roughness can be understood, and so an adequate application of this material property can be identified.

Dual-scale roughness

Surface roughness is a multi-scale problem (Larsson, 2021). Therefore, it can be described in different scales and amplitudes. This way, for a given form or texture, as we zoom in, small features can be found in small features, referring to different scales of roughness.

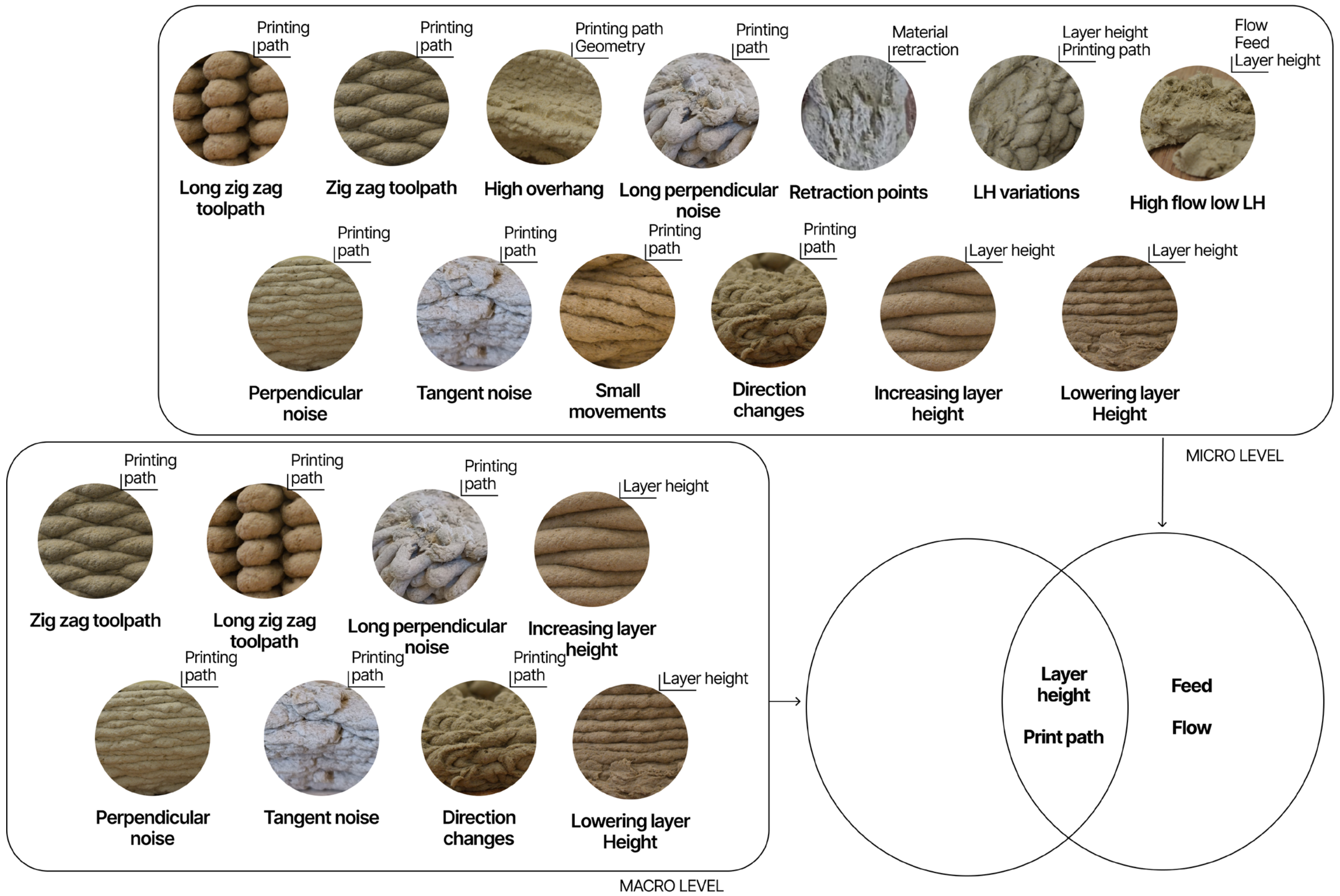
The origin or surface roughness can come from material properties, geometry, use of the surface, or the production technique (Larsson, 2021).

Roughness is a multi-scale property, and so it should be studied considering the different identifiable scales.

Figure 15 displays all of the found irregularities contributing to roughness by parameter type on a micro and macro level. In this visualization, micro-roughness refers to roughness within the material layers, such as visible fibers or cavities. Macro results include those achieved by layer-on-layer manufacturing, pattern formation, and noise within the printing path. Thus, though by adding noise in the printing path the piece becomes overall rough (macro), if we zoom in and also appreciate roughness within the layer we can find roughness on roughness (micro).

With this definition of roughness in two scales, we can conclude that the conducted tests gathered different parameters that affect the roughness of BM-1 on a micro and macro scale. The parameters contributing to macro roughness include horizontal variations in the printing path, and the layer-on-layer topology from 3D printing. For micro-roughness, all these parameters can achieve this roughness scale depending on the layer height, feed, and flow implemented. That is to say, the experiment results indicate that variations in the printing path and layer height affect macro and micro roughness, and that feed and flow variations affect the micro scale.

Therefore, to develop roughness as a controlled property, this process has to be developed by looking into layer height, feed, and printing path variations.



^

Figure 15 : Parameters contributing to the roughness of BM-1 with micro and macro influence

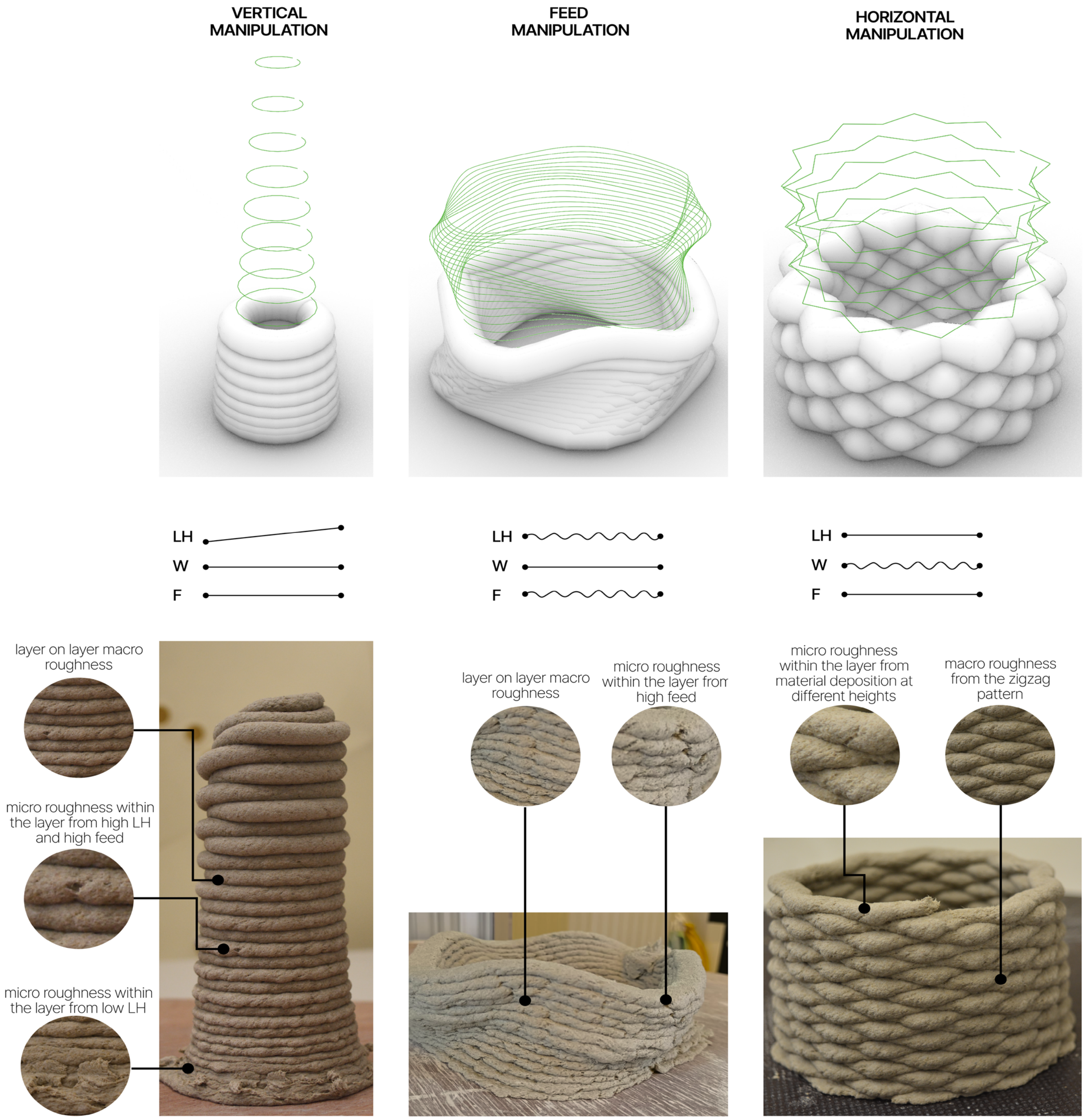
LH, feed, and printing path variation

With this distinction of parameter types, we can divide the parameters contributing to the roughness of BM-1 into three categories. Transformation of target positions in the horizontal plane, variation of the printing feed and thus in the material deposition, and variations in the vertical direction concerning the layer height (Breseghello et al., 2021).

Figure 16 shows the evolution of layer height (LH), print section width (W), and feed (F) during each layer, for three experiments targeting different types of toolpath manipulations. This figure also shows the surface roughness output for these parameter variations.

These parameters influence both the macro and micro scale of roughness in most cases, and thus to be able to develop a 3D printing process that controls the roughness of BM-1 it is important to define specific types of roughness achievable by 3D printing with BM- 1, to avoid ambiguity.

> The control of roughness should be developed by looking into LH, feed, and printing path variations.



^

Figure 16 : Evolution of layer height (LH), width (W) and feed (F) during for different parameter manipulations

Architectural application

One remarkably mentioned application in the case study analyses was architectural acoustics. Furthermore, as mentioned in Chapter 1.3 Materials used for interior walls, acoustic properties are one of the main criteria for interior wall material selection.

In the field of acoustics, surfaces with complex sectional profiles have been shown to possess scattering properties, where the depth and width of undulations affect both the frequency and intensity of scattered sound (Cocks et al., 2023). Further, studies such as by Ciochon et al. (2023) demonstrated the influence of layer-by-layer fabrication on sound absorption. Others, like Zielinski et al. (2022) proved that the absorption of material is influenced by both the material ´s pore structure and the inherent microporosity introduced during the additive manufacturing process.

These studies underline that developing the roughness of BM-1 as an outcome of a 3D printing process could have an application in architectural acoustics.

3.5 CONCLUSION

The main finding of the analyzed experiments is the demonstration that roughness is highly dependent on toolpath design.

The influence of surface roughness on architectural acoustics has been proven by literature. Therefore, developing a process through which the roughness of BM-1 is controlled has a direct impact on architectural acoustics, and so it could be developed to enhance this architectural need.

Furthermore, being roughness a distinctive property of BM-1 that is highly influenced by parameter variation, exploring roughness as a controlled material property could underline the advantages of 3D printing with BM-1.

To develop a controlled process that modifies the roughness of BM-1, and so its acoustic properties, the following questions need to be answered:

> What specific surface characteristics emerge from different toolpath variations?
>
> How can the roughness of BM-1 be controlled?
>
> Do these variations in roughness influence the acoustic performance of BM-1?
>
> Can these toolpath variations enable BM-1 to have similar or better acoustic properties than materials used for interior walls?

CHAPTER 4: ROUGHNESS AS AN ARCHITECTURAL OPPORTUNITY

4.1 DESIGN GOAL

Given the ability of surface roughness to enhance sound scattering and absorption, developing surface roughness with BM-1 presents a promising opportunity for architectural acoustics.

Recognizing this potential, a design goal was formulated to guide the next phase of the project:

*The design goal is to **develop a 3D printing process** through which **the roughness of BM-1 is controlled** and **locally varied** to **achieve material properties of indoor walls** tailored to the needs of the space. By varying the intensity and location of the material **roughness on a micro and macro scale**, the wall´s acoustic characteristics vary. Accordingly, walls can be designed to **enhance acoustic performance** by adapting to the specific functional needs of each space.*

4.2 ACOUSTIC MEASUREMENTS TO TEST

To assess the performance of a specifically designed roughness, physical or digital samples are needed to test at which ranges and with which intensities these configurations perform.

Sound absorption

Regarding sound absorption, acoustic performance measurements are conducted by comparing reverberation time with and without the test sample. The variation in reverberation time determines the absorption coefficient, which quantifies the proportion of absorbed energy relative to the incident energy (Cox & D'Antonio, 2009). The absorption coefficient ranges from 0, no absorption, to 1, full absorption.

To assess the influence of roughness on the absorption coefficient, an impedance tube method was implemented, as it was available within the Architecture Faculty facilities. This method allows for measuring the absorption coefficient considering a normal angle of incidence.

Sound diffusion and scattering

Sound diffusion, on the other hand, is a rather more complex property to measure. The primary way to measure surface reflections is by measuring in terms of polar responses (Cox & D'Antonio, 2009). Moreover, the reflection of a surface can also be characterized by the scattering coefficient. The scattering coefficient measures the ratio of sound energy redirected from the specular reflection direction, while the diffusion coefficient assesses how evenly reflections are distributed in space (Cox & D'Antonio, 2009). In other words, studying sound diffusion is relevant to design uniformly reflected energy, while characterizing scattering allows one to understand the amount of energy that is being scattered from specular angles.

Due to test facility limitations, fiscal tests for scattering measurement could not be implemented in this project. Thus, methods to simulate the polar responses of a surface were considered.

By adopting parametric modeling and computer programming techniques, the scattering performance of surfaces can be integrated into architectural design workflows (Shtrepi, 2019).

Nevertheless, tests simulating the scattering coefficient of a rough surface should include as much similarity to the 3D-printed roughness as possible. Therefore, testing solely 3D models of the piped toolpaths would not be the same as testing the roughness, but only the geometry achieved. Thus, the results would not be representative of the full scattering potential of roughness achieved through toolpath variation. An alternative could be to produce samples and 3D scan them to run scattering simulations. Nevertheless, it can not be guaranteed that a 3D scan records the exact full depth of all the cavities.

Further, since this project aims to design a 3d printed wall with this material behavior applied selectively, when building a full wall, the wall will be sectioned into building units. Adding, therefore, a further layer of macro roughness from the division between blocks. While assembly details have a great impact on acoustic performance (Leschok et al., 2023). Accordingly, the physical separation of single 3D-printed components does not provide full insight into the final performance of the assembled architectural piece.

Conclusion

Though literature indicated that surface roughness has a great influence on sound scattering, this opportunity can not be explored within the scope of this project due to facility limitations. Therefore, focus was placed on measuring the absorption coefficients.

To answer the question of how the variations in roughness influence the acoustic performance of BM-1, sound absorption coefficients were measured with an impedance tube method.

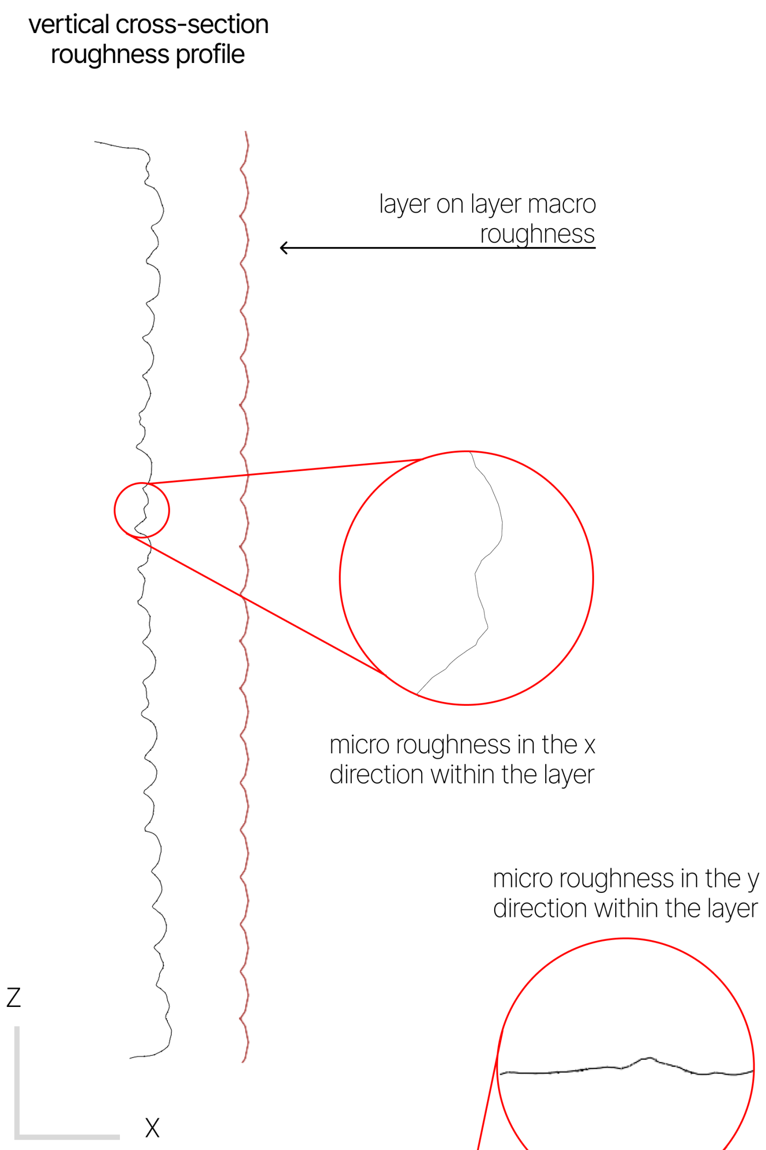
4.2 CHARACTERIZATION OF ROUGHNESS

Before jumping into discussing the influence of roughness on acoustic properties, it is important to fully analyze the achieved roughnesses. When talking about achieving a certain roughness through parameter variation, the parameter itself is the input, and the surface topology is the output. To accurately assess the impact of 3D printing parameters on surface roughness, it is essential to characterize the surface topology.

Within 3D-printed walls, roughness can be observed in a vertical and horizontal manner. Analyzing the cross-section of a rough surface helps to fully characterize the achieved roughness.

When analyzing a vertical cross-section of a wall 3D printed with BM-1, two types of roughnesses can be found. On a macro scale, the layer-on-layer roughness derived from additive manufacturing, and on a micro scale roughness within the layer as a result from layer height, feed, or flow variation (Fig. 18).

Further, looking at a horizontal cross-section of a layer of a wall 3D printed with BM-1 with no transformation of target positions in the horizontal plane, micro-roughness can be present. This micro-scale roughness within the layer can appear as a result of layer height, feed, or flow variation (Fig. 18).



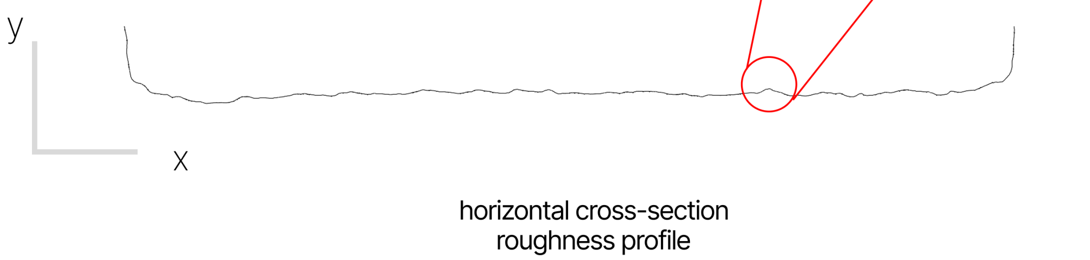
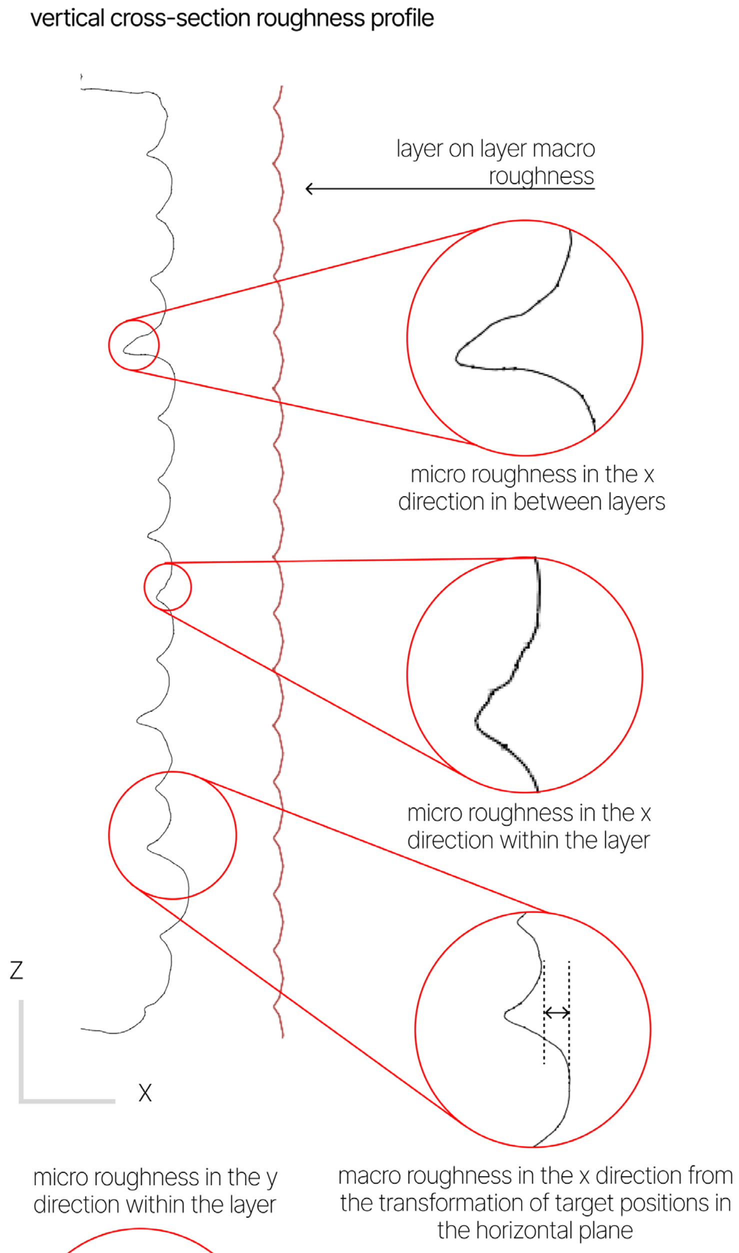


Figure 18 : Vertical and horizontal cross-sections roughness profiles of a wall vertically printed with BM-1 >

If horizontal printing path modifications are added, multiple additional types of roughnesses can occur in both the horizontal and vertical roughness profiles. In the vertical cross-section, macro roughness in the x direction can be present from variations in offsets of the target horizontal positions. Further, micro-roughness can also be present in between layers from increases in the material deposition height from the variations in position.

In the horizontal roughness profile, macro roughness in the y direction from the transformation of target positions in the horizontal plane is also present.

From this analysis of the cross-sections of walls printed with BM-1, it is clear that more irregularities contributing to roughness occur as printing path variations are implemented.



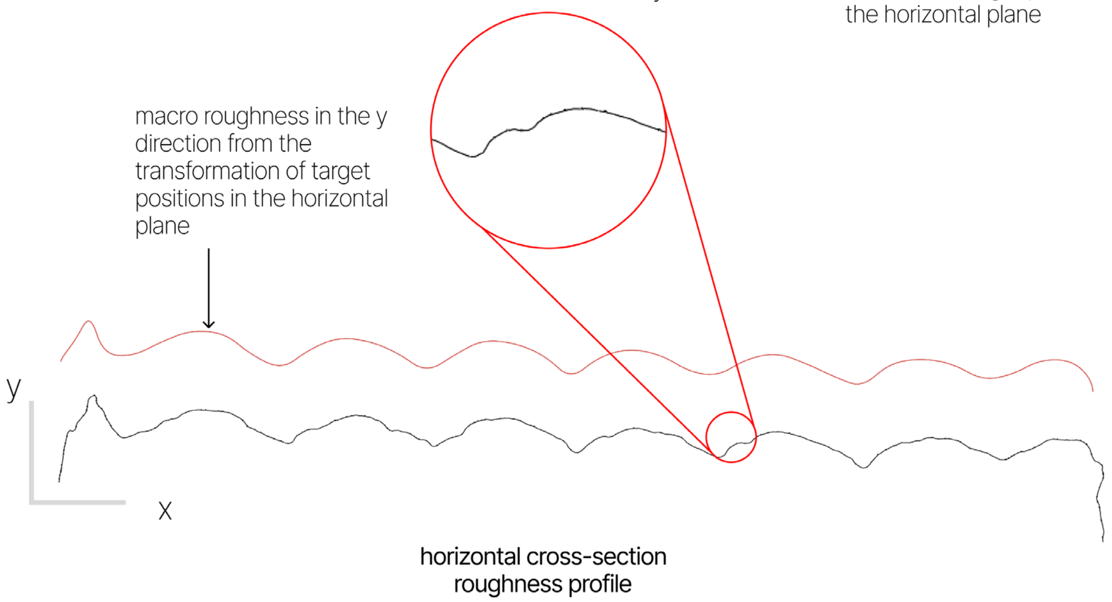
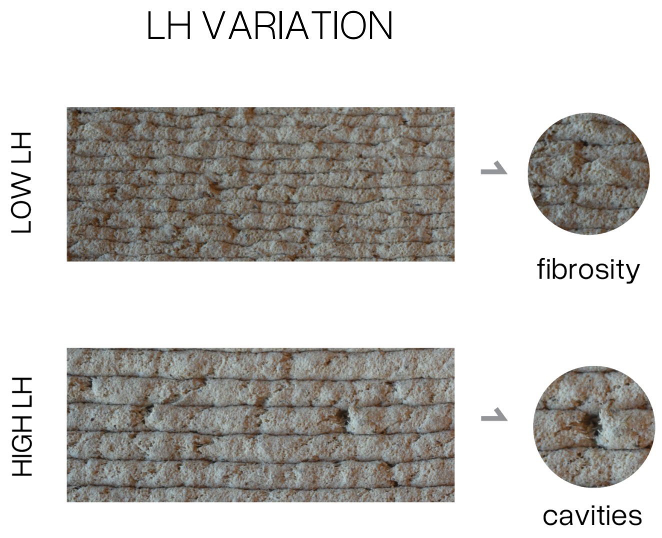


Figure 19 : Vertical and horizontal cross-sections roughness profiles of a wall vertically printed with BM-1 with horizontal modifications >

The listed roughnesses are caused by different toolpath variations. Next, the influence of the different 3D printing parameters on surface roughness will be discussed.

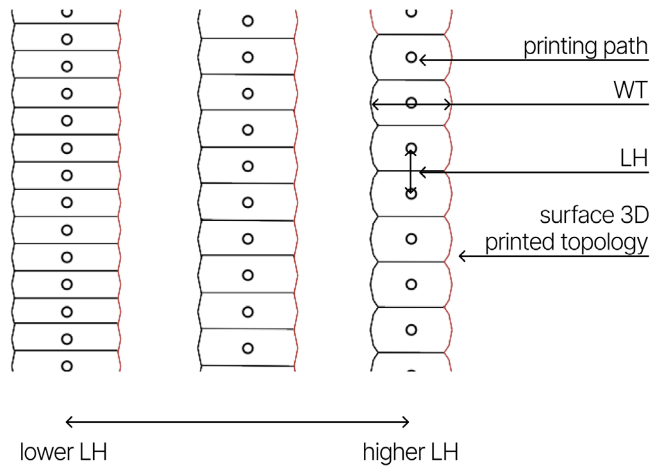
Roughness from LH variation

When printing at constant feed and flow rates, an increase in layer height reduces the wavelength of the surface undulations formed by layer connections. Additionally, the cross-sectional shape of the layers becomes more circular, whereas lower layer heights result in flattened cross-sections. Very low layer heights introduce roughness within each layer due to the material being compressed into the previous layer over a short distance, making the material fibers more pronounced. Very high layer heights can also contribute to roughness by creating small voids between layers, as a higher material flow rate is required to maintain a continuous layer deposition.



^

Figure 20 : Roughness in low and high layer heights

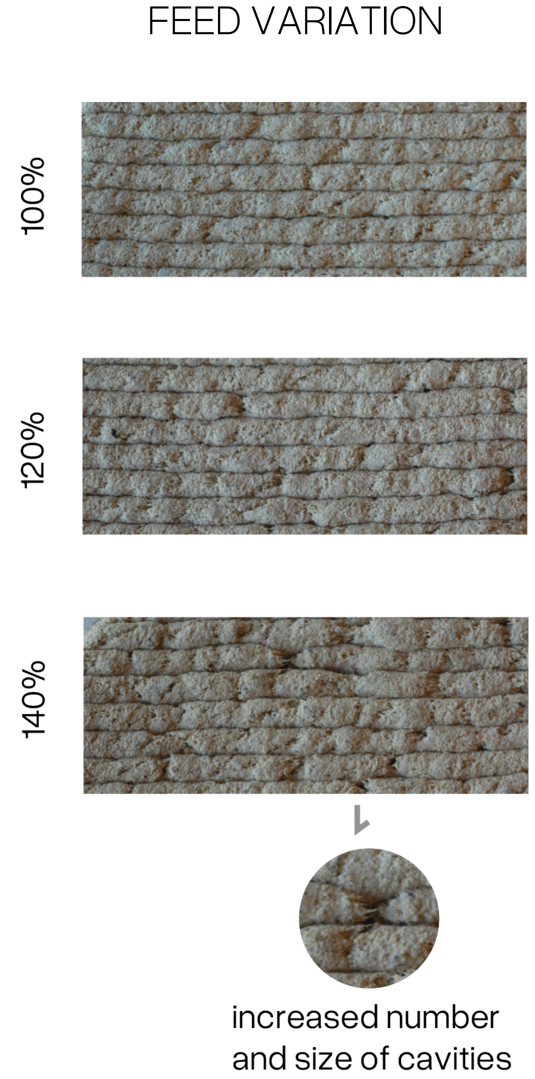


^

Figure 21 : Section of vertically 3D-printed parts with different layer heights

Roughness from feed variation

The higher the feed, the less material is deposited, and thus high feeds lead to gaps within the layer, while very low feeds compress the layers and make the material fibers more visible.

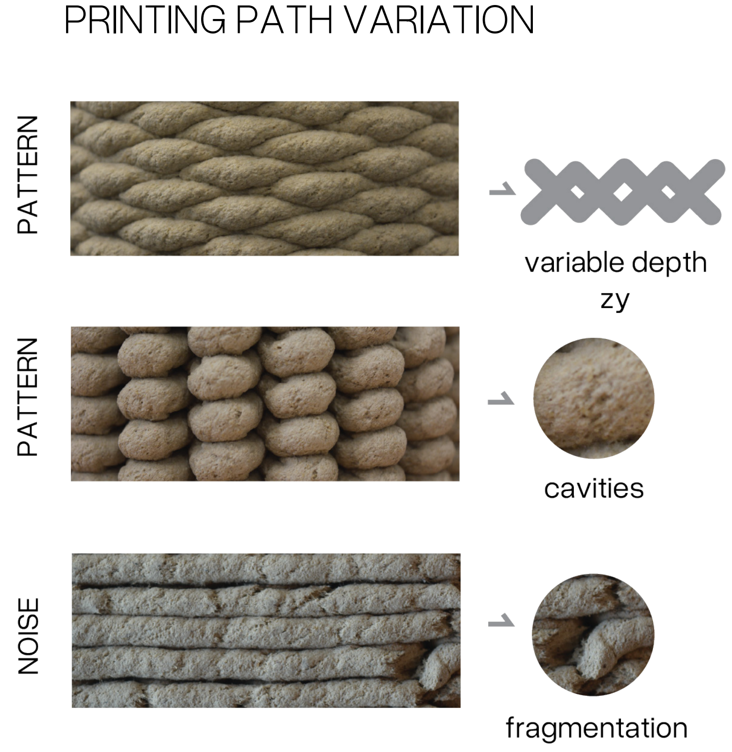


^

Figure 22 : Cavity formation due to feed increasement

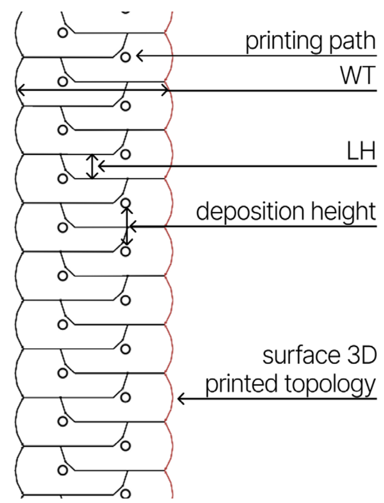
Roughness from printing path variation

Printing path variations can add roughness in the zy plane by varying depths due to variations in position. Further, moving toolpath points horizontally, leads to the material being deposited at a higher distance causing cavities. If these moves are repeated skipping layers, the deposition height increases even more, causing layer fragmentation.



^

Figure 23 : Cavity formation due tprinting path variation



^

Figure 24 : Section of vertically 3D-printed parts with horizontal target position variations

Conclusion

Figure 25 shows a summary of the identified irregularities contributing to roughness for different toolpath variation types. These characteristics describe the details that contribute to different types of topologies and thus influence the acoustic performance of a surface.

This way, when analyzing results from acoustic measurements, these identified characteristics derived from parameter variation, are the ones causing a certain acoustic behavior.

ROUGHNESS CAUSED BY LH VARIATION

LOW LH

- higher number of undulations of the topology
- flattening cross-sectional shape of the layers
- higher fibrosity within the layer due to material compression

HIGH LH

- lower number of undulations of the topology
- more circular cross-sectional shape of the layers
- cavities within the layers

ROUGHNESS CAUSED BY FEED VARIATION

LOW FEED

- higher fibrosity within the layer due to material compression

HIGH FEED

- cavities within the layers

ROUGHNESS CAUSED BY PRINTING PATH VARIATION

- variable depths
- layer fragmentation
- cavities due to higher deposition height

^

Figure 25 : Roughness by parameter type

4.3 CONTROLLING ROUGHNESS

The design goal is to develop a 3D printing process through which the roughness of BM-1 is controlled and locally varied. Once the characteristics of the different achievable roughnesses through a 3D printing process with BM-1 become clear, how to control these becomes relevant.

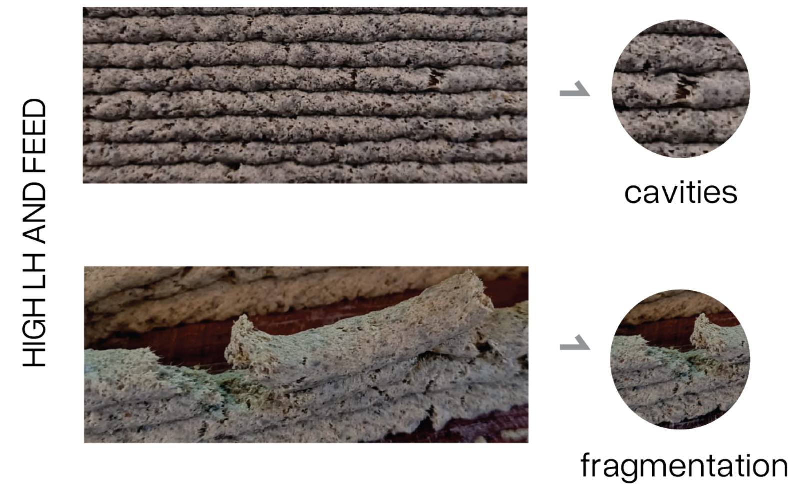
As defined by the design goal, the roughness of BM-1 should be controlled to modify acoustic properties. More specifically, sound absorption.

The absorption coefficient of porous absorbers is defined by their density and incidence angle (Long, 2014), and as the thickness increases, so does the absorption coefficient at low frequencies (Cox & D ´Antonio, 2009). Therefore, for the context of sound absorption, we should aim to generate cavities, layer fragmentation, and depth increase.

The problem with high layer height and feed

High layer heights and high feeds achieve cavity formation. When the lack of material rather than generating cavities, fully separates the layer into different segments, this roughness would be considered layer fragmentation.

Layer fragmentation can easily become a printing process failure without the correct settings. Furthermore, the higher the layer height the smallest the wall thickness, and the higher the feed the bigger the layer segmentation, resulting in weak walls. Applying a high LH and Feed would mean compromising the strength of the wall. Therefore, alternatives to implementing the achieved roughness while keeping the wall strong must be considered.



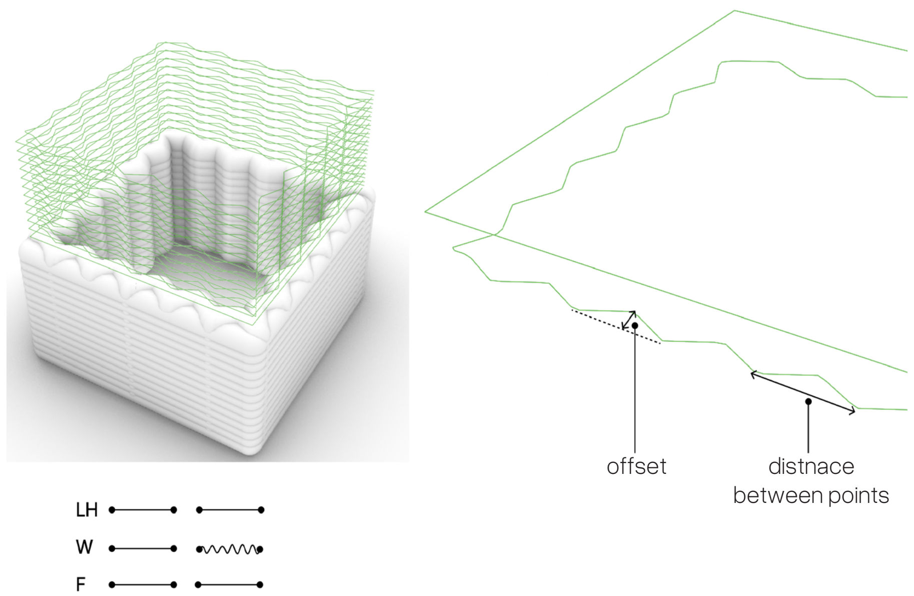
^

Figure 26 : Cavities and fragmentation due to high LH and feed

Layer fragmentation from printing path variations

The approach to arbitrarily applying different roughnesses should be able to achieve walls capable of withstanding vertical loads, while integrating roughness locally and within a desired range.

Cavity generation and layer fragmentation can be achieved through keeping a constant layer height and feed rate, and varying positions in the printing path for every other layer. This way, the material being deposited at the surface of the wall is being placed at double the layer height and generating cavities. Figure 27 shows the evolution of layer height (LH), print section width (W), and feed (F), for every two layers.

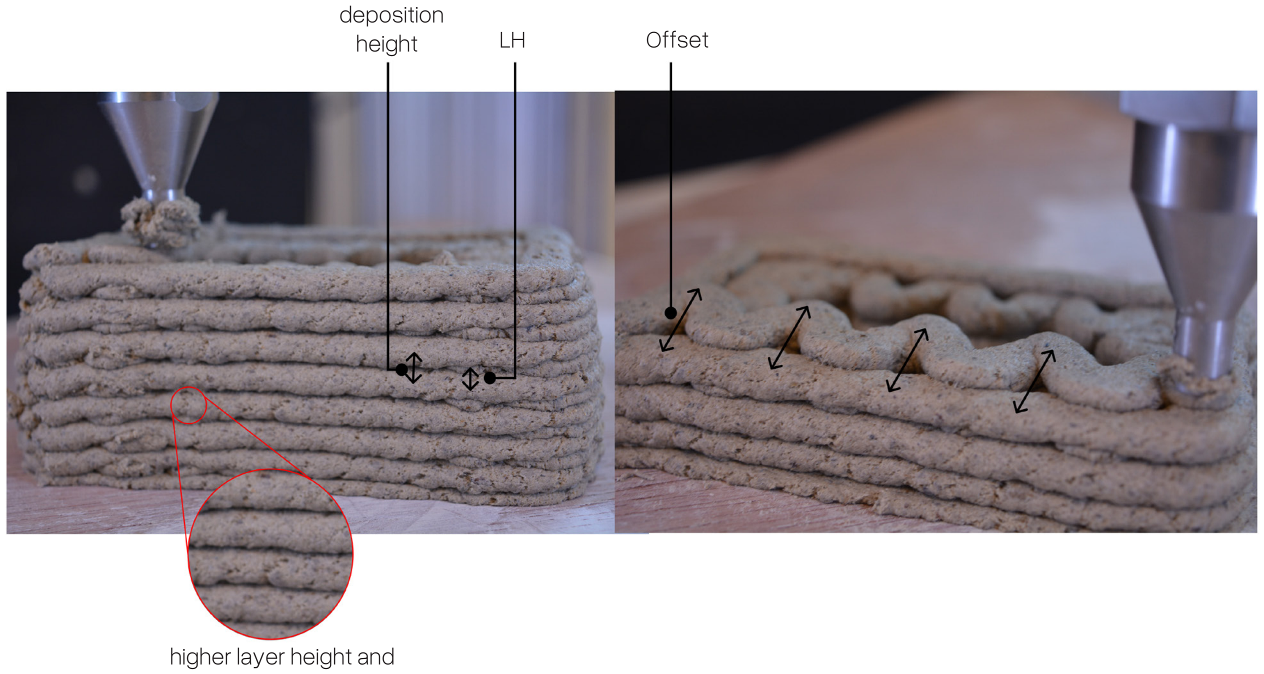


^

Figure 27 : Toolpath for cavity generation through horizontal printing path variation

Roughness through printing path variation

This approach leads to different topologies on each side of the wall. Figure 29 shows two types of roughnesses achieved with the same toolpath. (A) Shows the face of the wall points are extracted from. (B) The other side of the wall where a pattern is created as a result of the points offsetting.



^

Figure 28 : Printing path manipulation approach for cavity formation

^

Figure 29 : Two sides of the wall

If we analyze the 2D cross-sections of both sides of walls, we see multiple types of roughnesses manifested. In the vertical cross-section, two different regions can be recognized, the ones where points have an offset, and the ones that do not. The macro roughness is more pronounced in regions where there is an offset as the is a bigger depth between layers.

On face B no material segmentation is shown. While in face A micro material cavities and layer segmentation are present in the areas where points are offset. Moreover, variations in the z direction can be present as an outcome of gaps between layers.

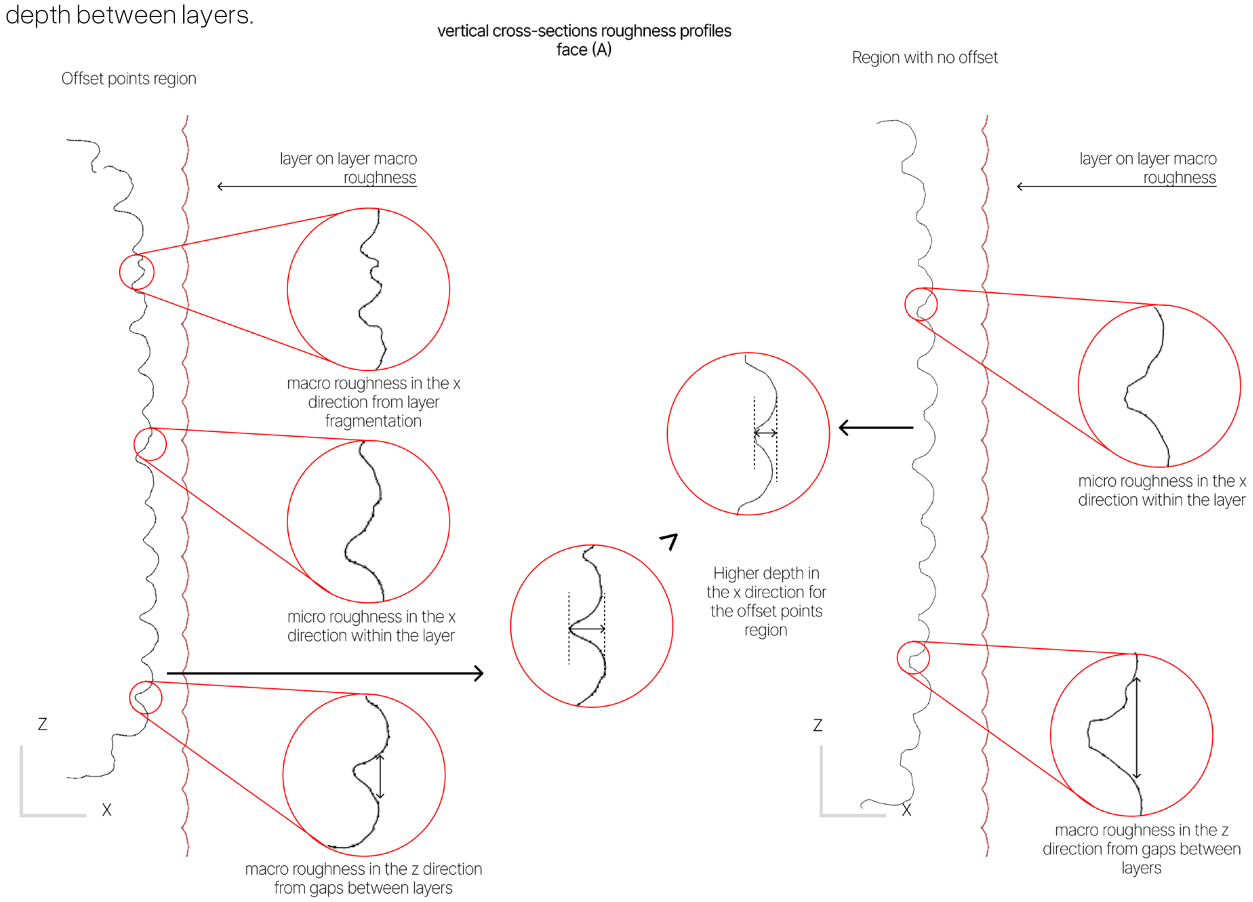


Figure 30 : Vertical > cross-section roughness profile of side A

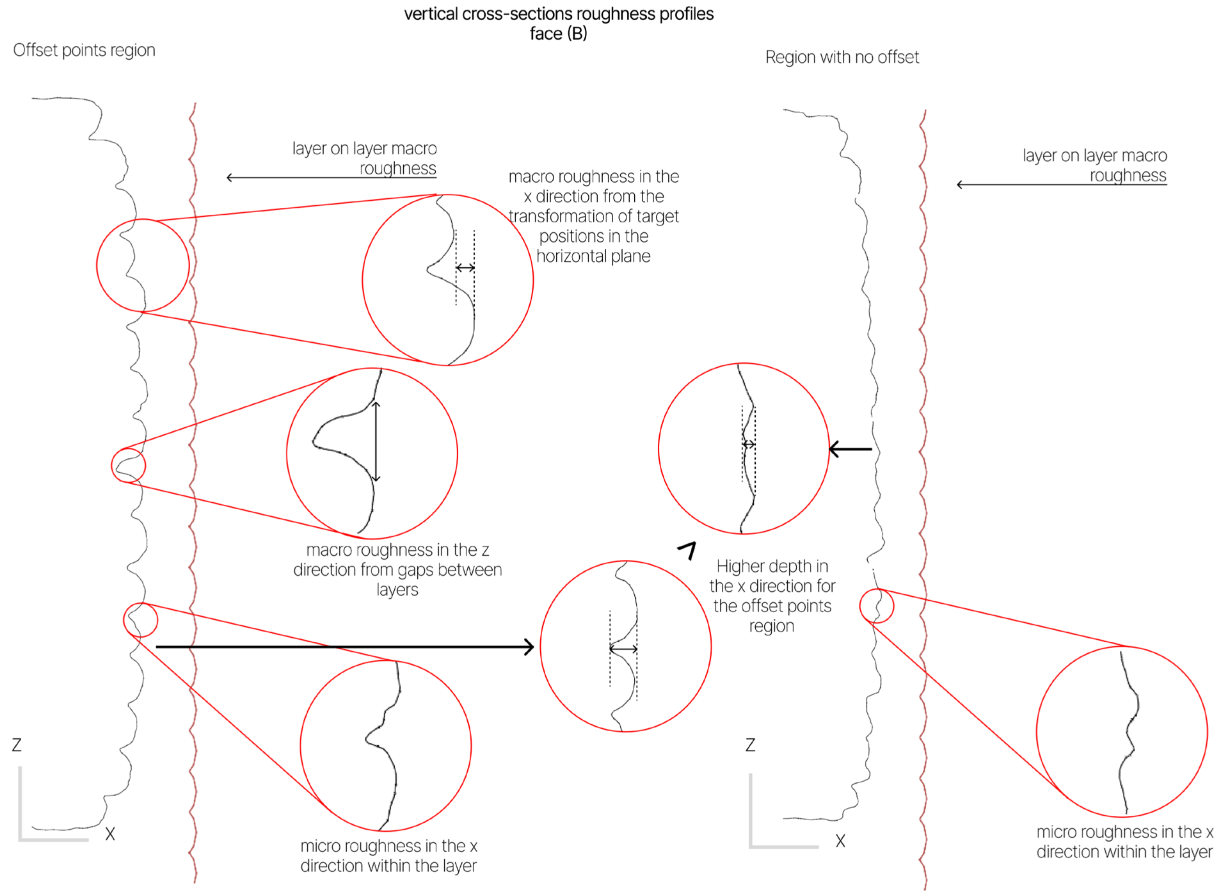


Figure 31 : Vertical > cross-section roughness profile of side B

In the horizontal roughness profile, macro roughness in the y direction from the offsets can be seen in face B. These horizontal manipulations are also visible in the in-between layers of side A. Furthermore, layer segmentation only occurs in face A.

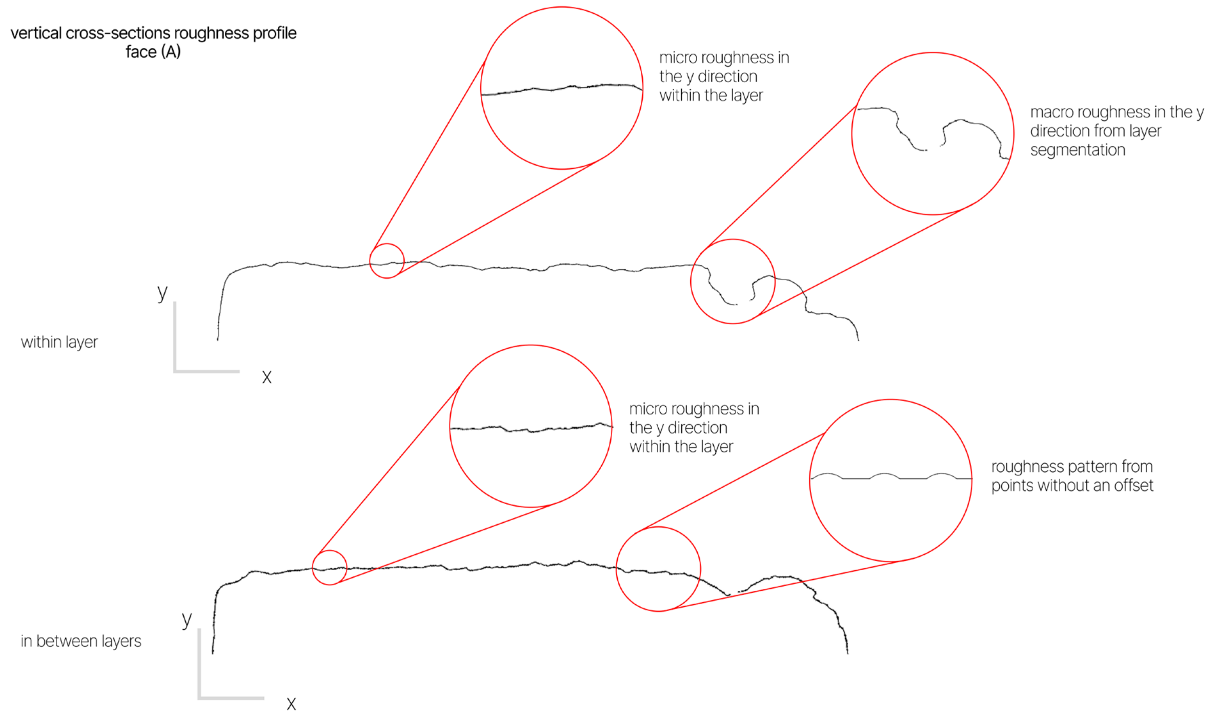


Figure 32 : Horizontal > cross-section roughness profile of side A

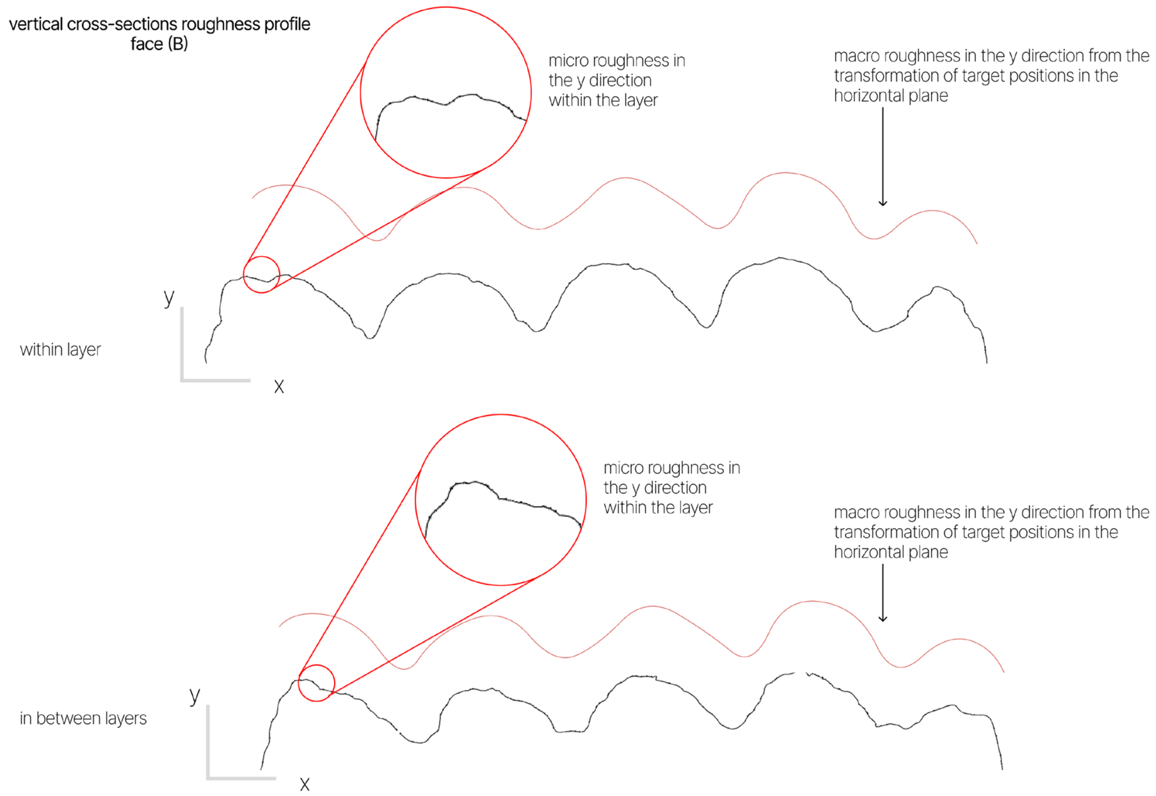


Figure 33 : Horizontal > cross-section roughness profile of side B

Figure 34 displays a summary of the identified roughnesses for this approach to controlling roughness. Here, it is visible that this approach achieves all of the roughnesses that can be achieved through LH, feed ,and horizontal variation. While this approach only modifies the point´s positions for every other layer.

ROUGHNESS CAUSED BY PRINTING PATH VARIATION

SIDE A	SIDE B
gaps between the layers	gaps between layers
layer fragmentation	macro roughness in the y direction from point offsets
roughness pattern from points without an offset	variable depths
variable depths	cavities due to higher deposition height
cavities due to higher deposition height	

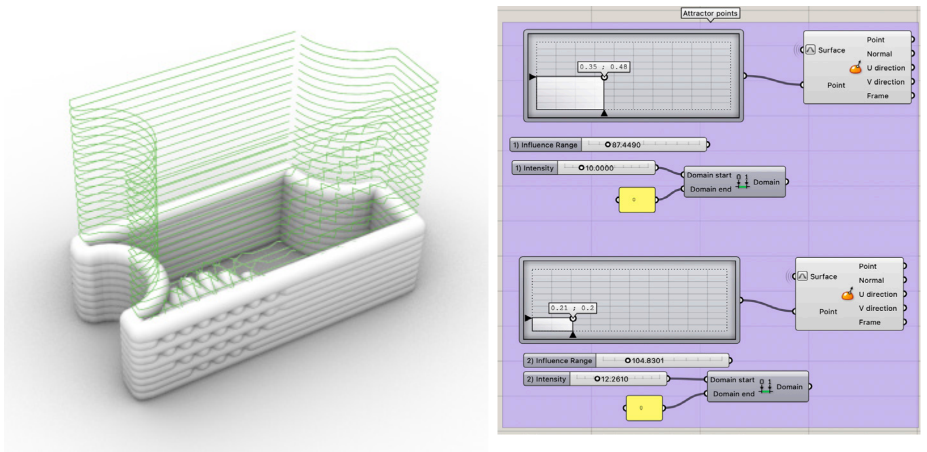
^

Figure 34 : Roughness caused by printing path variation

Location and intensity control

In order to apply the roughness locally and within a desired range, these horizontal target position variations should be applied only where indicated.

A common approach to generating patterns parametrically at specific locations and ranges is through attractors. This approach allows to create a parametric code where the offset of the points is dependent on their distance to a defined point or curve. This way the offsets are applied at a gradient, and so it is ensured that layers don´t collapse and air printing is avoided when defining big offsets. Figure 35 shows the designed toolpath variation for two attractor points. As displayed, with this approach three parameters define the final toolpath variations. The points where the roughness should be applied. The range of influence from those points, defining at what radius length the offset gradient should start. And the intensity, defining how big of an offset should be applied.



^

Figure 35 : Control of printing path variation through attractor points

4.5 PREDICTIONS AND QUESTIONS FOR ACOUSTIC TESTING

Since the achieved roughnesses have been characterized in the previous chapter, now a hypothesis can be formulated to what the results from the absorption coefficients might be.

It is expected that the higher the amount of cavities, the lower the density of the material, and the higher the depth of the sample, the higher the absorption coefficient.

This way, according to the achieved irregularities per toolpath variation, the higher the layer height and the lower the feed, the higher the absorption coefficient.

And, the higher the offset depth and the lower the density of points, the higher the absorption coefficient.

The previously identified roughnesses per toolpath variation and the test result predictions are displayed in Figure 36. The highlighted settings are the ones predicted to achieve the most absorptive results.

ROUGHNESS CAUSED BY LH VARIATION

LOW LH

- higher number of undulations of the topology
- flattening cross-sectional shape of the layers
- higher fibrosity within the layer due to material compression

HIGH LH

- lower number of undulations of the topology
- more circular cross-sectional shape of the layers
- cavities within the layers

ROUGHNESS CAUSED BY FEED VARIATION

LOW FEED

- higher fibrosity within the layer due to material compression

HIGH FEED

- cavities within the layers

ROUGHNESS CAUSED BY PRINTING PATH VARIATION

SIDE A

- gaps between the layers
- layer fragmentation
- roughness pattern from points without an offset
- variable depths
- cavities due to higher deposition height

SIDE B

- gaps between layers
- macro roughness in the y direction from point offsets
- variable depths
- cavities due to higher deposition height

^

Figure 36 : Predictions of most absorptive configurations

With these predictions, the following chapter will aim to answer the following questions:

Does the variation of roughness as an outcome of a 3D printing process influence the absorption coefficients of BM-1?

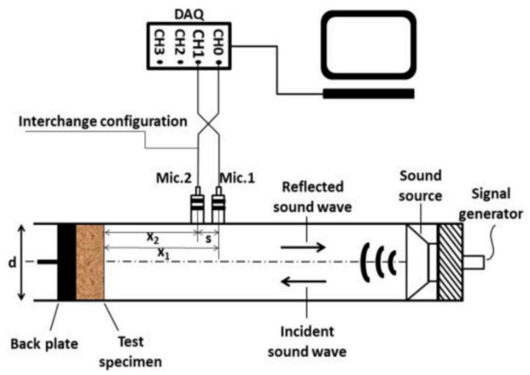
Are the defined predictions derived from the roughness characteristics correct?

Can these toolpath variations enable BM-1 to have similar or better acoustic properties than materials used for interior walls?

CHAPTER 5: INFLUENCE OF ROUGHNESS ON ACOUSTIC ABSORPTION

5.1 IMPEDANCE TUBE METHOD

To test the influence of the LH, Feed and printing path variations in the absorption coefficient of the material, a two-microphone impedance tube mechanism method was implemented. The impedance tube method is a widely recognized technique for evaluating the sound absorption performance of acoustic materials (Tie et al., 2020). This method requires relatively small test specimens, for 29 mm in diameter specimens high-frequency tests (>2000 Hz) can be conducted, and for larger specimens of 100 mm in diameter low-frequency tests can be run (≤2000 Hz).



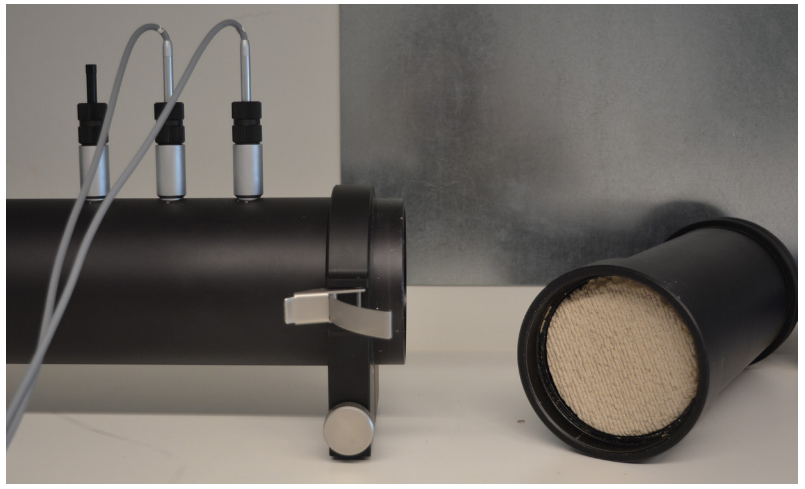
^

Figure 37 : Schematic diagram of impedance tube and measurement setup (Aslan & Turan, 2020).

In an impedance tube, the test specimen is placed at one end of the tube, and a sound pressure wave, produced by a signal generator is directed to the test specimen. Upon striking the specimen, part of its energy is absorbed, and the wave returns with a reduced amplitude (Aslan & Turan, 2020). By measuring the sound pressures detected by two microphones, the transfer function is derived, allowing for the calculation of the sound absorption coefficient. This method is called the standing wave method, where the absorption coefficient is calculated from the measured transfer function from the two microphones (Tie et al., 2020). Figure 37 shows the schematic diagram of the impedance tube and measurement setup.

Data processing

The data gathered from the impedance tube was processed using the PULSE Material Testing system. This software calculates the acoustic properties of the material from the differences between the signals and provides a graph of the recorded values.

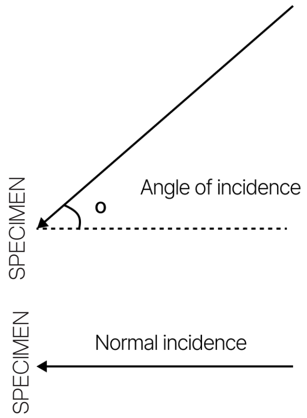


^

Figure 38 : BM-1 sample in impedance tube

Angle of incidence

Impedance tube measurements determine the absorption coefficients considering a normal incidence. That is to say, the sound waves directly hit the specimen with 0 degrees of inclination. The absorption coefficients are highly dependent on the angle of incidence, as when variating the angle of incidence the apparent depth of the material varies and thus the measurement results (Long, 2014). Therefore, it is important to address that the recorded results do not represent other angles of incidence.



^

Figure 39 : Angle of incidence

Reliability

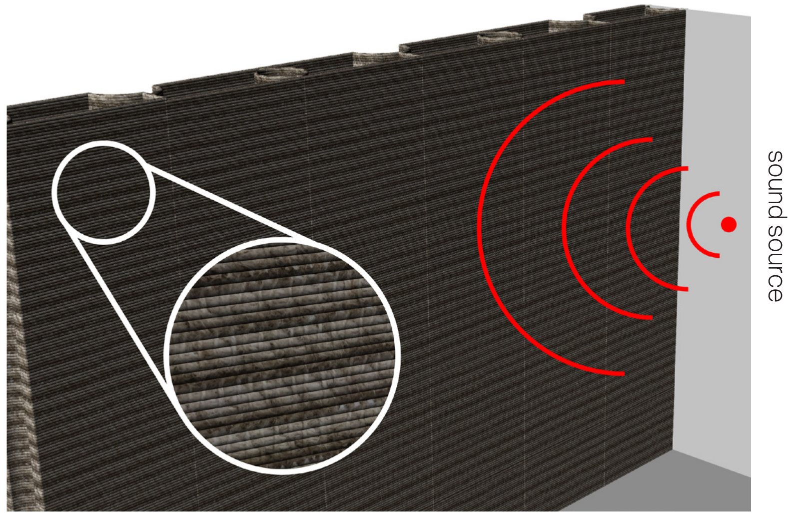
Furthermore, as the achieved roughnesses are not replicable and every sample will have cavities and inconsistencies at variable locations and sizes, it is important to test the replicability of the recorded absorption coefficients. For this multiple samples with the same settings should be produced and tested to compare the measured results. And thus understand how replicable the results are when reproducing a specimen.

Moreover, the main issue with the reliability of a scale relates to the scale's internal consistency, which indicates how well the items within the scale are connected (Aslan & Turan, 2020). Thus, it is essential to examine whether all items are measuring the same underlying concept. To do so, the degree of relationship between various tests or measurements conducted for the same scenario should be analyzed (Aslan & Turan, 2020). In this case, to assess the repeatability of the experimental measurements, each sample was measured three times.

5.2 SAMPLE PREPARATION

Layer orientation
In a 3D-printed wall, sound sources would be directed perpendicular to the layers (Fig. 40). Accordingly, the test specimens should be extracted from vertically printed samples.

To achieve the closest sample properties to those of a vertically printed wall, the test specimens were extracted from vertically printed samples. To shape them into the dimensions of the impedance tubes, molds were designed. These molds were designed to shape the specimens to fit the impedance tube dimensions. Also taking into consideration sample shrinkage during the drying process (around 5%) and the need for a precise fit within the tubes to prevent vibrations during testing.



^

Figure 40 : Layer orientation

Sample placement
To test a specimen, the specimen has to be placed inside the impedance tube at a height matching the top circumference of the impedance tube. When it comes to samples with varying heights, the top circumference of the impedance tube was matched with the lowest side of the surface.

^

Figure 41 : Placement of a flat sample

^

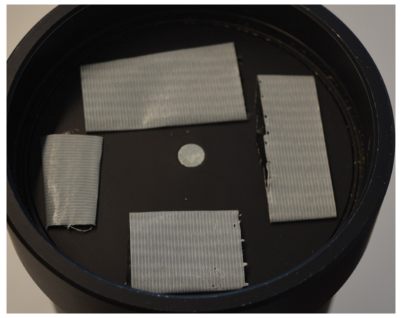
Figure 42 : Placement of a sample with depth variations

Dealing with imperfections
Further, due to mistakes during production some samples left small gaps between the sample and the tube could occur. To avoid influence from this in the testing, these were covered with wet material. Nevertheless, since these gaps and covered parts can alter the recorded absorption coefficients, this approach was used minimally, thus samples with too many gaps were discarded.

Additionally, for the thinnest samples to avoid vibration the specimens were taped to the bottom of the tube.

^

Figure 43 : Wet material to fill in gaps



^

Figure 44 : Tape to avoid vibration of thin samples

5.3 SPECIMENS

In this chapter, the test specimens to test for sound absorption are presented. The next pages display all of the test specimens.

Layer height variation
Five test specimens were produced varying the layer height by 0.5 mm from one sample to another.

Feed variation
Three test specimens were produced varying the feed rate from one sample to another. The samples were produced at 40%, 60% and 80% feed rates.

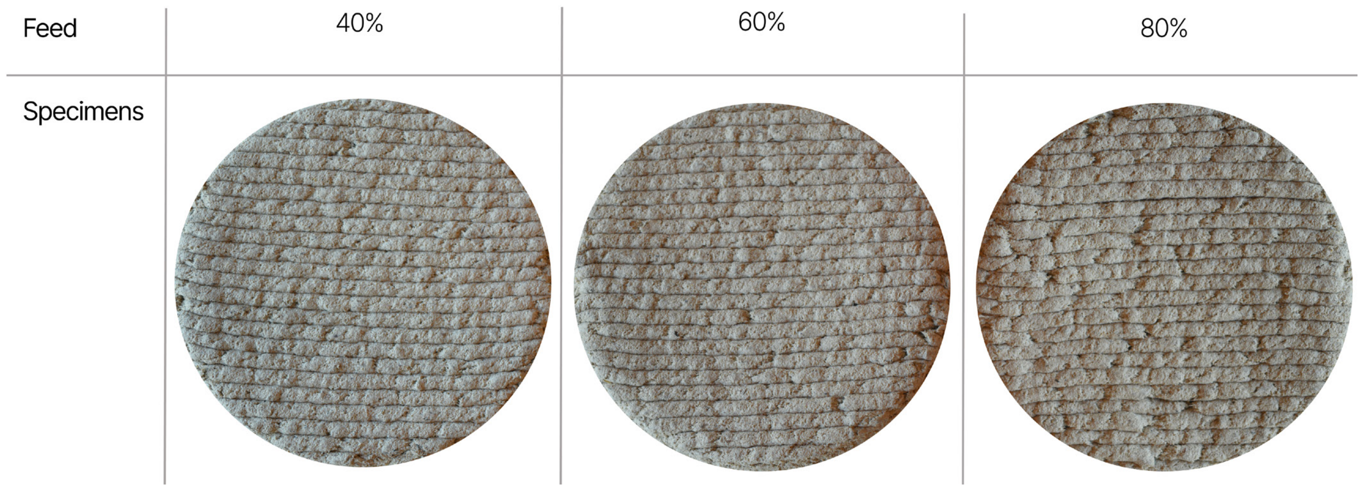
Printing path variation
In terms of horizontal printing path variations, two types of variation were generated.

The offset of the moved points and the density of points in the offset pattern. This is because these two parameters influence the depth and density of the samples, two aspects that as previously mentioned are defining for absorption.

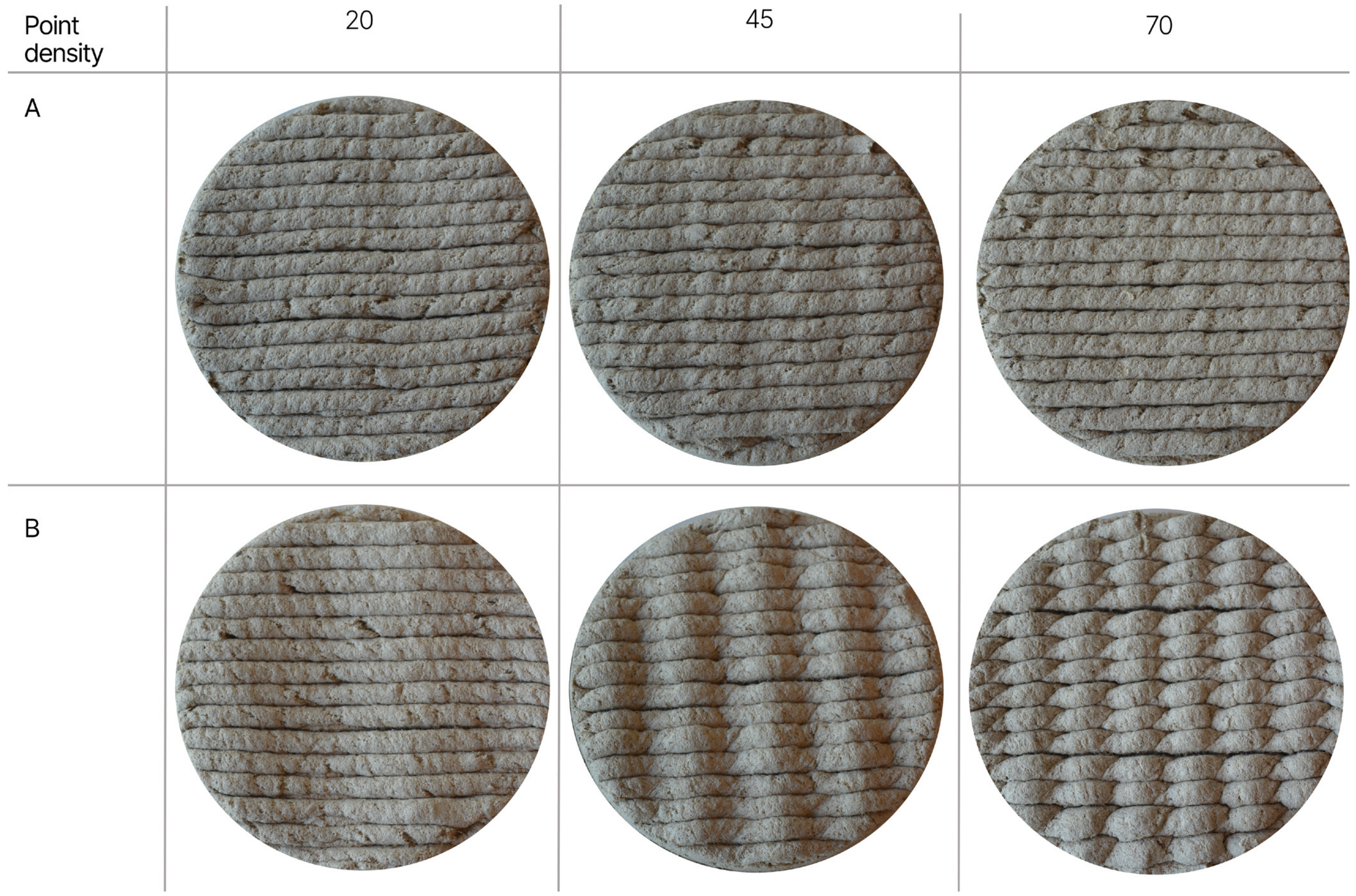
Three different offset depths of 5, 10, and 20 mm were tested. And three point densities of 20, 45, and 70.

Further, as the different sides of the wall are expected to have a different impact due to their different topologies, these configurations were tested for both wall sides.

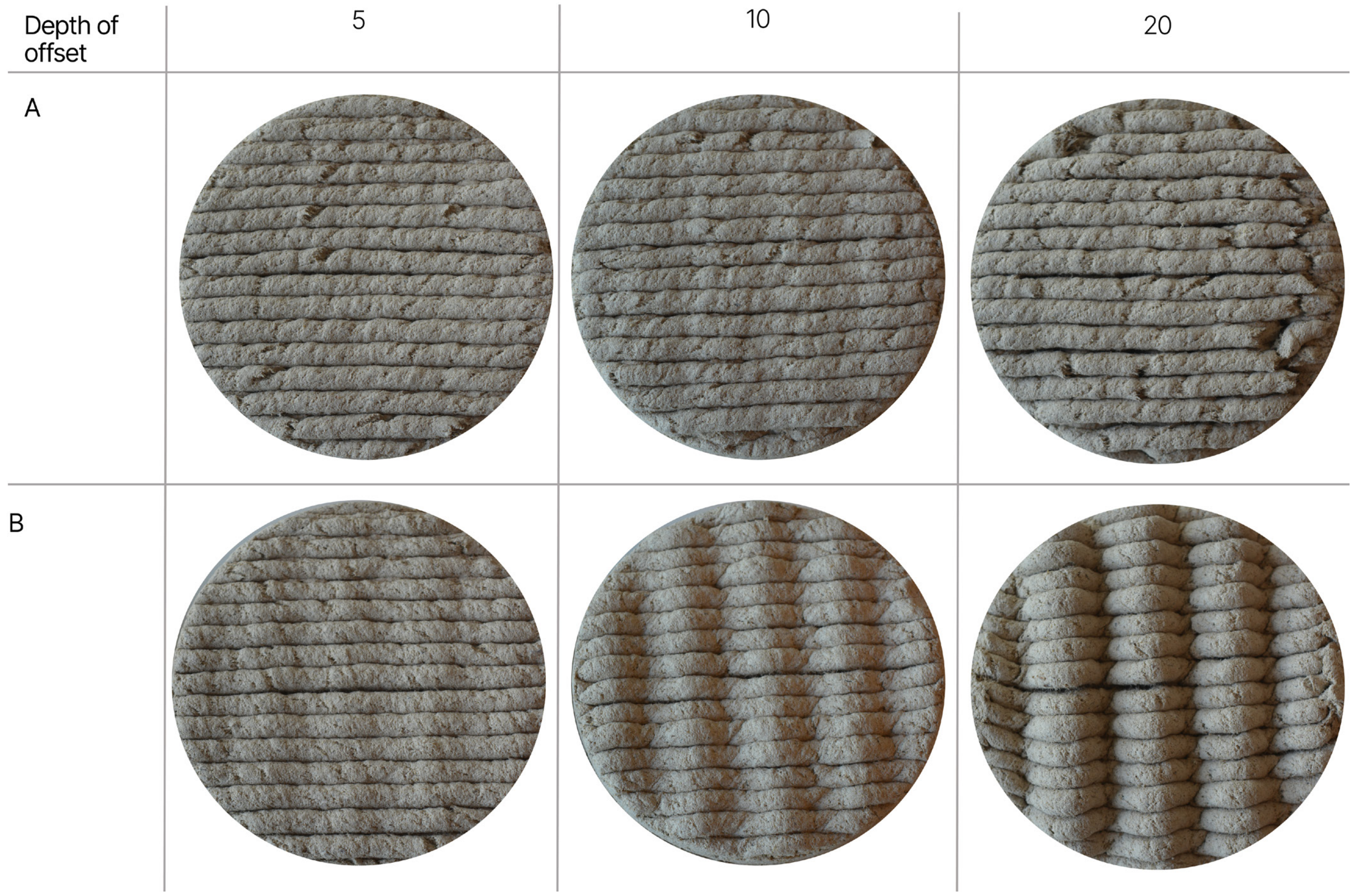
^
Figure 45 : LH variation specimens



^
Figure 46 : Feed variation specimens



^
Figure 47 : Density of points variation specimens



^
Figure 48 : Depth of offset variation specimens

5.4 RESULTS

Reliability of results

Regarding the specimens produced to test at mid-low frequencies, for very tightly fitting samples, the specimens were less prone to vibration. And so the deviation from one measurement to another was very small or even null. Nevertheless, for samples that did not fit perfectly and were also very thin, specimens were more prone to vibration. Accordingly, replacing the same sample and measuring a second time, produced a notable deviation as well as peaks in the results due to sample vibration.

In terms of specimens produced with exactly the same settings to test the repeatability of results, for two samples with LH3, the deviation from one sample to another was quite small, and thus the internal consistency of the results is reliable. On the other hand, for three samples with LH4, the deviation from one sample to another was visibly big, indicating that the internal consistency of the results is rather questionable, and the deviation of the measurement results from one sample to another underlines the poor replicability of the samples.

For the samples produced for high-frequency testing, replacing the same sample and measuring a second time, produced a notable number of peaks in the results. Nevertheless, the underlying behavior was rather constant with a few around 100Hz deviations. Furthermore, there was not as a strong coherence between samples produced with the same settings and tested separately.

A more detailed analysis of the reliability tests can be found in Appendix 3.

Mid-low frequencies

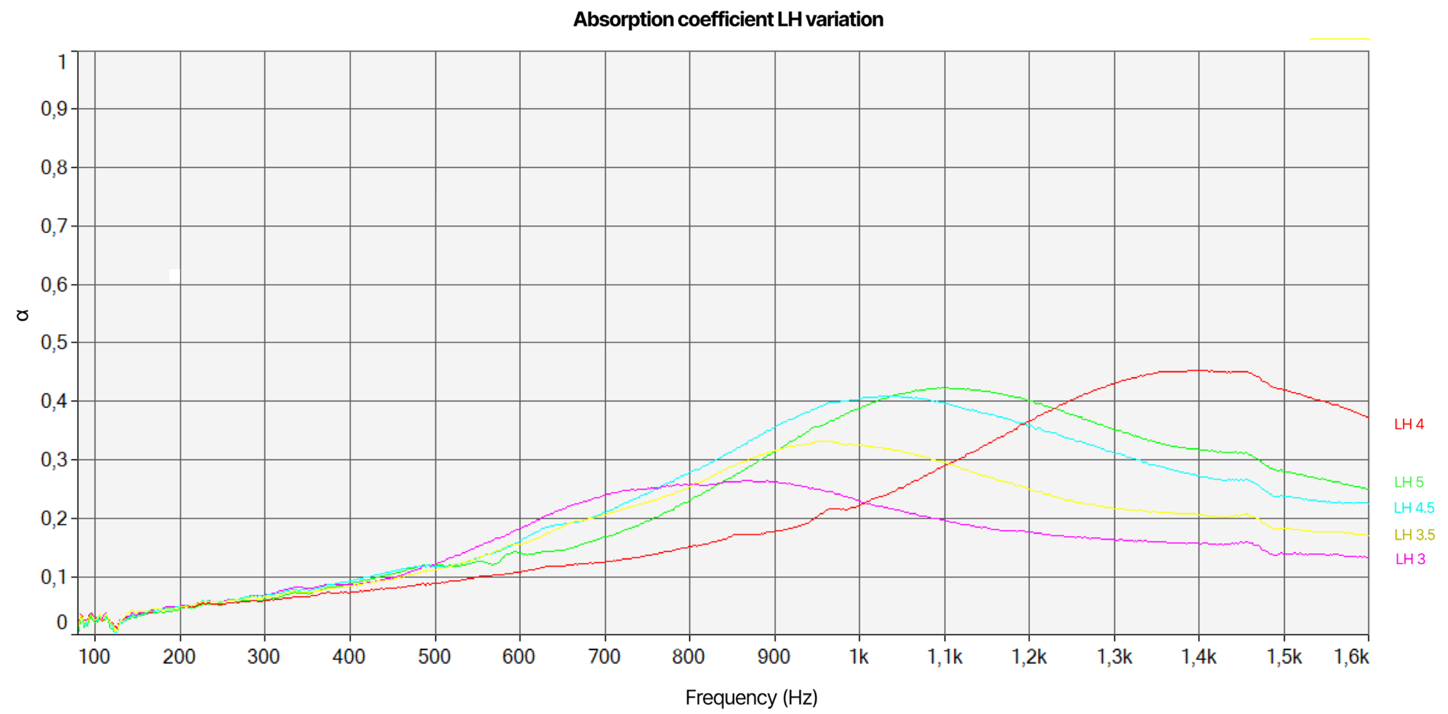
LAYER HEIGHT

Figure 49 shows the recorded absorption coefficients in mid-low frequencies, varying from one sample to another only the layer height.

From the recorded results, for the mid-low frequency range a tendency for the increase of the absorption coefficient as the layer height increases can be seen. Nevertheless, due to the already discussed vibration recorded for the samples with LH 4 mm, this result presents the highest absorption coefficient on top of the highest layer height (5 mm). Further, the highest absorption of 0,4 occurs from 1 to 1,2 kHz for samples with 4.5 and 5 mm layer height.

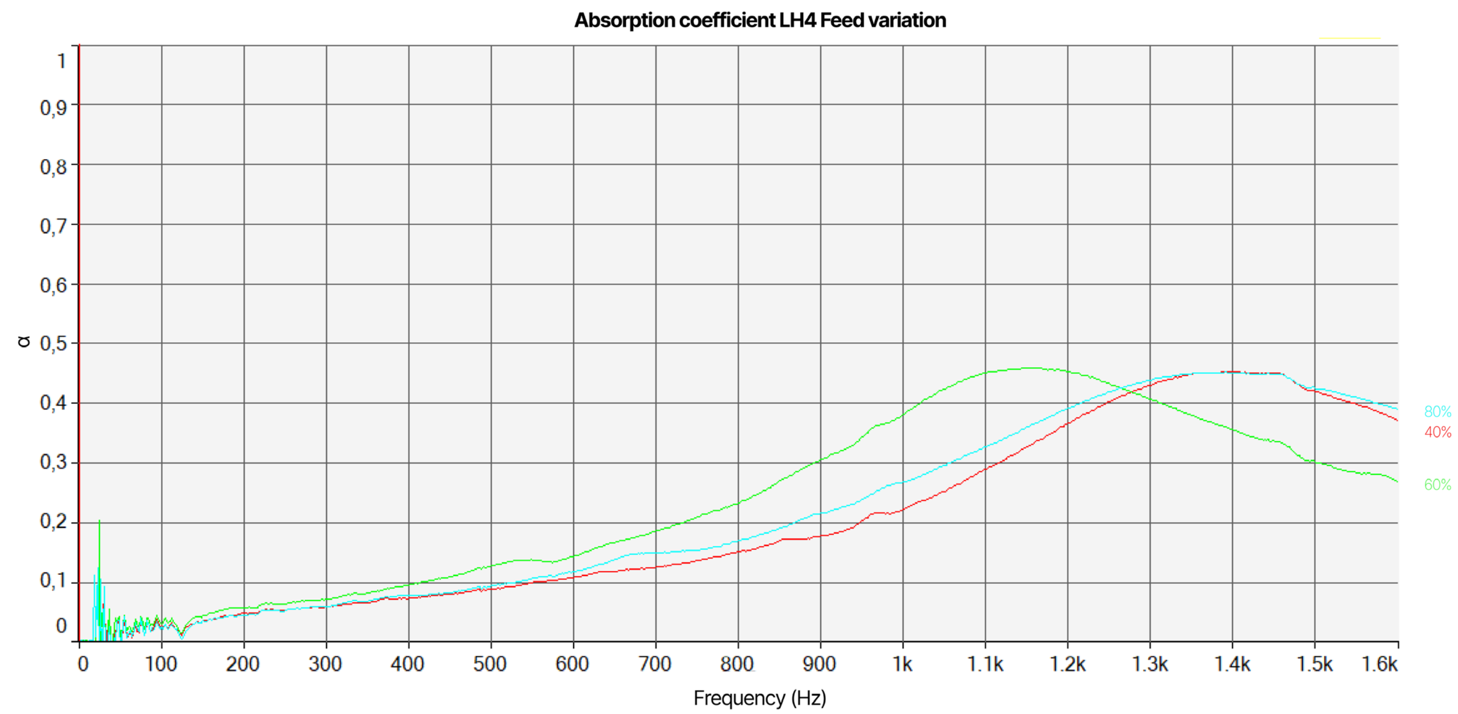
FEED

Figure 50, shows the absorption coefficients for three samples with LH 4 mm and with feed rates of 40%, 60% and 80%.. The samples produced with a very high feed (80%) led to a thin and weak sample that did not fit tightly in the impedance tube. The repetition in measuring absorption coefficients for the same sample showed an evident deviation from one measurement to another. Nevertheless, taking into account the lowest recorded absorption coefficients for a feed rate of 80%, the measured coefficients are slightly higher but similar to the ones for the sample with a feed rate of 40%. When comparing these to the sample produced at 40% feed, we see a deviation of around 250 Hz. This could mean that these three samples produced with the same layer height and flow, could be underlining the same acoustic behavior regardless of their feed rate.



^

Figure 49 : LH variation
mid-low frequencies



^

Figure 50 : Feed variation
mid-low frequencies

DENSITY OF POINTS

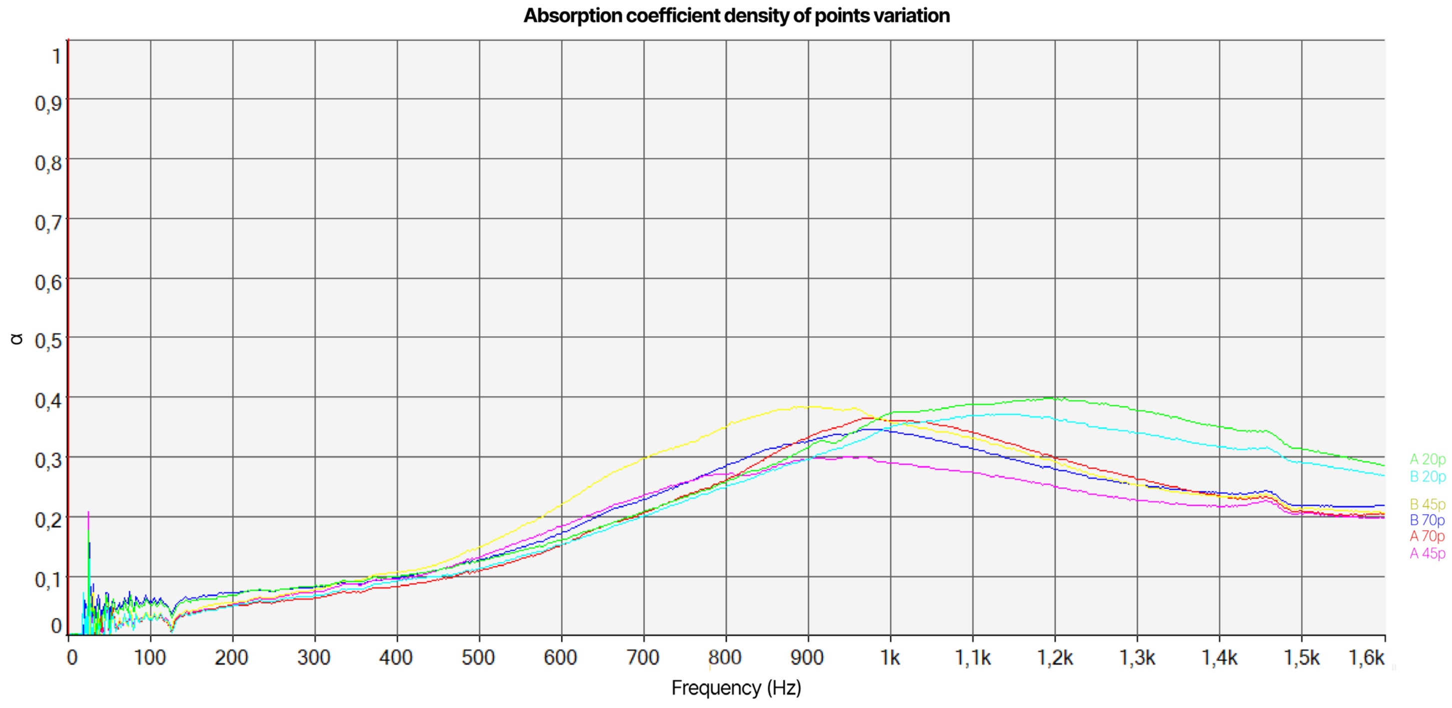
The results of the absorption coefficients of samples varying the density of points, suggest that there are similar absorption coefficients for samples with a high density in points, and higher absorption coefficients for the specimens with the lowest density of points.

DEPTH OF OFFSETS

Regarding the measured absorption coefficients for samples varying the depth of the offset, lower depths of 10 and 5mm showed similar coefficients, with a slightly higher result for depth 10 mm. Samples with the highest depth of 20mm, showed remarkably higher absorption coefficients.

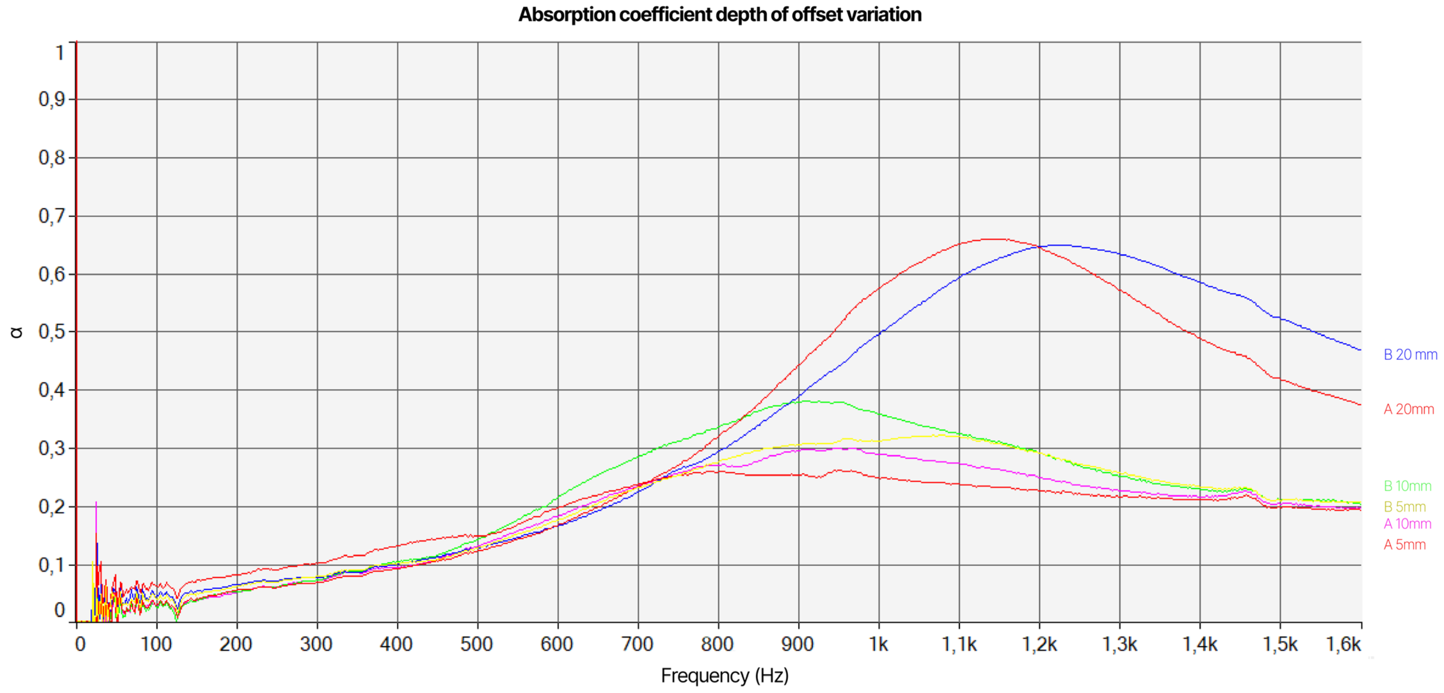
WALL SIDES

Lastly, in terms of the influence of the topology of side A (side points are offset from) or B (pattern created from the offset points), in most cases side B would have slightly higher results. Nevertheless, as stated, samples with high point densities, and low depths, show very similar results. While the samples with the highest depth and the lowest point density, show a more absorptive behavior. In these last cases, for the point density side A had a higher result, while for the offset depth side B did. This difference could mean that they present a similar absorptive behavior, and thus with the currently available data we can not conclude whether side A or B is more absorptive, or if they present similar absorption coefficients.



^

Figure 51 : Density of points variation mid-low frequencies

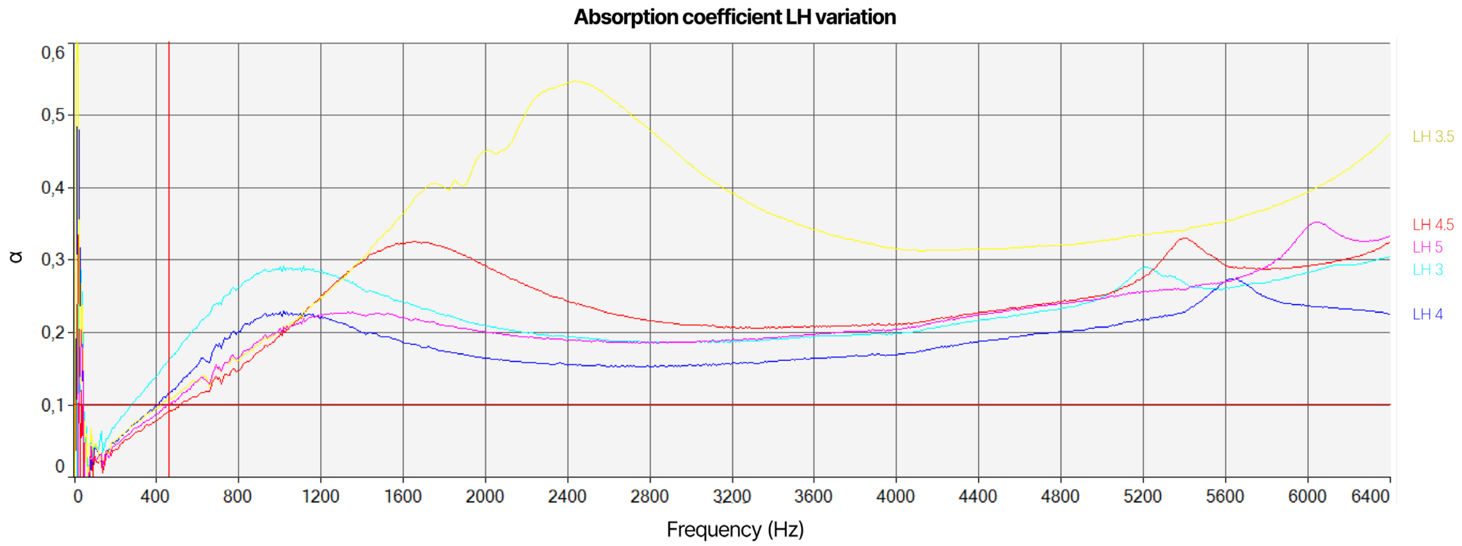


^

Figure 52 : Depth of offset variation mid-low frequencies

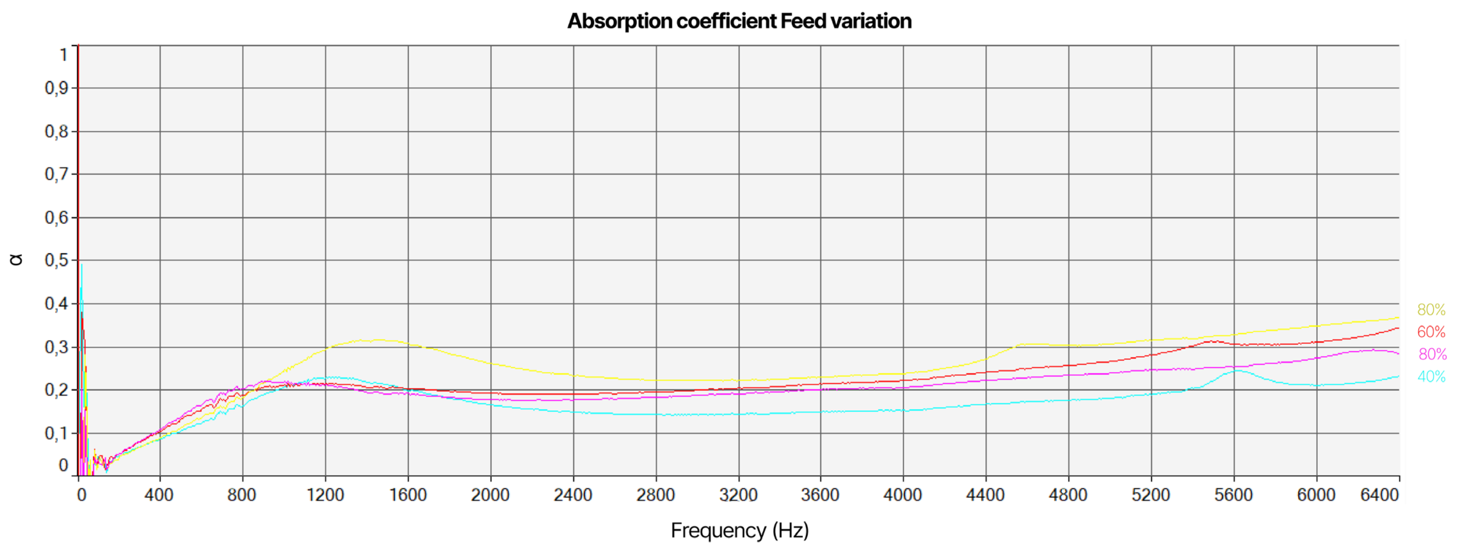
High frequencies

Figures 53 , 54, 55, and 56 show the absorption coefficients for the different parameter variations. No correlation for any of the parameter variations was found. It is also relevant to mention that a lot of peaks from vibration are visible in the absorption coefficients. These results might suggest that this toolpath variation approach is not suitable for high frequencies.



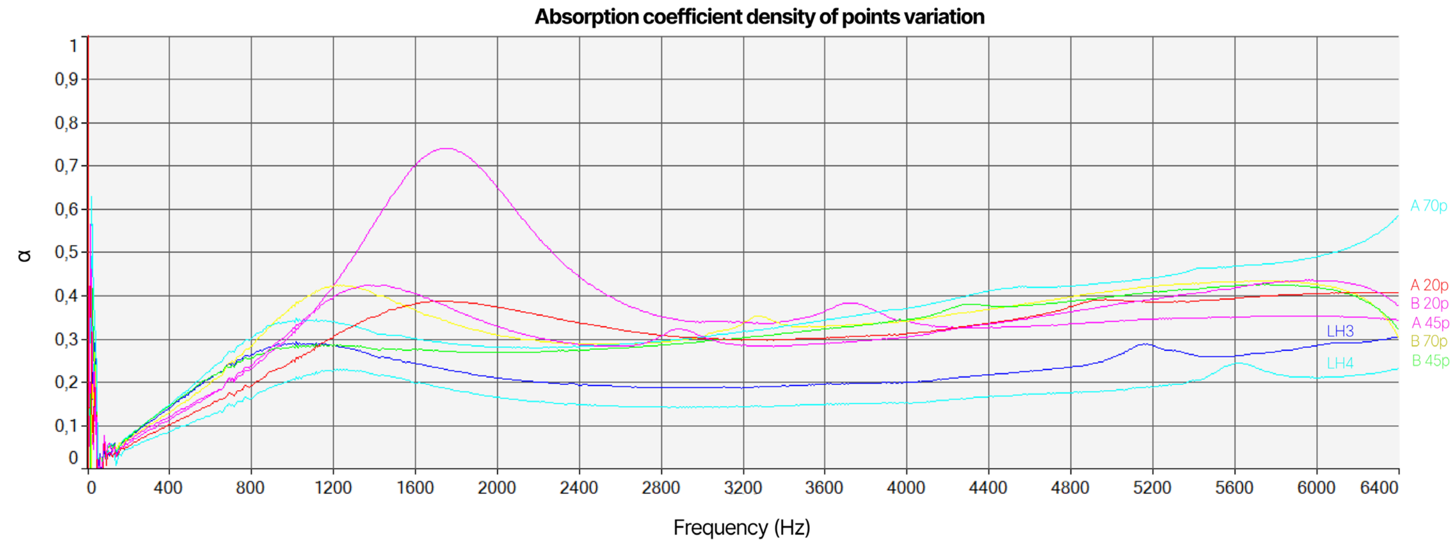
^

Figure 53 : LH variation high frequencies



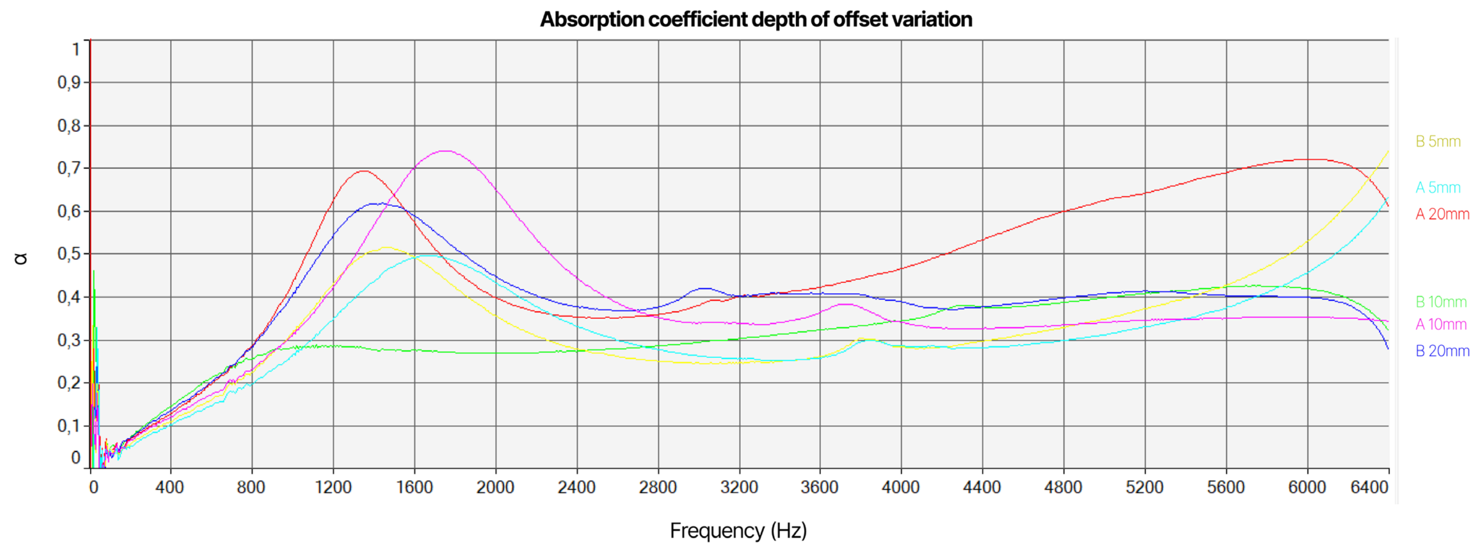
^

Figure 54 : Feed variation high frequencies



^

Figure 55 : Density of points variation high frequencies



^

Figure 56 : Depth of offset variation high frequencies

5.5 DISCUSSION

No identified tendencies for high frequencies

The variation in layer height and feed does not present an influence in the absorption coefficient at higher frequencies.

This could mean that the recorded absorption coefficients are merely related to material properties rather than production ones.

Zielinski et al. (2022) developed a sound-absorbing material based on dual-porosity influenced by the additive manufacturing process. This optimal acoustic performance was achieved at mid-low frequencies, underlining that roughness defined by the production of the specimens is not a suitable approach for high frequencies. Further, Ciochon et al. (2023) demonstrated that the influence of layer-by-layer fabrication technique on acoustic properties occurs towards lower frequencies.

When targeting high frequencies, the fibrosity and porosity of the material are the most influential. Since fibrous and porous materials are widely implemented as passive absorbers, which are highly effective at reducing high-frequency noise (Xie et al., 2020).

Mid-low frequencies

NO TENDENCIES FOR FEED VARIATION

The results from the impendence tube absorption coefficient measurements, show no correlation between feed rate variation and acoustic behavior. Nevertheless, it was predicted to have an influence as high feeds generate gaps. This increased number of cavities as a side effect of the 3D printing process has been demonstrated to have an impact on acoustic properties (Zielinski et al., 2022). Kennedy et al. (2019) compared metamaterial structures manufactured with three different technologies with numerical models, where the largest deviations were observed for the roughest FDM samples. Thus, it is clear that for very rough samples deviations in absorption coefficients are common. Accordingly, the lack of correlation between feed variation and absorption coefficient within the gathered results, could also mean that further data is needed. The existence or absence of an influence of feed in the acoustic behavior of BM-1 should be further assessed.

THE HIGHER THE LH THE HIGHER THE ABSORPTION

The results from the impendence tube absorption coefficient measurements show a tendency for the higher the layer height, the higher the absorption coefficient in a mid-low frequency range. Though the difference in absorption coefficients is not so distinctive (0,05 absorption coefficient difference for every 5 mm higher), a tendency is presented.

Furthermore, this correlation has been validated for small-scale 3D-printed samples using PLA. Ciochon et al. (2023) in their research on the effects of the surface roughness arising from the layer-by-layer fabrication technique on the acoustic properties of additively manufactured parts, showed that with the increase of the layer height, a rise in sound absorption occurred and that the peak value shifts towards lower frequencies. In their results, the two smallest layer heights were very close to each other, while the two greater layer heights were more distinct.

This coherence with existing research into the influence of layer height in acoustic absorption confirms the found tendency.

THE DEEPER THE OFFSET AND LOWER THE DENSITY THE HIGHER THE ABSORPTION

The results of the samples with horizontal variations suggest that higher absorption coefficients are achieved for lower point density and for higher depth of the offset. However, more data is needed to fully assess this phenomenon. Nevertheless, as previously discussed, the absorption coefficients of porous absorbers are defined by their density (Long, 2014), and the increase in thickness increases so does the absorption coefficient at low frequencies (Cox & D´Antonio, 2009). This correlation has been widely proven and is used in the design of optimized absorptive materials. Therefore, though further data is needed to confirm this correlation, acoustic theory indicates that the impact of depth and density are influencial.

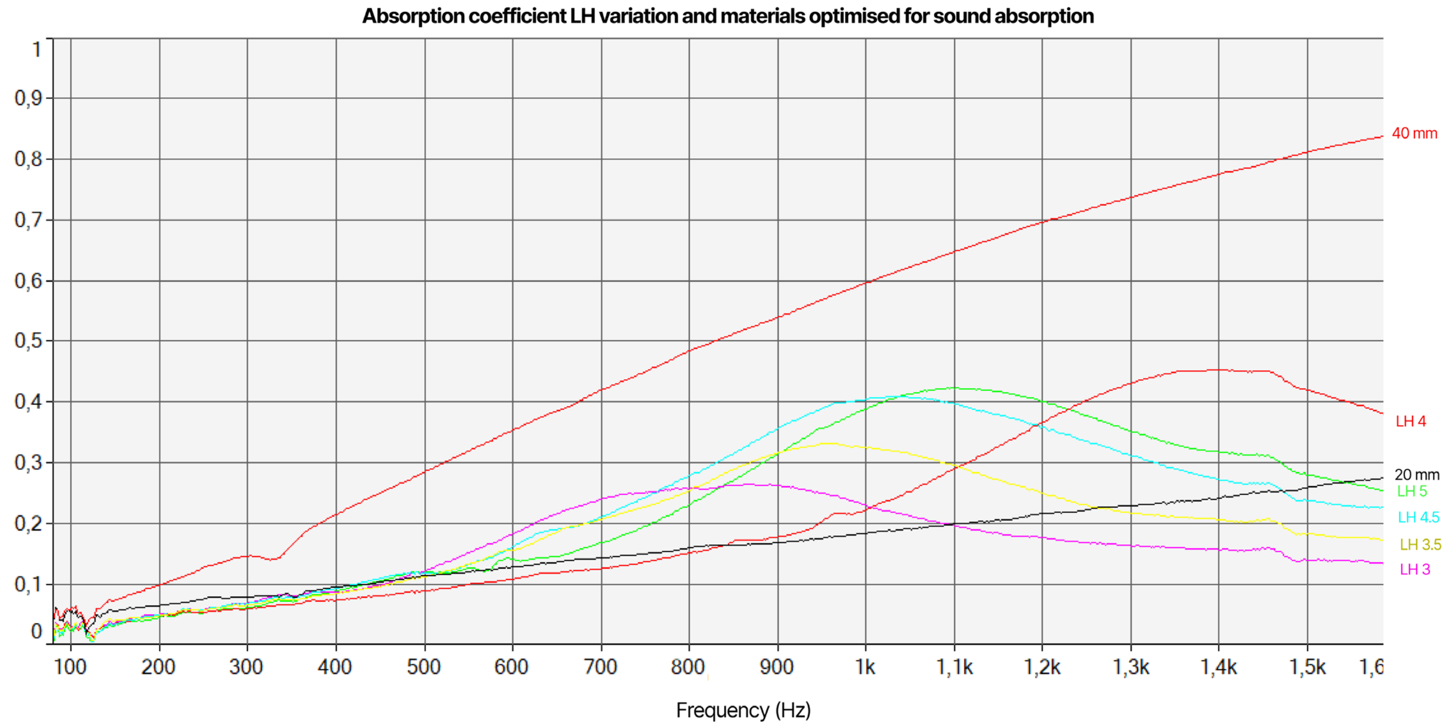
Lastly, in terms of the influence of the topology of side A (side points are offset from) compared to B (pattern created from the offset points), no significant differentiation was found.

ENHANCING THE ACOUSTIC PERFORMANCE OF BM–1

Further, to assess if the toolpath variations are having a significant impact on the acoustic performance of BM–1, a solid piece molded by hand using BM–1 was tested. Measuring an almost constant absorption coefficient of 0.7 for mid–low frequencies. All of the toolpath variations have a tendency to present a higher absorption coefficient than 0.7, and thus the achieved increasements in absorption coefficient through toolpath variation present an opportunity to enhance the acoustic performance of BM–1.

COMPARISON TO MATERIALS OPTIMISED FOR ABSORPTION

For porous or fibrous materials optimized for sound absorption, the normal incidence sound absorption coefficients tend to increase with increasing frequency operation (Sabri et al., 2018). Figure 57 shows the recorded results for layer height variations compared with a material that has been optimized for absorption, which has a similar thickness (20 mm). As well as one with double the thickness (40mm). Visibly, the recorded results, even the highest achieved, do not present this correlation. Whether BM–1 can be optimized for sound absorption through 3D printing still needs to be further researched.



^

Figure 57 : LH variation mid–low frequencies and materials optimised for sound absorption of 20 and 40mm thickness

COMPARISON TO MATERIALS FOR INTERIOR WALLS

If we compare these results from the measured absorption coefficients with the materials presented in materials integrated for indoor walls, a clear opportunity is presented. Concrete generally has an absorption coefficient of 0.05 considering a mid-low frequency range, standing below the recorded coefficients using BM-1. Further porous concrete has an absorption coefficient of 0.08, also standing below the recorded values. Moreover clinker concrete has an absorption coefficient from 0.4 to 0.6 at a mid-low frequency range, which is near and 0.1 over the achieved results. This last similarity could be an opportunity to fine-tune the correlation between production parameters and the acoustic performance of BM-1 towards achieving a similar or greater performance to absorptive concrete.

Though plaster generally has a 0.05 absorption coefficient considering a mid-low frequency range, the absorption coefficient of acoustic plaster can go up to 0.7. This type of acoustically treated plaster stands remarkably higher than the achieved coefficients. To analyze whether BM-1 can perform at a similar absorption coefficient, the optimization of the acoustic performance of BM-1 still needs to be further researched.

	Frequency (Hz)					
Material	*125*	*250*	*500*	*1000*	*2000*	*4000*
Concrete						
Rough concrete[20]	0.02	0.03	0.03	0.03	0.04	0.07
Smooth unpainted concrete[18,9]	0.01	0.01	0.02	0.02	0.02	0.05
Smooth concrete, painted or glazed[18,9]	0.01	0.01	0.01	0.02	0.02	0.02
Concrete block, coarse[2]	0.36	0.44	0.31	0.29	0.39	0.25
Concrete block, painted[2,5,13]	0.10	0.05	0.06	0.07	0.09	0.08
Porous concrete blocks without surface finish, 400-800 kg/m³ [9]	0.05	0.05	0.05	0.08	0.14	0.20
Clinker concrete, no surface finish, 800 kg/m³ [8,9]	0.10	0.20	0.40	0.60	0.50	0.60
Bricks and blocks						
Brick, unglazed[2]	0.03	0.03	0.03	0.04	0.05	0.07
Brickwork, plain painted[6]	0.05	0.04	0.02	0.04	0.05	0.05
Smooth brickwork with flush pointing, painted[17]	0.01	0.01	0.02	0.02	0.02	0.02
Brick, unglazed, painted[2]	0.01	0.01	0.02	0.02	0.02	0.03
Smooth brickwork with flush pointing[18,9]	0.02	0.03	0.03	0.04	0.05	0.07
Smooth brickwork, 10 mm deep pointing, pit sand mortar[8,9]	0.08	0.09	0.12	0.16	0.22	0.24
Breeze block[6]	0.2	0.3	0.6	0.6	0.5	0.5
Plaster						
Lime cement plaster[18]	0.02	0.02	0.03	0.04	0.05	0.05
Glaze plaster[18,9]	0.01	0.01	0.01	0.02	0.02	0.02
Painted plaster surface[8,9]	0.02	0.02	0.02	0.02	0.02	0.02
Plaster with wallpaper on backing paper[18,9]	0.02	0.03	0.04	0.05	0.07	0.08
Plaster, gypsum, or lime, rough finish on lath[21,10]	0.02	0.03	0.04	0.05	0.04	0.03
Plaster, gypsum, or lime, smooth finish on lath[2]	0.14	0.1	0.06	0.04	0.04	0.03
Plaster, gypsum or lime, smooth finish on lath[21,10]	0.02	0.02	0.03	0.04	0.04	0.03
Plaster, on laths/studs, air space[6]	0.3	0.1	0.1	0.05	0.04	0.05
Plaster, gypsum, or lime, smooth finish on tile or brick[2]	0.013	0.015	0.02	0.03	0.04	0.05
Plaster, lime of gypsum on solid backing[6]	0.03	0.03	0.02	0.03	0.04	0.05
Acoustics plaster[6]	0.30	0.35	0.5	0.7	0.7	0.7

^

Figure 58 : Table of absorption coefficients of different concrete and plaster (Cox & D'Antonio, 2009)

DEVICES TARGETING MID-LOW FREQUENCY ABSORPTION

Since the found influence of 3D printing process parameters in the acoustic performance of BM-1 concerns a mid-low frequency range, controlling the roughness of the material through toolpath variation could achieve absorption control for this frequency range.

Mid-low frequency absorption control is currently targeted using resonant structures like membranes, Helmholtz resonators, and micro-perforated panels. These structures function as mass-spring-damping systems that absorb sound at specific resonant frequencies, but their effectiveness is typically limited to a narrow frequency range (Yilmazer et al., 2022). To expand this absorption range, researchers have explored using networks of micro-perforated panels arranged in series and parallel, allowing for multiple resonances and broader frequency coverage (Yilmazer et al., 2022).

Additionally, the micro-perforated panel´s absorption bandwidth can be significantly increased by implementing multiple-layer designs (Cobo & Simón, 2019).

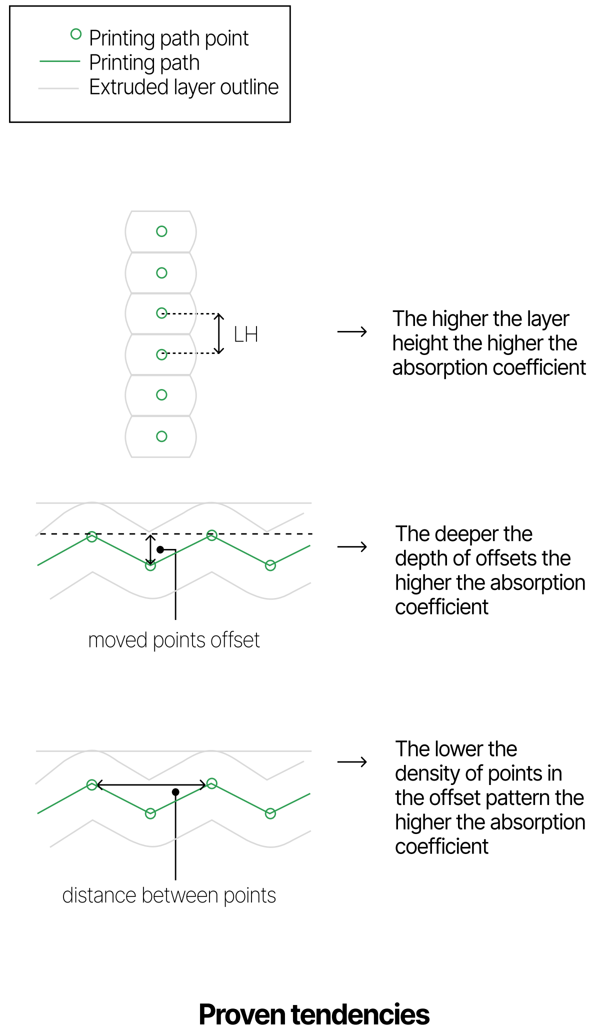
If mid-low frequency absorption can be targeted by toolpath variations in the construction of the wall itself, many multi-layer production and assembly problems faced when producing micro-perforated panels would be avoided. Thus, the space for 3D printed BM-1 as an acoustic device is clearly present.

5.6 CONCLUSIONS

The results from the impedance tube absorption coefficient measurements of specimens presenting different roughnesses achieved through 3D printing, show an impact of the achieved topologies on acoustic performance. The found correlations (Fig. 59) demonstrate the advantage of additively manufacturing multi-scale roughnesses with BM-1. This found correlations between parameter variation and absorption coefficients at mid-low frequencies, underlines an opportunity to integrate 3D printed BM-1 to enhance acoustic performance.

This found correlation proves why BM-1 should be 3D printed, and how controlling a distinctive characteristic of the material helps meet an architectural need. Thus, underlining a unique advantage for indoor walls, that is achieved through additively manufacturing BM-1.

Figure 59 shows the influential parameters in the absorption coefficients of BM-1 at mid-low frequencies. These correlations are relevant to define guidelines for implementing the gathered knowledge in the design of a sound-absorbing wall.



^

Figure 59 : Found tendencies

CHAPTER 6: DESIGNING A WALL WITH CONTROLLED ROUGHNESS

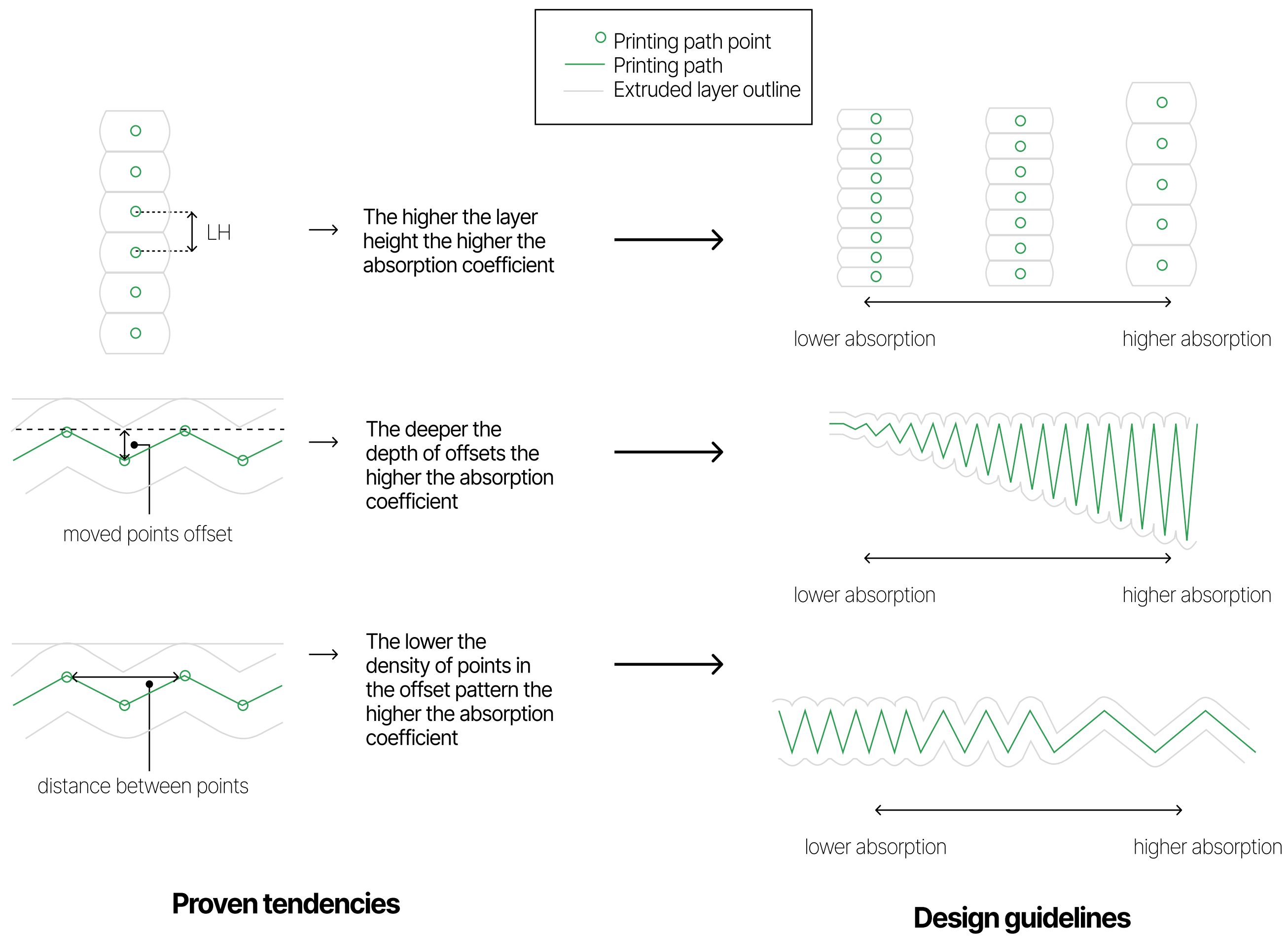
6.1 DESIGN GUIDELINES

The test results revealed tendencies to higher the absorption coefficient. These findings are extremely useful for designing a 3D-printed absorptive wall with BM-1.

Exactly the ranges in layer heights, distances, and number of points that achieve predictable absorption coefficients are still unknown. Further testing would have to be conducted to conclude this.

However, based on the proven tendencies, some guidelines to support the design of a 3D-printed wall with enhanced sound absorption targeting mid-low frequencies can be formulated (Fig. 60).

Following these guidelines, the design of a wall with selectively more and less absorbing areas can be designed. This way, the design of a demonstrator was developed to showcase how applying the generated knowledge could look in interior architecture.



^

Figure 60 : Design guidelines

6.2 PLACEMENT AND ORIENTATION OF ROUGHNESS

Acoustic performance of soundabsorbersaccording to their placement

Further than through surface design, the acoustic qualities of a room are also highly influenced by the optimal placement of absorption panels (Labia et al., 2020). Thus, when defining an application of incremented surface roughness in acoustic architecture, the wall should include toolpath variations in regions and not in the totality of the wall.

Cucharero et al. (2019) tested the placement of absorptive material in a room, and demonstrated that corners, followed by any edge between two surfaces of the room, are the less efficient placements in terms of reduction of reverberation time. The acoustic design with better absorption results was where the material was placed in the upper part of the room and avoided the edges.

Moreover, Labia et al. (2020) in their research recommended the application of absorptive materials on the ceiling or on the perimeter of the ceiling, and on the upper part of one of the walls. In regular-shaped rooms around 500 m^3, it's best to cover 50–70% of the ceiling and 20–40% of the walls (including the back wall) with sound-absorbing material. For smaller meeting rooms around 300 m^3, covering 20–30% of the ceiling and up to 15% of the back wall is recommended (Labia et al., 2020).

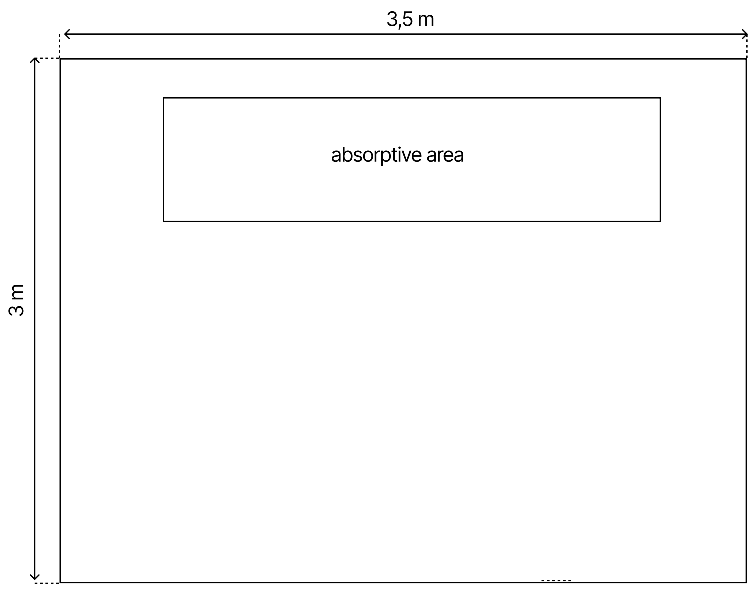
The gathered information suggests that better acoustic treatment using absorbing materials is achieved when these are placed on the upper walls and ceiling o a room, avoiding corners and covering smaller than half of the area of the wall and most of the ceiling area.

Furthermore, the scope of this project focuses on building vertical walls with BM-1, and thus configurations including the ceiling of a room will not be considered.

Since the designed approach to increased and decreased roughness can be controlled at defined locations and ranges, the roughness variations should be applied at the regions where a better acoustic performance can be achieved.

Therefore, the configurations incrementing the sound absorption coefficients should be placed on the upper part of the wall and avoiding corners.

Figure 61 highlights the region of a wall of 3 by 3,5 meters, where the absorbing configurations should be placed.



^

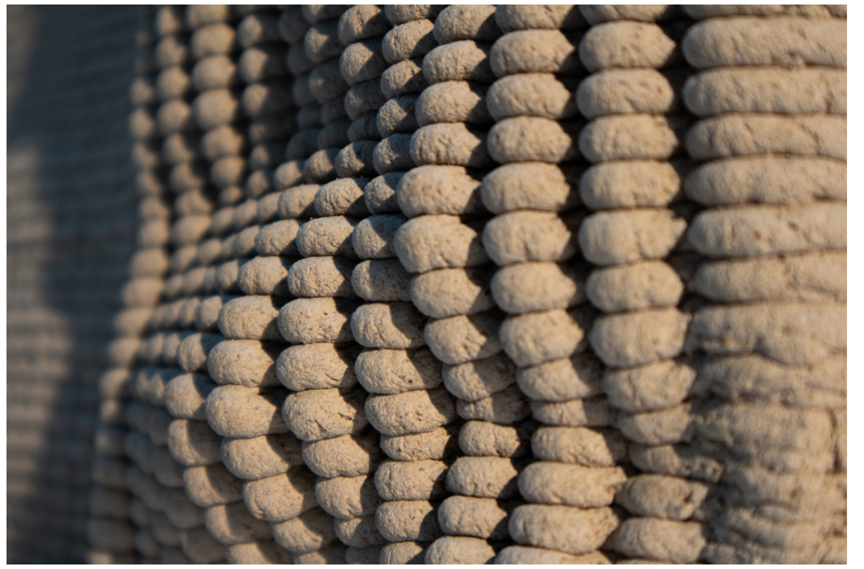
Figure 61 : Absorptive region of a wall to achieve better sound quality

Orientation of offsets

As indicated in the absorption coefficient results, for the printing path variation approach, in terms of the influence of the topology of side A (side points are offset from) compared to B (pattern created from the offset points), no significant differentiation was found.

While side A, presents a more seamless roughness including cavities within the layers and a higher layer height, side B has a more distinctive and visually alternating appearance. Side B clearly displays the regions where the offsets are present as well as the depths and densities. This way, the visual appearance of the design can be clearly modified varying attractor locations influence ranges, depth of the patterns, and point densities.

Due to its visual versatility and clarity of the print path variations, the side where the pattern is created from the offset points was selected as the visual side of the wall.



^

Figure 62 : Side B with point offsets

6.3 DEMONSTRATOR REQUIREMENTS

Producing 3D-printed components with BM-1 presents significant challenges. To achieve consistent and predictable results, it is essential to design elements with BM-1's production and post-processing constraints in mind.

Therefore, before delving into applying the generated knowledge to the design of a wall, considerable topics regarding construction with BM-1 and the requirements of building interior walls must be addressed. This way, the design of the demonstrator should showcase the generated knowledge, while managing to successfully print and post-process an interior wall element printed with BM-1.

3D printing with BM-1

When producing parts using BM-1 it is important to take into account the drying process of the material. To be able to dry samples printed with BM-1 it is important to keep an open structure along the prototype so the whole prototype can dry adequately. Furthermore, after drying, BM-1 shrinks around 5% in volume. This second aspect must be integrated when defining the measurements of a design.

Furthermore, as already demonstrated through the preliminary experiments, vertical walls with no reinforcement easily collapse. Thus, parts printed using BM-1 must take into account reinforcement to enable the construction of tall, vertical walls during the printing process. Once dried, this reinforcement aspect is important as it allows for prototypes to withstand load-bearing conditions.

Production with the WASP 40100 LDM

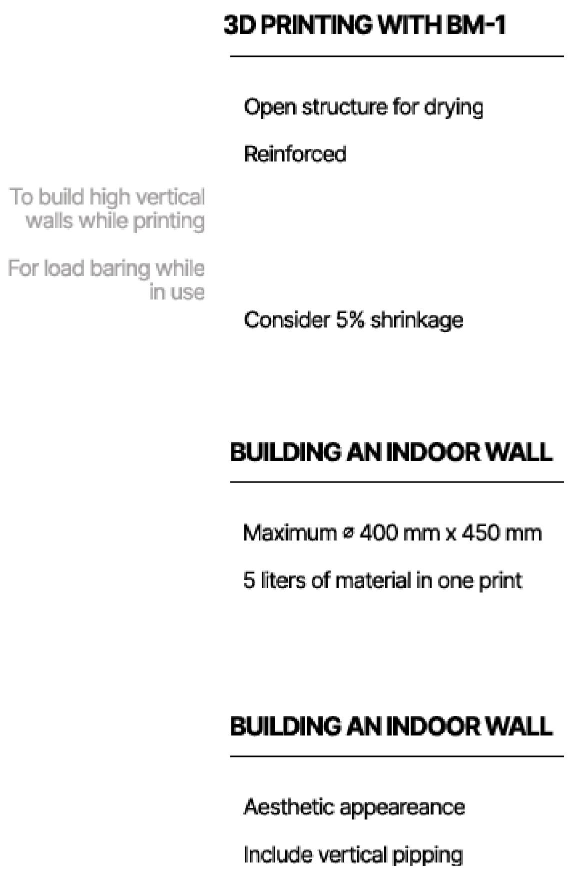
Furthremore the dimensions of the demonstrator are as well constrained by the print volume and material tank of the printing machine.
Print volume: ⌀ 400 mm x 450 mm

Material tank capacity: 5 liters

Interior walls

When designing interior spaces the aesthetic appearance is of key importance. The surface finish and form should contribute to an architectural language suitable for interior applications. Though the designed property already has a quite distinctive appearance, where and how it is placed has a crucial role in the appearance.

Further, indoor walls include piping. Thus, for a ready-to-implement product, the prototype should include space for vertical piping.



^

Figure 63 : Demonstrator requirements

Block geometry

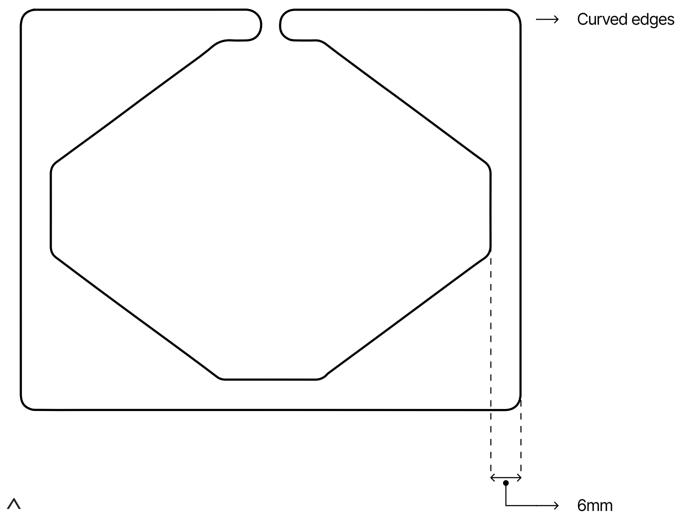
Based on this set of requirements, a geometry that satisfies all constraints must be developed to ensure a successful demonstrator that reflects the gathered knowledge in context.

Given that the wall is entirely 3D printed and constrained by a maximum print diameter of 400 mm, it must be subdivided into modular building blocks.

Considering the 5-liter maximum tank capacity and the material consumption required for the wall with toolpath variations, the unit block dimensions were defined as 180 mm (L) × 150 mm (W) × 160 mm (H). Accounting for an estimated 5% shrinkage, the final dimensions are expected to be approximately 171 mm × 142.5 mm × 152 mm.

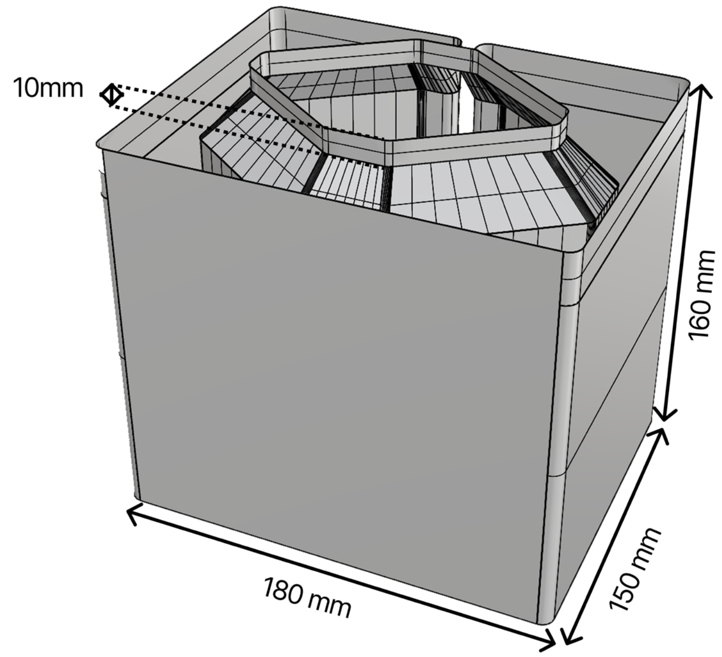
To meet the material and interior architecture requirements, each block must feature an open structure to facilitate drying, as well as an infill geometry that reinforces the print while allowing space for internal piping. To do so, an inner geometry construction a double wall along 40 mm for each wall was formulated (Fig. 64). Furthermore, a 2mm material overlap was considered to ensure proper wall bonding. Considering a 3mm layer height and approximately 14mm wall thickness, the model line distance was set to 6mm.

To ensure that the demonstrator stands still without the use of mortar or other post-processing procedures or materials, the blocks must be able to connect to each other. To solve this while not exceeding the material capacity of the tank, an offset of 20 mm from the inner geometry was made. And a ramp of 20 mm was created to transition from a wider to a smaller geometry. Then the last 3 layers constructed the connecting piece to the bottom of a block placed on top (Fig.66).



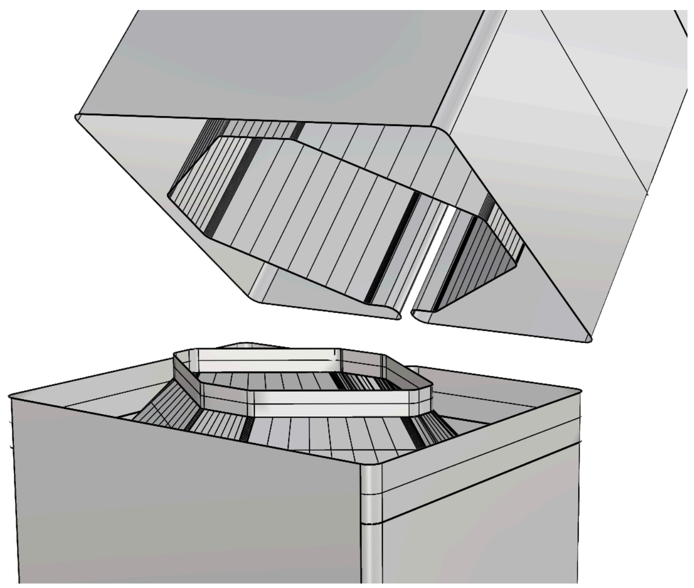
^

Figure 64 : Block infill geometery



^

Figure 65 : Block dimensions



^

Figure 66 : Connectivity

^

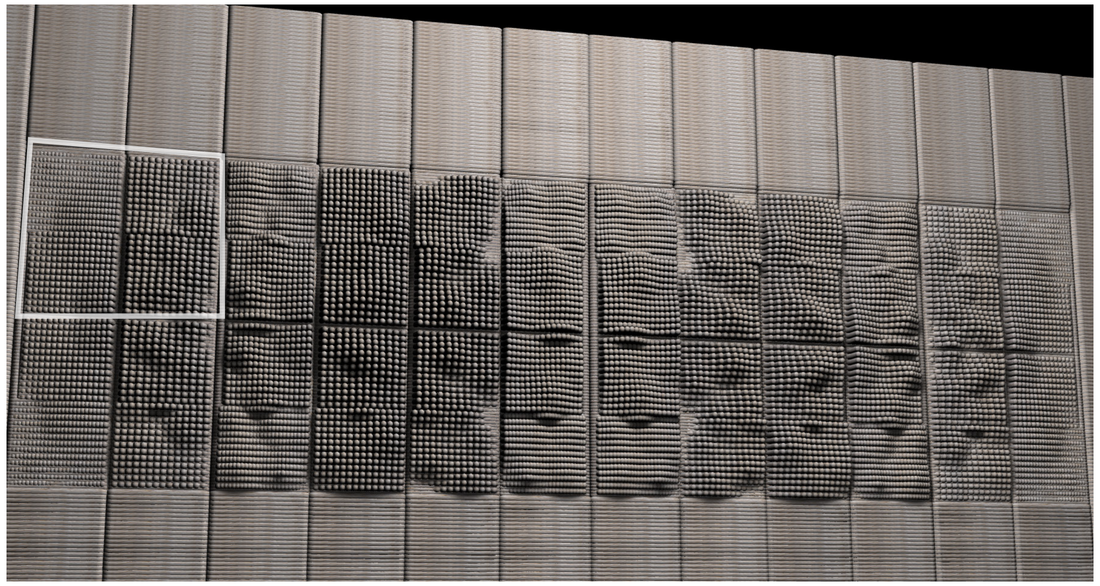
Figure 69 : Full wall render

6.4 Demonstrator

Given the configurations of toolpath variations that achieve more and less absorptive results, the requirements for building an indoor wall with BM-1, and the location and orientation of the roughness to achieve better acoustic performance and a visually appealing look, a design of an interior wall was formulated.

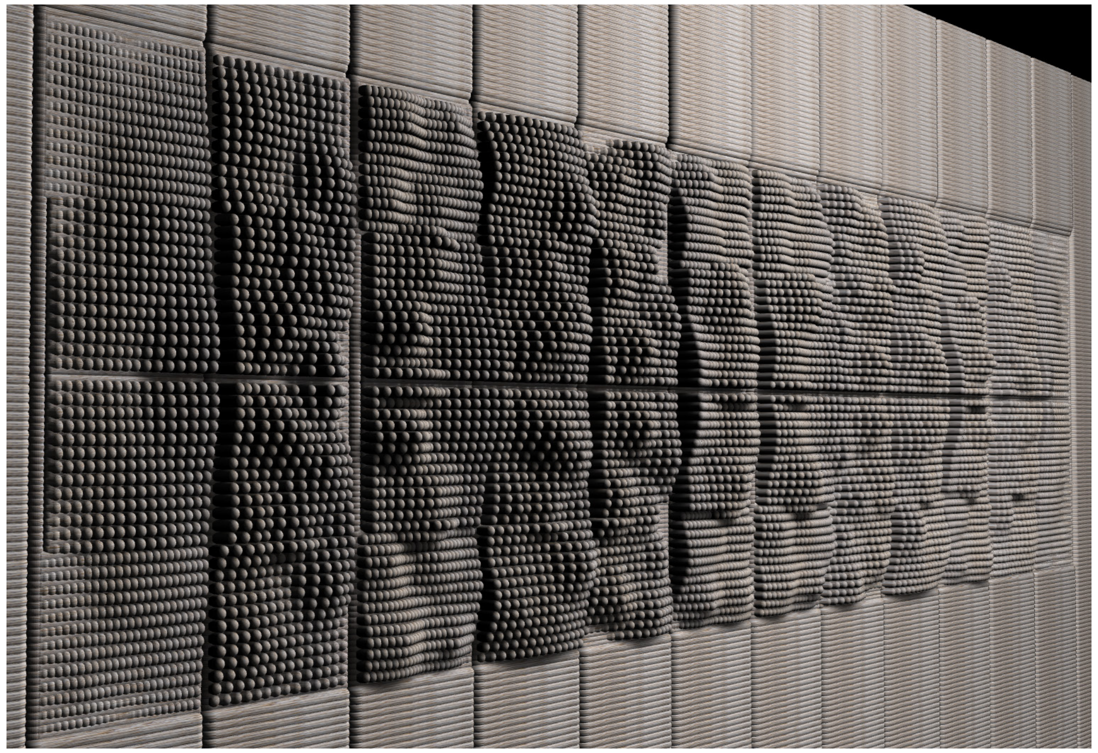
Once the wall was designed, a group of blocks was selected (Fig. 67) to produce with BM-1 to showcase the developed 3D printing process that controls and locally varies the roughness of BM-1.

To make this controlled aspect visible in the produced prototype, four blocks connected and at the edge of the absorptive region were selected. This way a contrast from none to very pronounced printpath variations could be visible.



^

Figure 67 : Region to produce with BM-1



^

Figure 68 : Designed absorptive area

^

Figure 70 : Demonstrator

Printing path variation

The four blocks produced with BM-1 display the defined design guidelines from less absorptive settings to more absorptive. Accordingly, going from lower deposition height, lower pattern depth, and higher point density, to higher deposition height, deeper pattern depth, and lower density of points.

As part of the beginning of the absorptive area of the designed wall, display contrast from none to very pronounced printing path variations.

^

Figure 71 : Block connection area detail

Visual appareance

The designed approach to controlling the roughness of BM-1 generates a distinctive visual appearance.

The application of variations in the printing path to vary the roughness allows for a wide range of surface results. This way, architects and designers can modify the printing path settings of a 3D-printed wall for aesthetic purposes.

^

Figure 72 : Assembly

The demonstrator showcases the developed 3D printing process through which the roughness of BM-1 is controlled and locally varied. Further, the inner geometry of the building blocks allows for building high vertical walls during printing, and holding one block on top of another.

The demonstrator displays the found tendencies going from less absorbing with fewer print path variations and thus less deposition height increase, shorter offsets, and higher point density in the pattern. To more absorbing with more print path variations and thus deposition height increase, longer offsets, and lower point density in the pattern.

^

Figure 73 : Connection areas

CHAPTER 7: CONCLUSIONS AND FUTURE RESEARCH

This project started with the goal to identify a material property of BM-1 that can be controlled through the 3D printing process. To then develop the 3D printing parameter and material property correlation in an application that underlines the advantages of controlling that material property in the architectural context.

Through a methodology combining case study analysis and experimental iteration, this project successfully identified roughness as a specific material property of BM-1 that can be controlled to meet architectural needs.

By correlating 3D printing parameters with the roughness of BM-1, and a literature review on roughness and architectural acoustics, a targeted design goal was established.

The defined design goal was to develop a 3D printing process through which the roughness of BM-1 is controlled and locally varied to modify the acoustic properties of indoor walls 3D printed with BM-1.

To meet this design goal, knowledge in terms of parameter variation, BM-1 roughness output and absorption coefficients was generated through testing with an impedance tube method.

The results from testing were translated into a set of design guidelines that outline which 3D printing parameters and how to manipulate them to achieve more or less acoustically absorptive BM-1 pieces.

This design project culminated in a final demonstrator that embodies the integration of the design guidelines, production with BM-1 and the interior architecture context, in the design of an interior wall with varying acoustic properties. A design that was validated through the production of four wall blocks with BM-1.

Through developing the distinctive characteristic of roughness inherent to 3D printed BM-1 pieces, this project underlines the unique advantages of 3D printing with BM-1 in the context of interior architecture.

The knowledge generated in this project serves as a start in the correlation between 3D-printed bio-based material outputs and acoustic performance. Underlining the potential for future exploration into controlling acoustic properties of bio-based materials through a 3D printing process.

7.1 SUMMARY OF FINDINGS

Controlled roughness

The experimental phase concluded that the roughness of BM-1 can be modified and selectively applied through toolpath variation.

As roughness is a multi-scale characteristic, the identified results were divided into two dimensions. Micro roughness refers to roughness within the layers, such as visible fibers or cavities. And macro results including those achieved by the layer-on-layer manufacturing, pattern formation, and noise within the printing path.

Both micro and macro roughness were modified through printing path and layer height variation. And micro as well with feed and flow variation.

Further, this parameter identification, allowed to characterize the specific irregularities contributing to roughness per parameter type. Being able to further understand how different parameter configurations modify the acoustic properties of BM-1.

Roughness and acoustic performance

Testing an array of test specimens varying in layer height, feed rate, and horizontal path variations, concluded in the following information.

- No correlation was found between feed rate, layer height, and horizontal path variations with absorption coefficients at high frequencies
- No correlation between feed rate variation and absorption coefficients at mid-low frequencies
- A tendency for the higher the layer height, the higher the absorption coefficients in a mid-low frequency range was identified
- A tendency for the deeper the zigzag depth the higher the absorption coefficients was identified
- A tendency for the lower the number of points the higher the absorption coefficients was identified

Design guidelines for acoustic control with BM-1

With the gathered tendencies a set of design guidelines to modify the absorption coefficients of BM-1 were defined

- The higher the layer height the higher the absorption coefficient
- The deeper the depth of the offsets the higher the absorption coefficient
- The lower the density of points the higher the absorption coefficient

7.2 PROJECT LIMITATIONS

This project also presents some limitations due to constraints in available tools and time. This chapter will review these limitations that are important to address in performing future research.

Roughness control approach

In this project, as in any project conducted by a single designer, the approaches, decisions, and outcomes presented in this work are inherently shaped by the specific knowledge, design criteria, and methodological preferences of the project author. Consequently, this project should not be interpreted as a comprehensive or definitive framework for controlling surface roughness in BM-1. The experiments designed and the parameters tested represent a focused subset of the broader spectrum of possible toolpath strategies available in the domain of large-scale 3D printing with bio-based materials. While the findings contribute valuable insights into the relationship between 3D printing parameters and surface roughness, they do not encompass the full range of toolpath variation techniques, nor do they capture all possible material properties achievable. As such, this work serves as a foundational exploration rather than a conclusive guide, and it invites further investigation to fully understand and utilize the design potential of BM-1 in architectural applications.

Defining a correlation

The absorption coefficient test results revealed tendencies indicating that greater layer heights and increased offsets, as well as lower point densities, generally correspond to higher absorption coefficients. These preliminary findings are promising and provide valuable direction for designing acoustically controlled, 3D-printed wall systems using BM-1. However, the precise parameter ranges, such as the specific thresholds of layer height, depth, and point density, that critically influence acoustic performance remain undefined.

At this stage, the data only suggest trends rather than establishing statistically robust, quantifiable correlations. The experiments conducted provide a foundational understanding, but the limited number of tests, constrains the generalizability of the conclusions. Consequently, while the observed tendencies point to certain influential factors in acoustic behavior, they do not yet offer a comprehensive or predictive model.

Difficulty in repeatability

The reliability analysis of the impedance tube measurements underlined a notable deviation in measured absorption coefficients for samples that were thin and did not tightly fit the impedance tube, and thus were more prone to vibration. For samples with these characteristics, the deviation in measurements was quite big. This indicated that the internal consistency of the results is rather questionable, and the deviation of the measurement results from one sample to another underlines the poor replicability of the samples. This might be influenced by difficulty in replicability due to shrinkage and manual handling of the samples.

Though the discussed results were contrasted with experts to ensure that the named tendencies could be concluded, the difficulties in replicability need to be further studied to generate more conclusive results.

Characterization of roughness

The roughness profiles of BM-1 achieved through parameter variation, were only analyzed by what could be visually perceived. Therefore, the addressed roughnesses referred to visible surface irregularities as a result of the manufacturing process.

For the scope of this project, this was a sufficient characterization to contrast with literature and predict acoustic behaviors. Nevertheless, a fine explanation as to why a certain 3D printing configuration presents a measurable influence on acoustic behavior remains unclear. Further material roughness, and perhaps porosity, measuring techniques, could help answer why on a material science level the found tendencies occur.

Strength

The most absorptive samples were the ones with the higher layer height, the deeper the offset, and the lower the point density. These all are the weakest settings in terms of layer bonding and overall strength. Though it seems like the attractor approach to horizontal variations in a gradient provides stronger walls than single wall samples with a high layer height, testing into the strength of the samples needs to be conducted to ensure the strength of the samples.

Drying

Though BM-1 can dry in normal room temperature conditions, some last remaining humidity can only be dried with the use of temperature. This aspect is essential as it assures strength and prevents growing mold. To dry BM-1 samples, industrial dryers, or even a regular oven that can run ventilation at 40 or 30 degrees can be used.

Nevertheless, closed/semi-closed surfaces are harder to dry. The designed horizontal offset variation generated a pattern varying in depths and density, leading to parts that were harder to dry due to their closeness. If the samples are directly placed in controlled temperature and ventilation conditions this can be avoided. However, if the samples are not put into drying conditions within approximately 24h hours after production, mold can easily grow in these regions.

This is an essential aspect to account for implementing this approach to build infrastructure with BM-1.

Building block iterations
The design of the building blocks of the demonstrator serves as an answer to applying the design guidelines on an indoor wall while meeting the material and machine constraints. Nevertheless, due to time limitations and focus on the material surface properties, the geometry of the building block was minorly iterated upon. And some aspects of this geometry could be still improved.

Since the material is mixed manually, some inconsistencies from one day to another can occur in terms of material consistency. This easily leads to differences in the needed production pressure, feed and flow, influencing the wall thickness. Accordingly, the material overlap in the wall connection parts was small or even did not overlap at all at times. For further iterations, the wall lines should fully cross one another to avoid gaps due to variations in material consistencies.

Regarding the connection part, due to tank capacity limitations, the transition and the connection layers are rather short. This led to a higher overhang and thus a weaker wall. Moreover, horizontal connectivity must be considered as well to ensure a rugged wall constitution.

Furthermore, though the dimensions are rather small to meet the tank capacity limitations of the machine, in order to actually build an interior wall with BM-1 the blocks should be bigger to reduce assembly, production, and post-processing times.

8.3 FUTURE WORK

While this project establishes initial tendencies and relationships between 3D printing parameters, roughness of BM-1 and acoustic performance, further research could help develop a more comprehensive and conclusive understanding these correlations.

Roughness quantification
Introducing standardized tools or workflows to quantify surface roughness of 3D printed elements will be crucial. Existing metrics to quantify roughness could help bridge the gap between roughness output and measured acoustic performance.

A strong correlation
To better capture the complexity of acoustic behavior in additively manufactured BM-1 components, future studies should include a wider range of samples for each parameter type. This could help draw significant conclusions and identify threshold values that critically influence the acoustic performance of BM-1.

Final evaluation
Beyond isolated specimen testing, future studies should assess the acoustic performance of the material in full-scale architectural applications. Evaluating the integration of BM-1 components in real interior wall assemblies will provide insights into the practical effectiveness and limitations of the proposed design guidelines.

REFERENCES

A

ABOUT — Center of Design Research for Regenerative Material Ecologies. (n.d.). Center of Design Research for Regenerative Material Ecologies. https://www.regenerativematerialecologies.com/about

Agarwala, M. K., Jamalabad, V. R., Langrana, N. A., Safari, A., Whalen, P. J., & Danforth, S. C. (1996). Structural quality of parts processed by fused deposition. Rapid Prototyping Journal, 2(4), 4–19. https://doi.org/10.1108/13552549610732034

Arquitectura Viva (2024). Prototipo de vivienda TOVA - IAAC Arquitectura Viva. https://arquitecturaviva.com/obras/el-iaac-construye-el-primer-edificio-de-espana-hecho-con-tierra-y-una-impresora-3d

Aslan, R., & Turan, O. (2020). Gypsum-based sound absorber produced by 3D printing technology. Applied Acoustics. https://www.sciencedirect.com/science/article/pii/S0003682X19308345

B

Bedarf, P., Szabo, A., Zanini, M., & Dillenburger, B. (2023). Robotic 3D printing of geopolymer foam for lightweight and insulating building elements. 3D Printing and Additive Manufacturing, 11(1), 1–9. https://doi.org/10.1089/3dp.2023.0183

Binggeli, C. (2008). Materials for interior environments. Ebook Central. https://ebookcentral-proquest-com.tudelft.idm.oclc.org/lib/delft/reader.action?docID=1365052&ppg=1

Breseghello, L., Sanin, S., & Naboni, R. (2021). Toolpath Simulation, Design and Manipulation in Robotic 3D Concrete Printing. University of Innsbruck. https://www.researchgate.net/publication/350470887_Toolpath_Simulation_Design_and_Manipulation_in_Robotic_3D_Concrete_Printing

Building Materials and the climate: Constructing a new future. (2023). UNEP - UN Environment Programme. https://www.unep.org/resources/report/building-materials-and-climate-constructing-new-future

C

Chadha, K., Vasey, L., Kango, A., Aejmelaeus-Lindström, P., Gramazio, F., Kohler, M., Assunção, J., Brumaud, C., Habert, G., Malczyk, G., & Hutter, M. (2024). Impact printed structures: design systems and construction strategies. https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/668921/4/jj.11374766.28.pdf

Ciochon, A., Kennedy, J., Leiba, R., Flanagan, L., & Culleton, M. (2023). The impact of surface roughness on an additively manufactured acoustic material: an experimental and numerical investigation. Journal of Sound and Vibration. https://www.sciencedirect.com/science/article/pii/S0022460X22006174#fig5

Clarke-Hicks, J. (2021). GRADING LIGHT: Utilizing plastic deformation to functionally grade ceramic light screens. In A Thesis Presented to the University of Waterloo in the Fulfillment of the Thesis Requirement for the Degree of Master of Architecture. https://uwspace.uwaterloo.ca/items/51628400-bbe8-4691-9269-a7f5f09a9384

Cocks, R., Nguyen, J., & Peters, B. (2023). Wieringa Surface: The Implementation of Aperiodicity into Architectural Acoustics. https://www.semanticscholar.org/paper/Wieringa-Surface%3A-The-Implementation-of-into-Cocks-Nguyen/fda68be9dc11892e8e939ed11f1d753bc937844fw

Costalonga, V. (2024). BE-AM | Symposium 2024 [Video]. BE-AM | Built Environment Additive Manufacturing. https://www.youtube.com/live/iO2XdG_hqfY

Conference presentation on 3D Printing of Natural Fibre Filaments fo Architecture by Vanessa Costalonga

Cox, T., & D´Antonio, P. (2009). Acoustic absorbers and diffusers.

Cucharero, J., Hänninen, T., & Lokki, T. (2019). Influence of Sound-Absorbing material placement on room acoustical parameters. Acoustics, 1(3), 644–660. https://doi.org/10.3390/acoustics1030038

E

ETH Zurich Sustainable Construction. (2023). ETH Zurich. https://sc.ibi.ethz.ch/en/news/2023/05/Julie.html

G

García Cuevas, D., & Pugliese, G. (2020). Advanced 3D printing with Grasshopper.

Goidea, A., Floudas, D., & Andréen, D. (2022). Transcalar Design: An Approach to Biodesign in the Built Environment. Infrastructures. https://pdfs.semanticscholar.org/e6ac/a40ec8f750b9c4a017f731b9f0079019514f.pdf

Grasshopper. (2025.). Algorithmic Modeling for Rhino. https://www.grasshopper3d.com/

I

IAAC. (2024). TOVA: 3D Printed Prototype using Earth – IAAC. https://iaac.net/project/3dpa-prototype-2022/

J

J. Keep. (2020). "Formulating and Testing a Clay Body for Extrusion Clay 3D Printing" http://www.keep-art.co.uk/Journal/Test_FormulatingClayBody.pdf

K

Kennedy, J., Flanagan, L., Dowling, L., Bennett, G. J., Rice, H., & Trimble, D. (2019). The influence of additive manufacturing processes on the performance of a periodic acoustic metamaterial. International Journal of Polymer Science, 2019, 1–11. https://doi.org/10.1155/2019/7029143

L

Labia, L., Shtrepi, L., & Astolfi, A. (2020). Improved room acoustics quality in meeting rooms: Investigation on the optimal configurations of Sound-Absorptive and Sound-Diffusive panels. https://www.semanticscholar.org/paper/Improved-Room-Acoustics-Quality-in-Meeting-Rooms%3A-Labia-Shtrepi/91968b43bb8a4ab10f821a514e4e39b9873c77ba

Larsson, R. (2021, January 5). Surface roughness [Lecture]. YouTube. https://www.youtube.com/watch?v=-VzKqJdNRnk

Leschok, M., Cheibas, I., Piccioni, V., Seshadri, B., Schlüter, A., Gramazio, F., Kohler, M., & Dillenburger, B. (2023). 3D printing facades: Design, fabrication, and assessment methods. Automation in Construction. https://www.sciencedirect.com/science/article/pii/S0926580523001784#bb0050

Long, M. (2014). Architectural acoustics.

M

Mario Cucinella Architects. (2021). https://www.mcarchitects.it/en/projects/tecla-technology-and-clay

M. Imbern, F. Raspall, Q. Su (2017). Extruded tessellation: ceramic tectonics. MaP+S Group. https://research.gsd.harvard.edu/maps/portfolio/extruded-tessellation-cevisama-2016/

Ming, C., Ammar Mirjan, A., Medina Ibáñez, J., & Gramazio, F. (2021). Impact Printing. 3D Printing and Additive Manufacturing. https://www.researchgate.net/publication/354425284_Impact_Printing

O

Omlab. (2024). https://www.omlab.nl/

R

Rossi, G. (2023). BE-AM Symposium 2023. https://be-am.de/2023-2/

Rouquerol, J., Avnir, D., Fairbridge, C. W., Everett, D. H., Haynes, J. M., Pernicone, N., Ramsay, J. D. F., Sing, K. S. W., & Unger, K. K. (1994).

Recommendations for the characterization of porous solids (Technical Report). Pure and Applied Chemistry, 66(8), 1739—1758. https://doi.org/10.1351/pac199466081739

S

Setaki, F., Tian, F., Turrin, M., Tenpierik, M. J., Nijs, L., & van Timmeren, A. (2023). 3D-printed sound absorbers: compact and customisable at broadband frequencies. Architecture, Structures and Construction, (146), 1–11. https://doi.org/10.1007/s44150-023-00086-9

Severi, A. (2024, June 26). 3D printed cooling system in ceramic | TerraMound. 3D Printers | WASP. https://www.3dwasp.com/en/3d-printed-cooling-system-in-ceramic-terramound/

Shtrepi, L. (2019). Advances in diffusive surface design using 3D architectural parametric modelling programs. In PROCEEDINGS of the 23rd International Congress on Acoustics. https://pub.dega-akustik.de/ICA2019/data/articles/000765.pdf

T

Takahashi, H., & Miyashita, H. (2017). Expressive fused deposition modeling by controlling extruder height and extrusion amount. Design Frameworks. https://doi.org/10.1145/3025453.3025933

Tie, T. S., Mo, K. H., Putra, A., Loo, S., Alengaram, U., & Ling, T. (2020). Sound absorption performance of modified concrete: A review. Journal of Building Engineering. https://www.sciencedirect.com/science/article/pii/S2352710219325847#bib9

U

Urban Reef - Media. (2024). https://www.urbanreef.nl/media

V

Vasey, L. (2024). BE-AM | Symposium 2024 [Video]. BE-AM | Built Environment Additive Manufacturing. https://www.youtube.com/live/iO2XdG_hqfY

Conference presentation on Impact printing by Lauren Vasey

W

WASP. (2024, March 6). 3D Printer House | Crane WASP. 3D Printers | WASP. https://www.3dwasp.com/en/3d-printer-house-crane-wasp/

WASP. (2025). Ceramic 3D printer | WASP 40100 LDM. 3D Printers | WASP. https://www.3dwasp.com/en/ceramic-3d-printer-wasp-40100-ldm/

WASP. (2024). TECLA | A 3D printed global habitat for sustainable living. 3D Printers | WASP. https://www.3dwasp.com/en/3d-printed-house-tecla/

WASP. (2024). How to tell that clay is ready to be used for printing | FAQ stampa 3d. 3D Printers | WASP. https://www.3dwasp.com/en/faq/how-to-tell-that-clay-is-ready-to-be-used-for-printing/

X

Xie, S., Yang, S., Yang, C., & Wang, D. (2021). Sound absorption performance of a filled honeycomb composite structure. Applied Acoustics. https://www.sciencedirect.com/science/article/abs/pii/S0003682X19311338?via%3Dihub

Y

Yilmazer, S., Fasllija, E., & Yilmazer, C. (2022). Modeling parallel arranged transparent micro-perforated panels to enhance low-mid frequency sound absorption. Acoustical Society of America. https://doi.org/10.1121/10.0011006

Z

Zieliński, T. G., Dauchez, N., Boutin, T., Leturia, M., Wilkinson, A., Chevillotte, F., Bécot, F., & Venegas, R. (2022). Taking advantage of a 3D printing imperfection in the development of sound-absorbing materials. Applied Acoustics. https://www.sciencedirect.com/science/article/pii/S0003682X22003152

APPENDIX 1:
CASE STUDIES

IAAC | TOVA

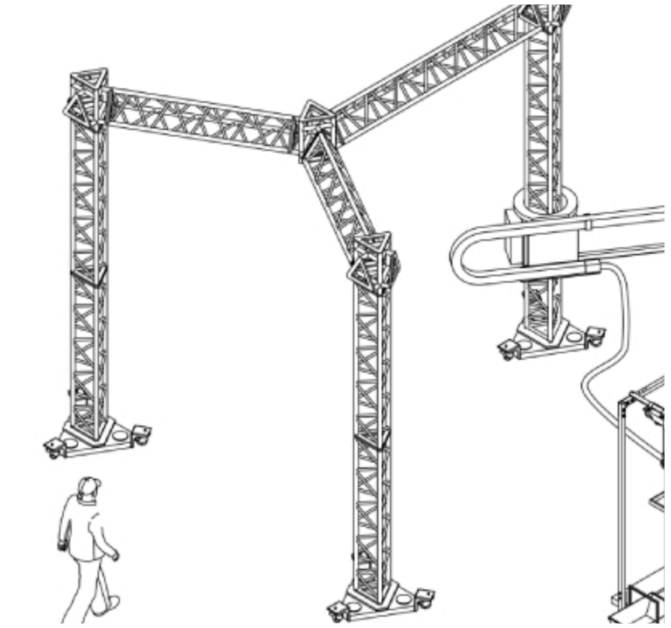
Site: Valldaura Labs in Barcelona
Architects: 3dPA students and researchers

CASE STUDY /01

Figure 15: TOVA: 3D Printed Prototype Using Earth (IAAC, 2024)

summary

TOVA is IAAC´s demonstrator of fast, waste-free and adaptable construction. This house was constructed in 7 weeks using a Crane WASP and km zero materials. This project aims to show a manufacturing system to be used anywhere and to help to housing emergencies.



technology

Figure 16: Crane WASP (WASP, 2024)

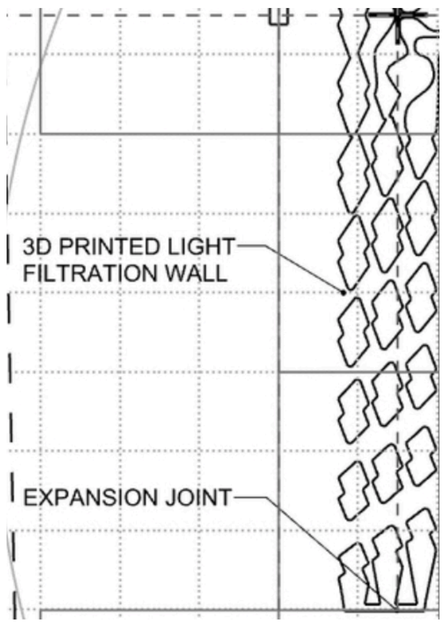


Figure 17: Wall inner geometry (Arquitectura Viva, 2024)

material

local earth, mixed with additives and enzymes, all 50 meter radius sourced. To ensure longevity, a waterproof coating is added using raw extracted materials such as aloe and egg whites (IAAC, 2024).

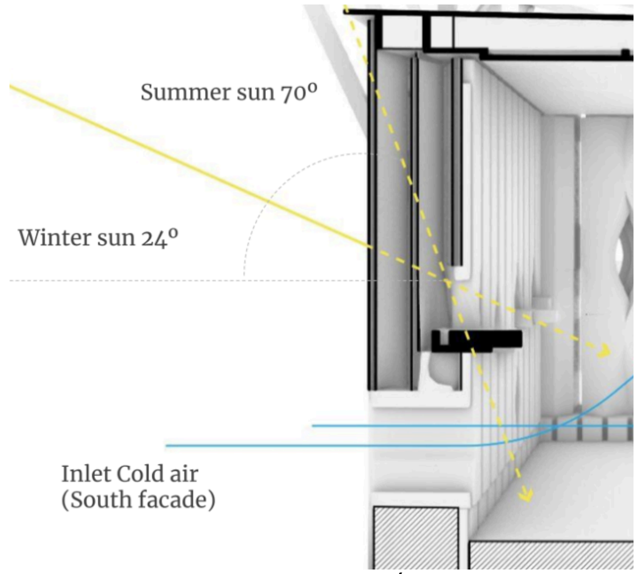


Figure 18: Light and air flow (Arquitectura Viva, 2024)

geometry

The walls are made up of a network of cavities that contain airflow and allow great insulation to prevent heat loss in winter and protect from solar radiation in summer.

Figure 19: 3D printing wall (Arquitectura Viva, 2024)

discussion

TOVA showcases material and geometrical aspects that ensure high architectural performance for 3D printing fabrication with dirt-based material. The infill structure allows **airflow**, **insulation** as well as **prevents heat loss**. TOVA is a great example of the implementation of computational design to achieve architectural features. Here it is clear why the material technology and geometry were selected. A selection that shapes a design that through one material 3D printed material multiple archhitectural needs are met.

infill for light filtration

TECLA

Site: Massa Lombarda, Italy
Architect: Mario Cucinella

CASE STUDY /02

Figure 20: TOVA (Mario Cucinella Architects, 2021)

summary

TECLA was established to satisfy the need for 0-km green housing. TECLA is an eco-sustainable housing prototype 3D printed from raw earth. Taking into account bioclimatic principles and using natural and local materials, the characteristics of the building envelope change for each project to provide the best-performing configuration for the specific site (Mario Cucinella Architects, 2021).

technology

Crane WASP (WASP, 2024).

geometry

The infill, composed of two layers with independent sinusoidal wave forms, varies according to such parameters as insulation, thermal mass, interstitial ventilation, and shading requirements (Mario Cucinella Architects, 2021).

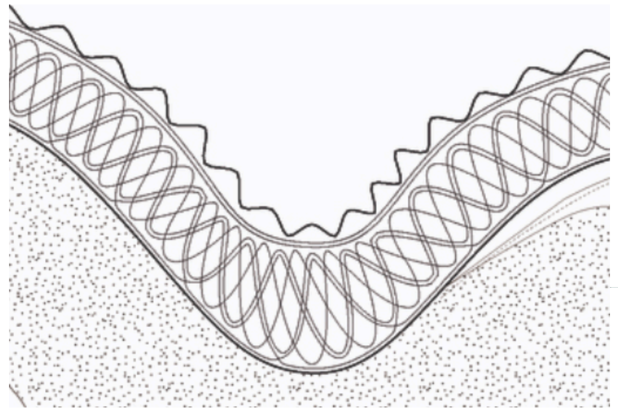


Figure 21: Infill wall (Mario Cucinella Architects, 2021)

Figure 22: Infill wall (WASP, 2024)

material

TECLA is created using reusable, recyclable materials taken from the local terrain (WASP, 2024).

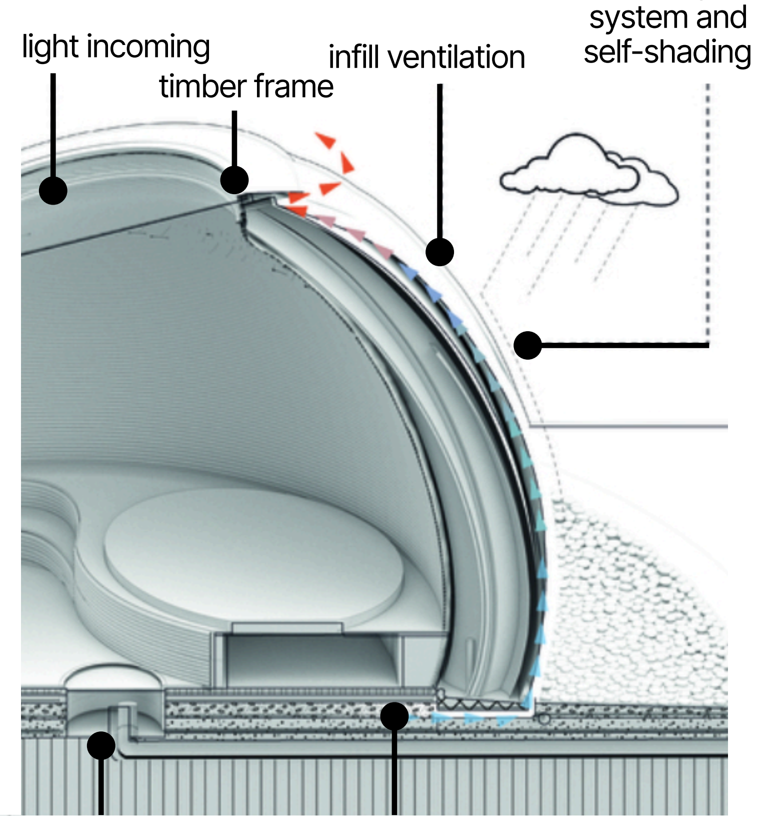


Figure 23: Geometry functionality(Mario Cucinella Architects. 2021)

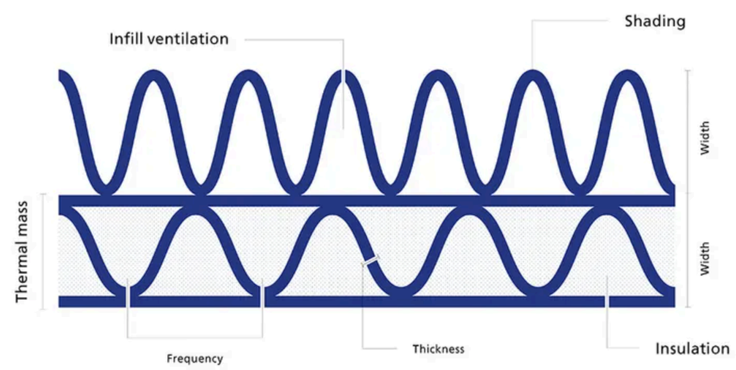


Figure 24: Infill waves (Mario Cucinella Architects, 2021)

discussion

TECLA gives a clear overview of how a wall structure affects **inner and outer performance** aspects. By sectioning the wall infill formation into two separate waves, TECLA addresses **multiple architectural needs**. TECLA, introduces th**e impact of infill variation** in the thermal and ventilation properties of the wall. This way, TECLA showcases a wall that changes its properties according to the needs of each location.

infill for heat insulation

IMPACT PRINTING

Site (of demonstrator): ETH Zürich
Architect: Lauren Vasey

CASE STUDY /03

Figure 25: Vertical wall fabricated with Impact Printing (Vasey, 2024)

technology

Impact printing is a novel, efficient, and sustainable robotic building method based on high-velocity discrete deposition using earth-based materials for larger structures (ETH Zurich Sustainable Construction, 2023). The robotic building process resembles 'shooting' from a close range, where parts of the material are deposited at high speeds and frequencies. As a result in monolithic material structures are constructed (Chadha et al., 2024). The high initial yield stress (>26kPa) keeps the continuous production straight (Vasey, 2024).

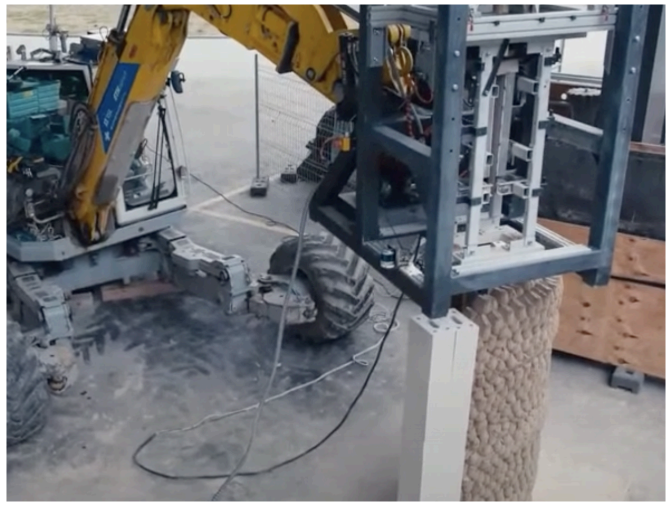


Figure 26: Impact printing (Vasey, 2024)

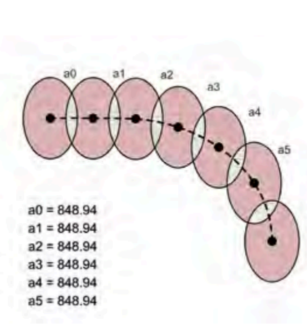


Figure 27: Iterative spacing (Chadha et al., 2024)

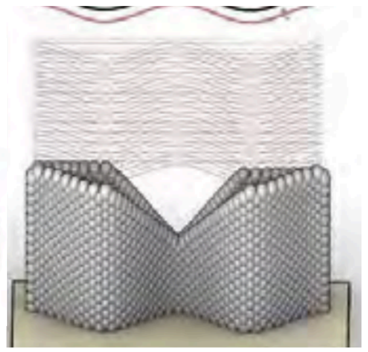


Figure 28: Nonplanar sequencing (Chadha et al., 2024)

material

75% local by products from construction company and 1-2% additives, this low percentage is due to the high initial yield stress. (Vasey, 2024).

Figure 29: Seamless material connection with no dry joints (Vasey, 2024)

geometry

Researchers from ETH Zürich have designed systems and construction strategies for impact printing to achieve complex geometries and implementing windows (Figure 30). Demonstrating the effective application of iterative spacing for tapered columns with varying toolpath lengths (Figure 27). And non planar sequencing to add frames (Figure 28).

Figure 30: Impact printed structures (Chadha et al., 2024)

discussion

This additive manufacturing process allows **mechanical bonding without any formwork** as it withstands vertical build-up without deformation. This way impact printing allows proper **mechanical bonding for materials with extremely high yield stress** as for example bio-materials. Unlike extrusion based, there is no need to wait for the material to gain mechanical strength as with this technique there is **no relying on the rapid curing of the material.** Thus, this project is a great example of controlling the properties of the material in terms of bonding and curation time through a manufacturing process.

material overlap for bonding

TERMITE STRUCTURES

Site: Venice
Architect: Vanessa Costalonga

CASE STUDY /04

summary

As an approach to bio design in the build environment field, transcalar design is used a method "which weaves together nonlinear dependencies using computational design tools and design methodologies through the biological generation of architectural components, is a way towards successful design implementations" (Goidea et al., 2022). This prototype is a wall that serves as a bio-receptive breathing system that allows piping and electricity. To materialise this project, a material compatible with fungus had to be designed, and the geometrical aspects of the wall, were defined by negotiating with the natural needs of the material.

Figure 31: Fungus growth (Costalonga, 2024)

Figure 32: Fungus and wood tower (Costalonga, 2024)

discussion

This project shows a clear example of how **material** and **form** can be thought of and produced simultaneously to minimise energy and material waste while **building behaviour throughout material systems in a synergistic manner** for new material expressions (DREAM, 2024). This project allows bio receptiveness and nature-integration not only by material recipe but by defining a geometry that meets the living material´s needs.

material

Substrade lignocellulosic stock/natural fibres. Mycelium binding the material together. This allows for the material to be hydrophibic and so it maintains its mechanical properties after being soaked as it binds together the wood fibres (Costalonga, 2024).

Figure 33: Prototype printing (Costalonga, 2024)

technology

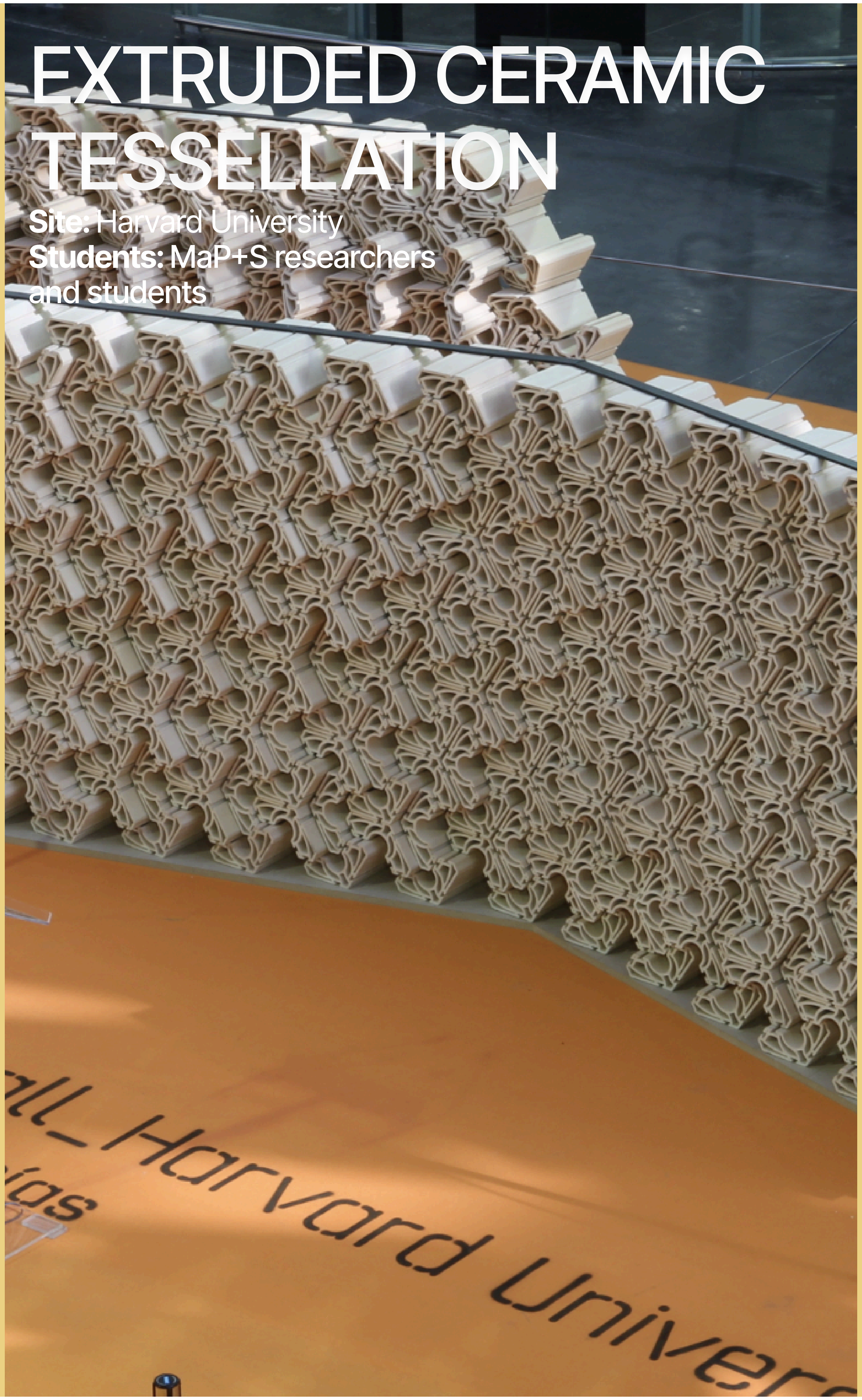
3D cartesian printer.
Honeycomb metal bed structure to achieve better bed adhesion.

geometry

In this project termite structures are used as an array of interconnected channels that move air from the inside to the outside using very low energy (Costalonga, 2024). It also includes functions such as piping and electricity as a multifunctional wall. As this wall is designed for growing urban bio diversity, thus the geometry is also defined by the need of the fungus to expand. And so the cavities is the prototype´s geometry are modelled to let the fungus breathe and to enable even drying with no cracks.

biomimicry

human and material needs



EXTRUDED CERAMIC TESSELLATION

Site: Harvard University
Students: MaP+S researchers and students

CASE STUDY /05

summary

'Hyper-Ceramic Tessellation' experiments with mass-customised construction through robotically 3D printed bricks (ExLab University of Melbourne, 2019).
When using robotic fabrication hyperbolic surfaces can be panelised into unique individual components than can be arranged into the desired surface. This research proposes a construction process for ceramic shells that reduces the requirements for formworks on-site work, and waste production (Imbern et al., 2017).

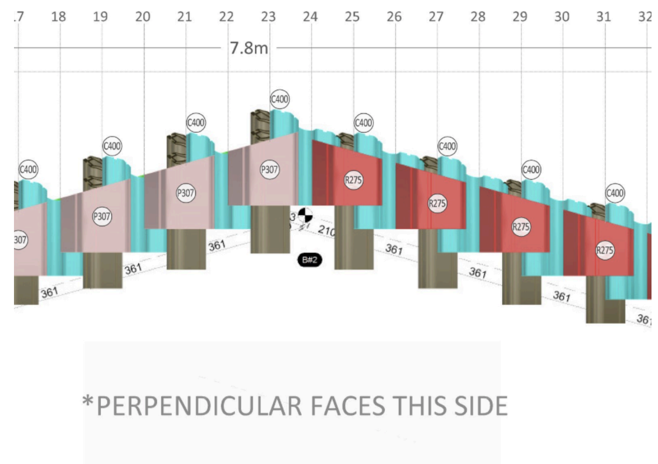


Figure 34: Panels top view (MaP+S Group, 2017)

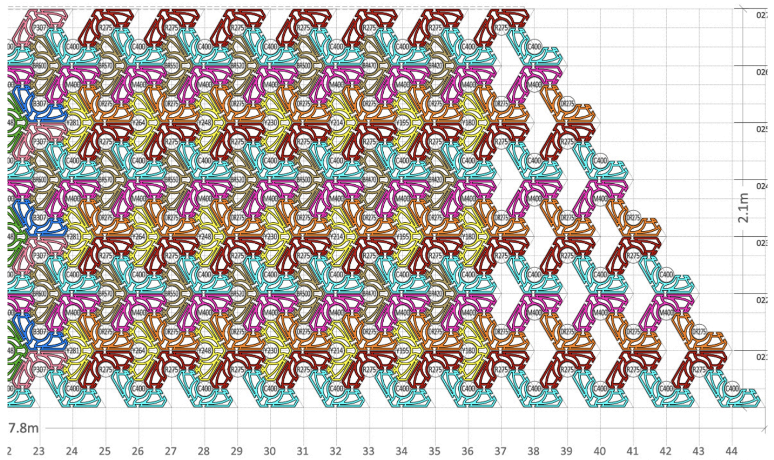


Figure 35: Panel types (MaP+S Group, 2017)

material

ceramics

technology and geometry

Robotic manipulators equipped with wire-cutters can be integrated into the production system to trim off the end surfaces at custom angles and lengths as the wet clay is extruded MaP+S Group (2017). Alternatively, CNC disk cutters can perform automated cutting operations after the large ceramic extrusions have been fired. Both strategies enable low-cost ceramic module customisation to control views and light, create a distinctive three-dimensional expression, and meet various wall structural requirements (MaP+S Group, 2017).

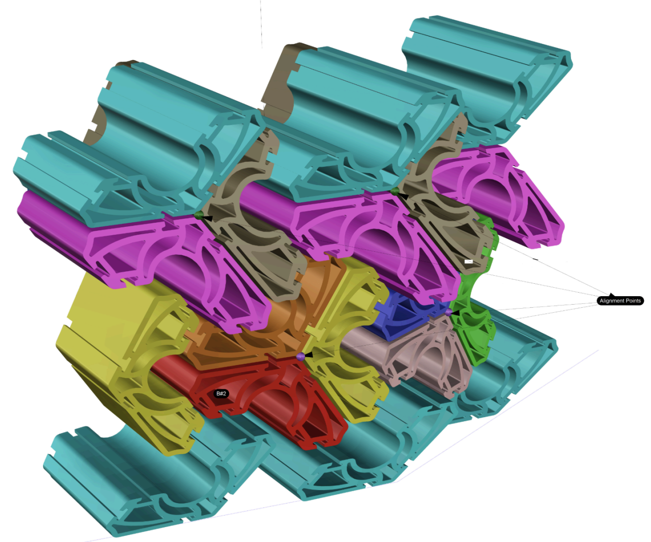


Figure 36: Panel allignment (MaP+S Group, 2017)

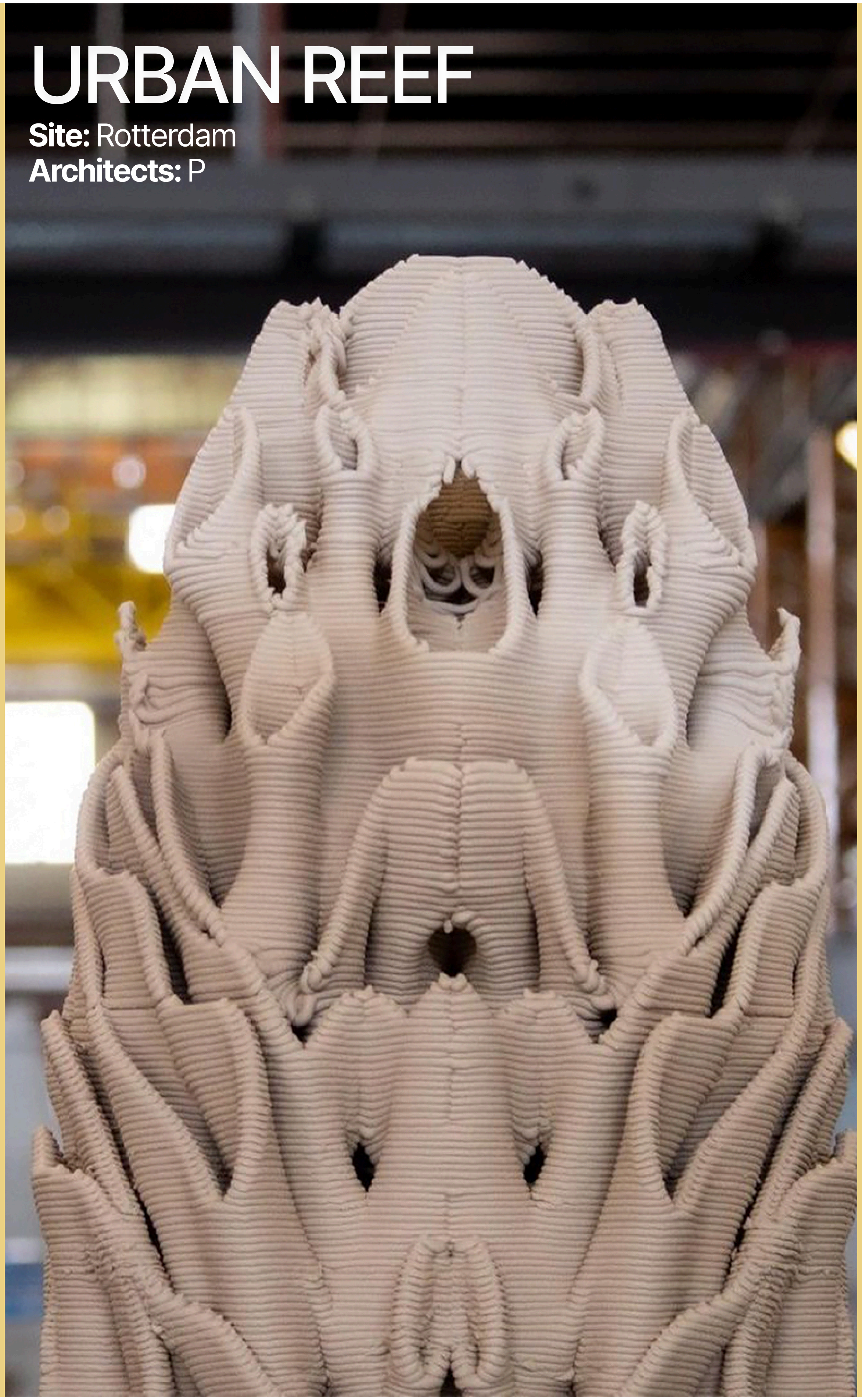
discussion

This wall building approach shows a clear application for **minimising material** and **not using of formworks**. The definition of **multiple unique elements** allows to create a **unique surface texture** on every wall surface while **maintaining consistency**. This project has a very **distinctive ornamental look** that expresses organised geometrical variations.
Though these tiles are extruded and not 3D printed, they are included in the case studies as they show an application of geometry specific parameter modification to build complex surfaces.

panelised design

URBAN REEF

Site: Rotterdam
Architects: P



CASE STUDY /06

summary

Urban Reef uses computational design, 3D printing technology and intrecate structures that rejuvenate urban landscapes.

technology

WASP 3D clay printer.

Figure 37: Green Village sample integration (Urban Reef, 2024)

Figure 38: Growing organisms (Urban Reef, 2024)

material

natural materials like clay, coffee grounds and mycelium.

geometry

These reefs are made to collect water and create a **porous wall that absorbs the moisture** creating a livable condition for plants or fungai.
To achieve this, the samples geometry consists of **intersecting pipes**. And the **printing path is altered to achieve further wall texture** for living organisms to grab onto.

Figure 39: Inner piping (Urban Reef, 2024)

Figure 40: Print path variations (Urban Reef, 2024)

discussion

Urban reef has its key point in making structures to nurture nature in the urban landscape. This is possible not due to only print geometry and in urban environment integration, but it is the **material porosity** that enables organisms to grow in. It is remarkable how this porosity is achieved also through **toolpath variations**.

printed porosity

CASE STUDY /07

MINERAL FOAM INSULATION

Site: ETH Zürich
Architects: Patrick Bedarf, Anna Szabo, Michele Zanini, and Benjamin Dillenburger

summary

This projects aim is to build wall systems that are monolithic, lightweight, and immediately insulated, minimizing material use, labor requirements, and associated costs (Bedarf et al., 2023). Thanks to its porosity, mineral foam may be placed in different densities, strategically dispersing strength and insulation where it is needed. This way the thermal efficiency and energy usage required to heat interior rooms can be optimised. Additionally, by using a single material with different densities it is easier to in the future reuse and recycle the parts.

technology

The robotic F3DP setup is used to continuously mix a stream of base slurry with hardener and air, extrude it to a foam beam, and print it. A six-axis robotic arm is used to print. The printhead acts as a mixing and foaming chamber.

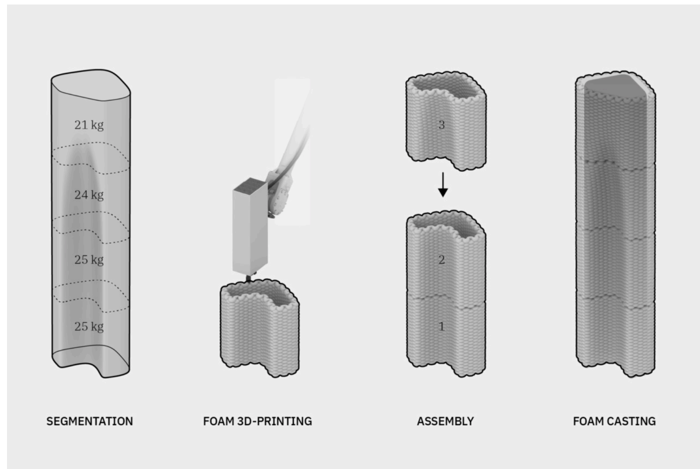


Figure 41: Design and fabrication sequence (Bedarf et al., 2023)

material

Cement-free mineral foam made from recycled waste. (FenX, 2024)

geometry

This prototype is composed of four hollow segments, that construct a wall when assembled. Each piece is sliced with a toolpath that creates a contour-perpendicular zigzag shell. Each piece's corrugated texture gives the finished structure more strength and structural integrity.
Mineral foam can be poured into the central cavity, resulting in a monolithic formation.

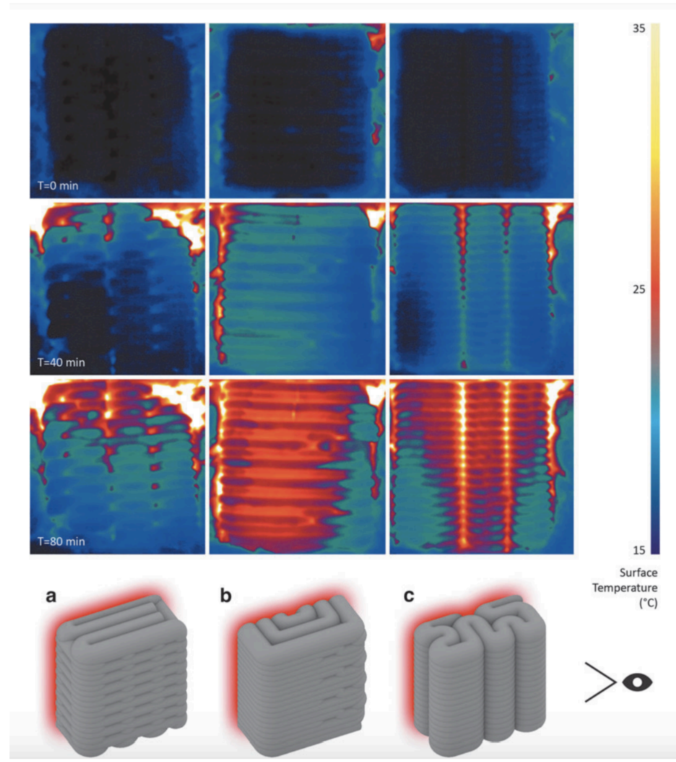


Figure 42: Thermographic comparison of infill schemes after 0, 40, and 80 min (Bedarf et al., 2023)

discussion

This project is a clear example of developing novel applications that leverage **advanced print path schemes to optimize thermal and structural performance with varying material densities**. The final prototype is made hallow to fill it with foam or concrete for structural integrity. Nevertheless, the analysis of of the printed samples in terms of thermal insulation, show a clear **correlation between printing path and acquired insulation**.

printing path as insulation

3D-PRINTED SOUND ABSORVERS

Site: TU Delft Faculty of Architecture
Architects: Foteini Setaki

CASE STUDY /08

summary

Conventional sound absorption technologies fail to implement optimised performance due to the difficulty of producing complex shapes. This research shows an implementation of wave propagation theory on a 3D environment by applying additive manufacturing.
The computational tool used to automate the process of form customisation, via free-form shapes, and optimising acoustic performance is benefcial for increasing the quality of a space, and demonstrates the potential of the additive manufacturing technique.

technology

The SLS printing method and PA12, a polyamide, were used to produce the output geometry.

material

Cement-free mineral foam made from recycled waste. (FenX, 2024)

geometry

This research showcases two walls that are constructed by panels that have open tube structures. The amount of tubes and the tubes lengths and radius are defined by the sound frequency that is aimed to be reduced calculated basing of based on the model of Zwikker and Kosten for viscothermal wave propagation in prismatic tubes (Setaki et al., 2023). With this, Rhino/Grasshopper software is used to generated the desired geometry using TADO. TADO is based on an algorithm that packs tubes with circular profiles on a given surface (Setaki et al., 2023).

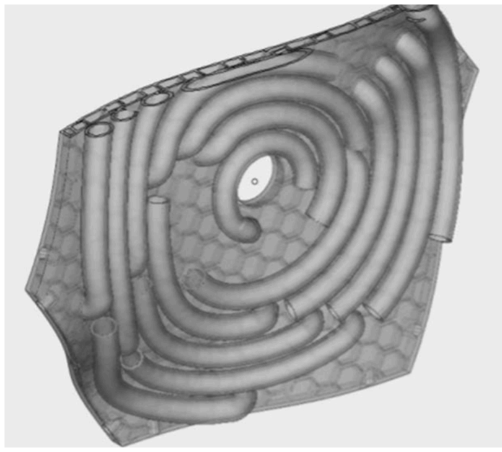


Figure 43: Single panel (Setaki et al., 2023)

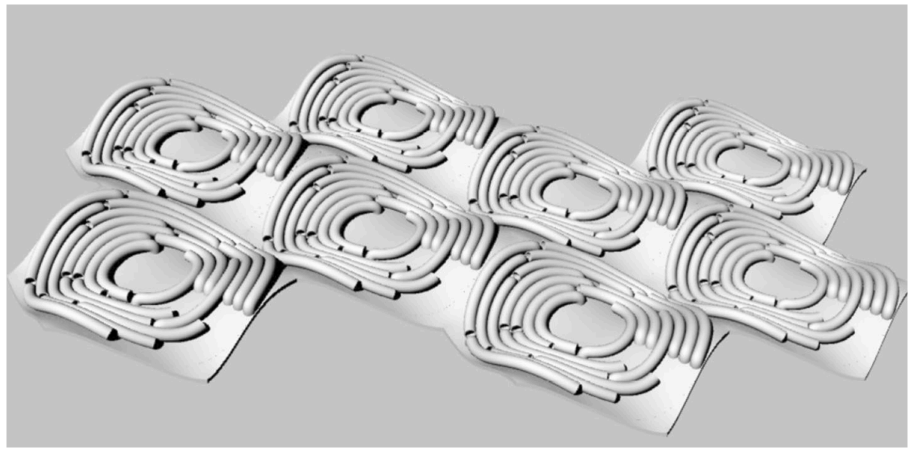


Figure 44: 3D wall model (Setaki et al., 2023)

discussion

This research demonstrator shows a possibility of producing compact resonant absorber panels for low frequencies by taking advantage of additive manufacturing. By implementing **open tube structures** in a walls structure, notable **sound frequency reduction** was experienced, an interesting finding that could be implemented in a wall´s infill geometry. Though this project is not in the cold extrusion AM technology field, it is included for its **geometrical feature showing an application of theory for building wall sound insulation.**

geometry for sound absorption

CASE STUDY /09

Terra Mound

Site: Bartlett School of Architecture's
Architects: Rameshwari Jonnalagadda

summary

TerraMound is an ecologically driven, natural cooling system for the built environment. These 3D printed clay prototypes showcase a solution for the efficient cooling of buildings. Minimal surface geometries offer a high surface area, ideal for maximizing cooling and airflow – key elements for an efficient cooling system. This porous network system has also the advantages of bio-receptivity and acoustic control.

technology

Delta WASP 40100 Clay (Severi, 2024).

material

Terracotta clay. This material is suitable for cooling as it absorbs water effectively. As the water evaporates, it helps lower the surrounding air temperature.

geometry

With the mathematical minimal matter principal using gyroid unit cells, a system of porous networks is created.

Figure 45: Demonstrators (R. Jonnalagadda, 2024)

Figure 46: Infill geometry (R. Jonnalagadda, 2024)

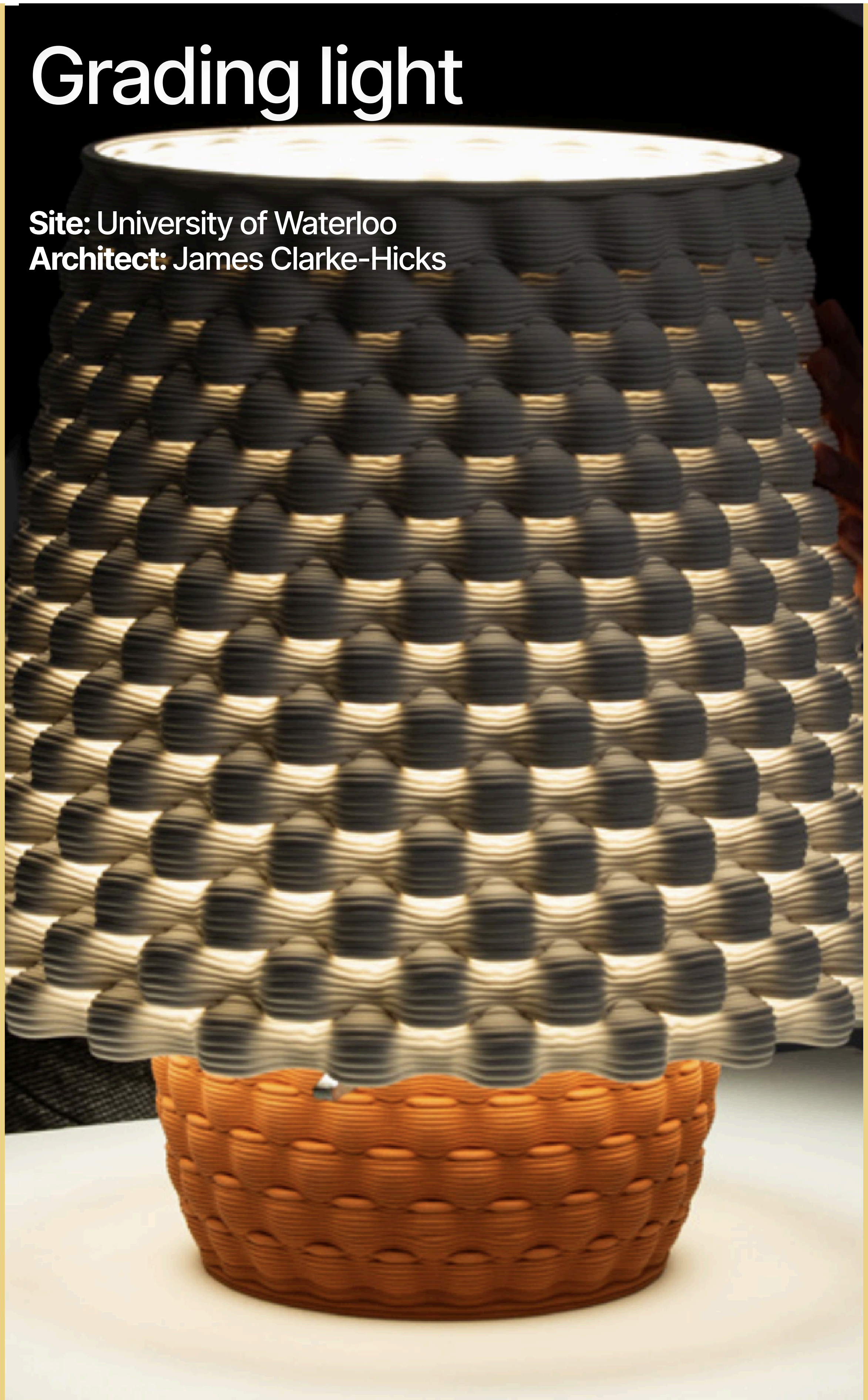
discussion

This project shows a clear application of minimal matter, a principal normally used in the aerospace context. Through geometry, a system of porous networks is made, which is beneficial for **ventilation, bio-receptivity and acoustic control**. Further, minimal surfaces can be **incorporated into walls to create adaptive interfaces** to manage heat, air, and light. Accordingly, minimal matter does not only solve the problem of minimal use of material, but also achieved architectural features through the variation of infill.

minimal material

Grading light

Site: University of Waterloo
Architect: James Clarke-Hicks



CASE STUDY /10

summary

Grading light is a project that studies digital tooling methodologies that respond to material behaviour. By studying porcelain's translucency combined with cavity generation through toolpath variation, Grading light features a wide range of prototypes that achieve variable lighting outputs.

technology

3D clay printer

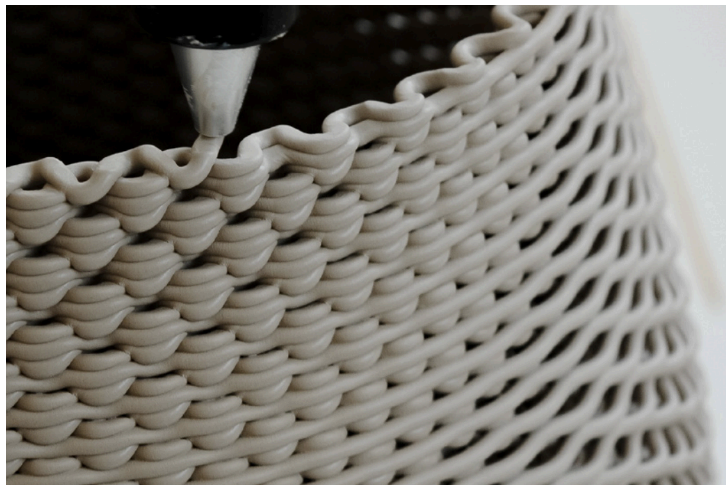


Figure xx: Printing of toolpath variations (Clarke-Hicks, 2021)

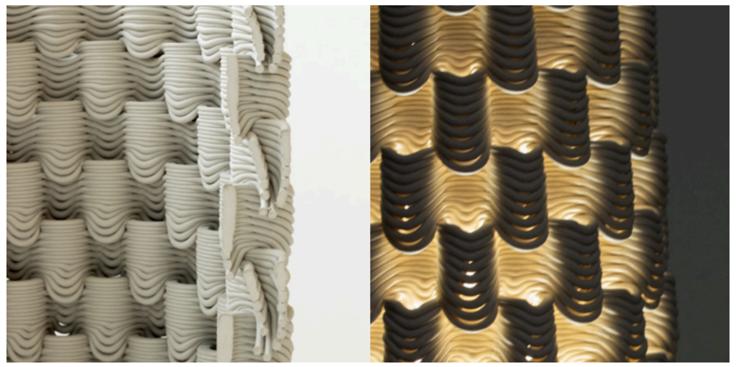


Figure xx: Section of print and light integration (Clarke-Hicks, 2021)

material

Terracotta clay. This material is suitable for cooling as it absorbs water effectively. As the water evaporates, it helps lower the surrounding air temperature.

geometry

Grading light showcases an in depth study on toolpath variation to modify the perception of depth and alter illumination. The two parameters studying to modify outputs were the number of layers in a print pattern and wave divisions. Generating different typologies that influence light grading differently.

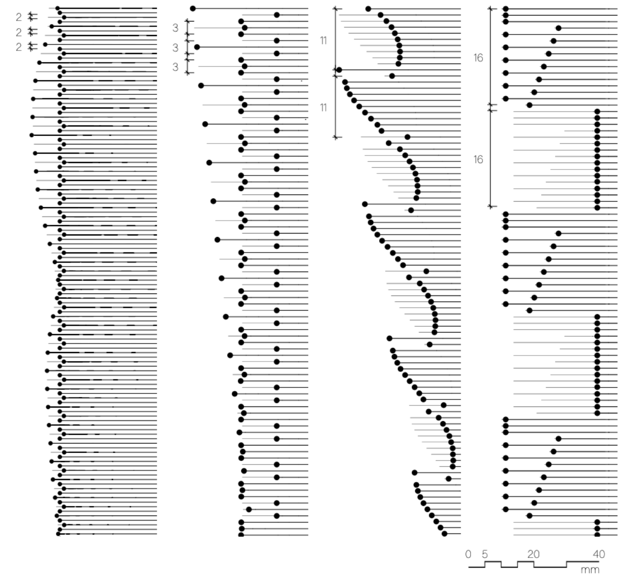
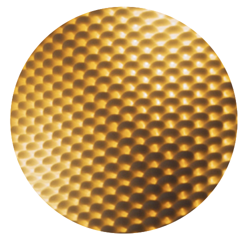


Figure xx: Toolpath sections (Clarke-Hicks, 2021)

discussion

Grading light is a great example of **studying toolpath variation and its impact in material outputs**, to control a certain feature. The prototypes generated in this project clearly show the combination of **understanding in toolpath variation and achieved material behavior**.



control lighting

Appendix 2: Preliminary experiments

MATERIAL PRINTING RESOLUTION EXPERIMENTS

Detail resolution and overhang

Collapse without infill

Cleanness of material retraction

DETAIL RESOLUTION AND OVERHANG
13/12/24
TEST 7

prototype goal

What is the detailing accuracy and overhang limit of the material?

testing

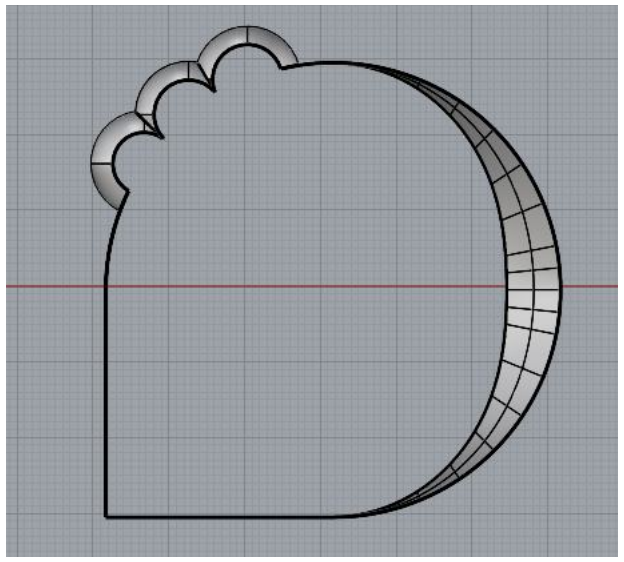
3D print sliced using Simplify3D. Printed with a WASP printer and 6mm nozzle

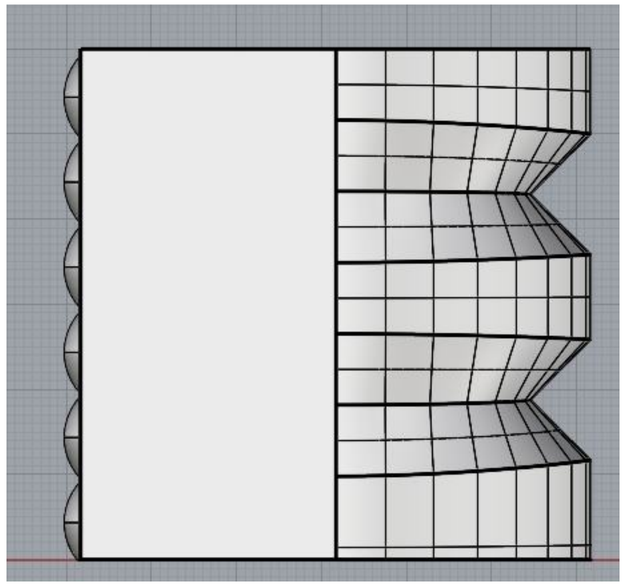
approach

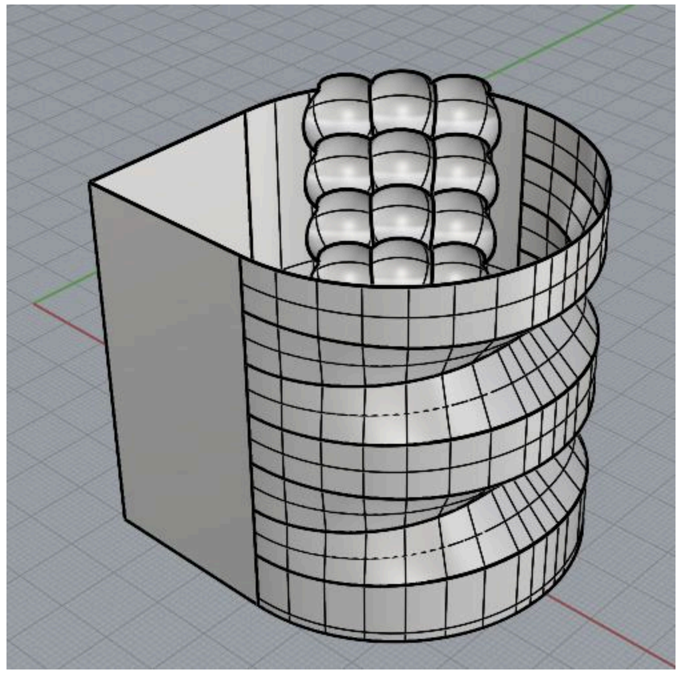
Geometry -Test piece defined for “Formulating and Testing a Clay Body for Extrusion Clay 3D Printing” (J. Keep, 2020)

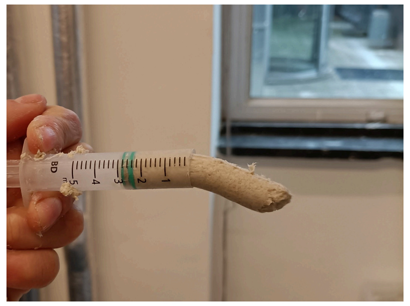
file

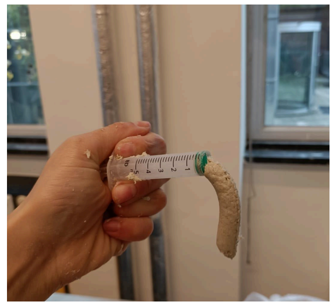
241106_test.gcode











material mixture

1000ml or water plus spraying

material syringe test

>45 degrees, too soft

production notes

Pressure: 0.5
Nozzle: 8mm
Flow: 0%
Speed: 0%

findings

The material can withstand a maximum of 30 degree overhang and the details are rather rough. The roughness achieved in this test is due to the material deposition being mainly because of the pressure and not motor (it was borken).

conclusions

- The material can withstand a maximum of 30 degree overhang

COLLAPSE WITHOUT INFILL
10/12/24
TEST 3

prototype goal

When does the material collapse when doing a single wall with wall angles?

testing

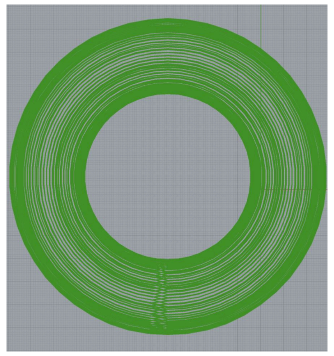
3D print custom polyline sliced using the Termite plug-in on Grasshopper. Printed with a WASP printer

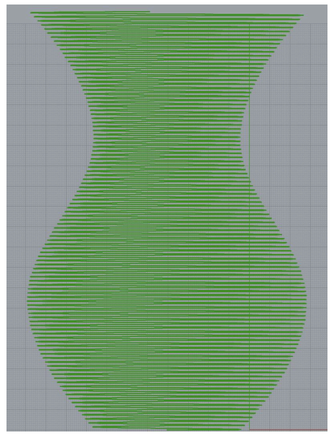
approach

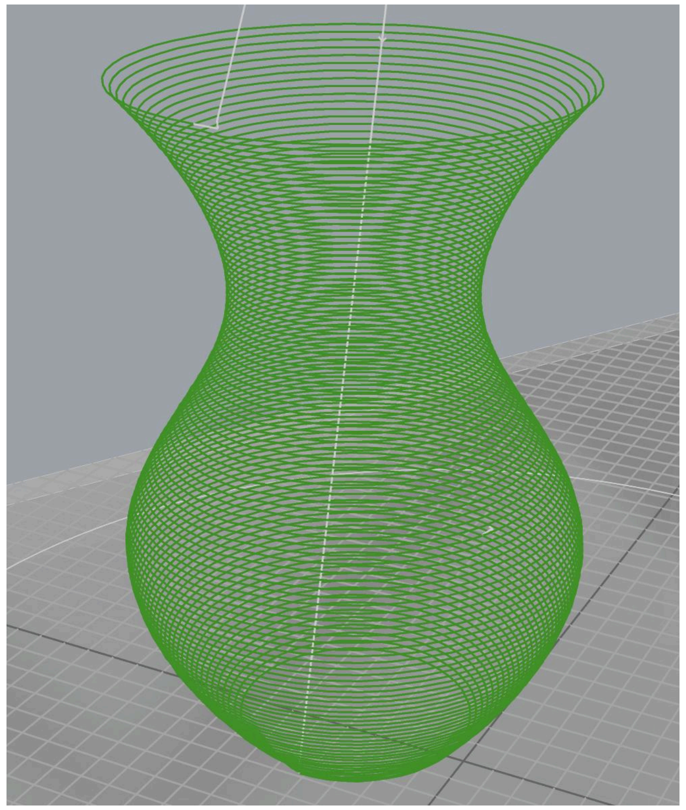
Creating a printing path single wall spiralized path with wall angles of up to 50 degrees

file

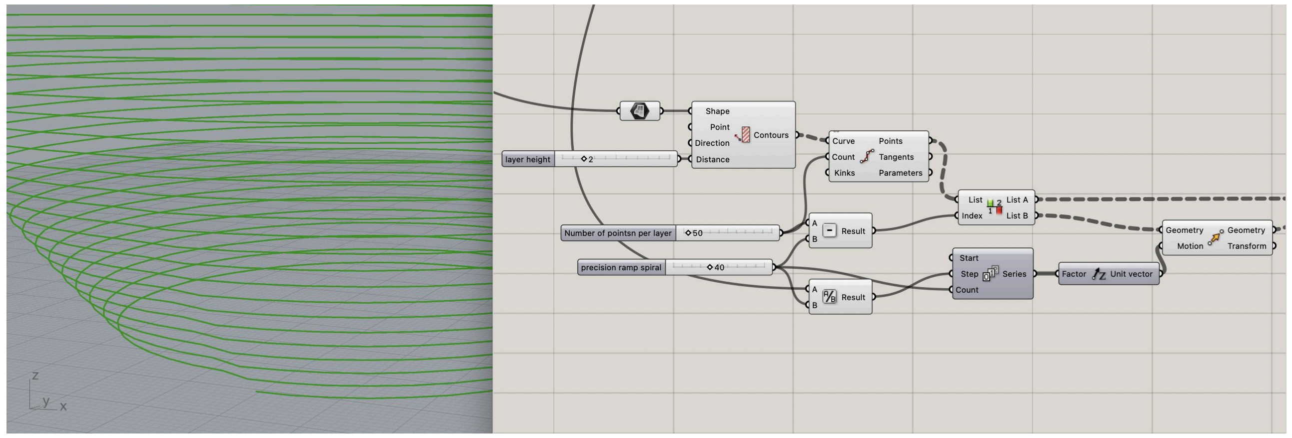
241210_nvase_simple.gcode



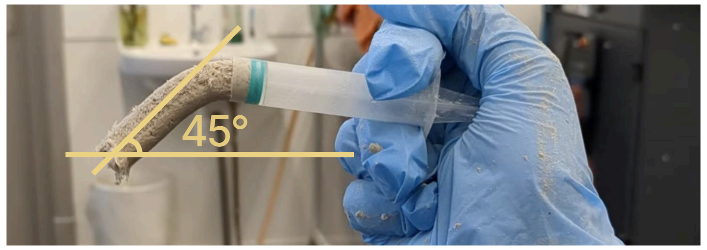




LH: 2mm
H: 205 mm
W: 137 mm



To hide the seam, the prototype´s polilyne was spiralised using 40 points for the precision ramp.



material mixture

1000ml or water plus 3 times spraying

material syringe test

45 degrees, good!

production notes

Pressure: 0.5
Nozzle: 8mm
Flow:50%
Speed: 100%
WT: 8.5mm

findings

The print deforms as the wall builds higher. The print can not be finished. Maybe the spiral is using too many points as the wall looks like it is twisted

conclusions

- Reduce spiral points
- For the next print track LH over time
- Try out drying layers as it prints for building higher walls
- Try adding an infill
- For next print document at which layer the print was stopped

RETRACTION TEST
13/12/24
TEST 7

prototype goal

How clean is the travelling retraction?

testing

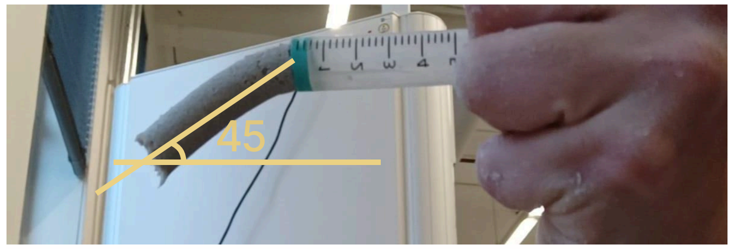
3D print sliced using Simplify3D. Printed with a WASP printer

approach

The start of a gyroid structure print involves multiple single lines separated from each other. Thus only the start of the print of a takes a lot of travelling retraction.

file

241213_gyroid.gcode



material mixture

1000ml or water plus 3 times spraying

material syringe test

45 degrees, good!

production notes

Pressure: 0.5
Nozzle: 8mm

findings

The retraction is quite sharp. When pulling the material to retract the fibres of the material become more visible and the surface becomes more rough.

LAYER HEIGHT VARIATION EXPERIMENTS

Extrusion rate

Feed rate

Feed rate with overhang

EXTRUSION RATE
13/12/24
TEST 7

prototype goal

How does the wall thickness stay the same when setting the flow rate by a percentage according to the layer height?

approach

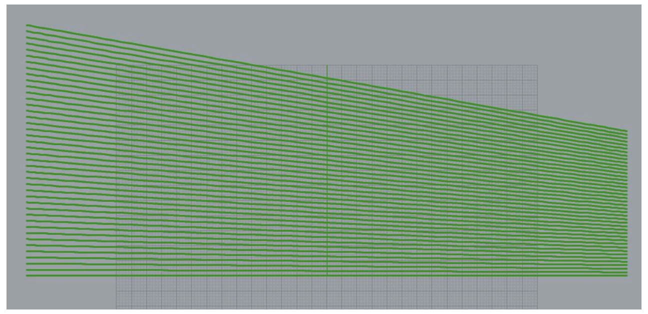
3D print non planar polyline sliced with a custom made slicer. In the slicer the vector lengths are remapped into 0.5 to 1. The number assigned from this defined range refers to the distance between layers.

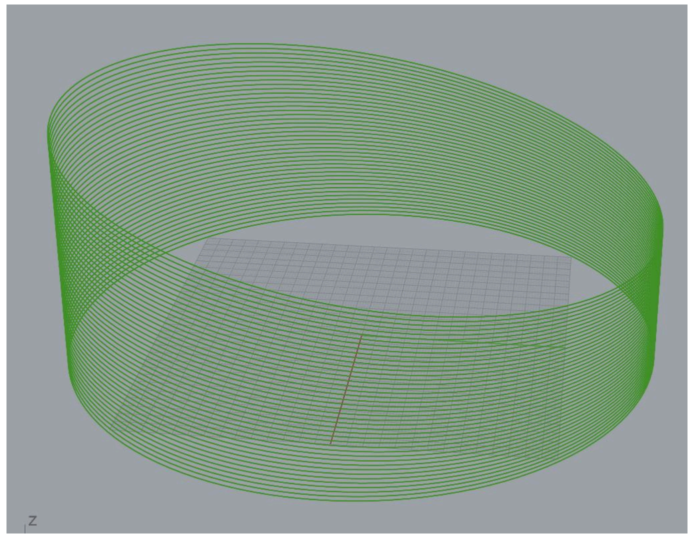
testing

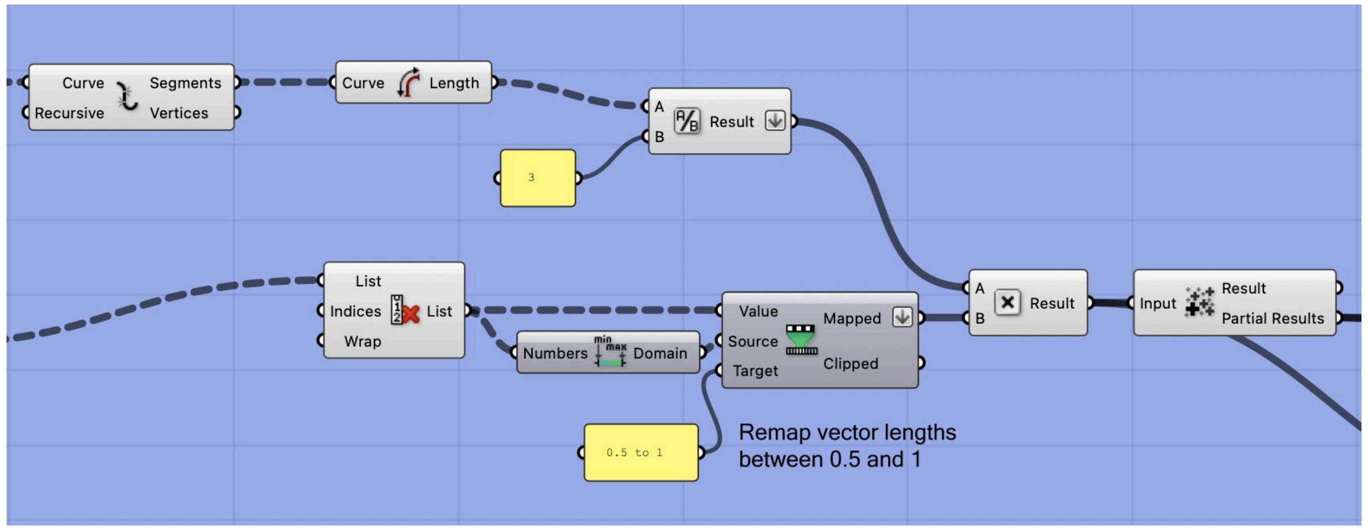
3D print non planar polyline sliced with a custom made slicer. Printed with a WASP printer

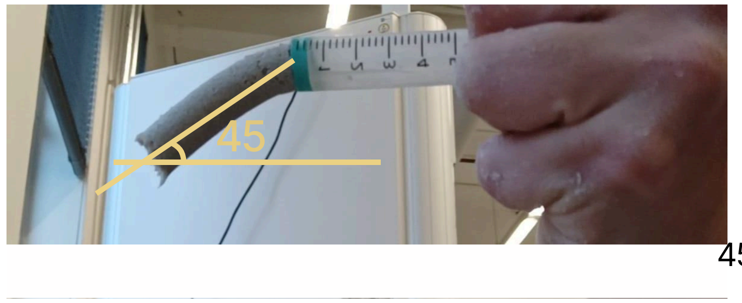
file

241213_1_carmenslicer.gcode









material mixture

1000ml or water plus 3 times spraying

material syringe test

45 degrees, good!

production notes

Pressure: 0.5
Nozzle: 8mm

findings

The WT does not stay the same and goes from 6mm to 11mm.

FEED RATE
13/12/24
TEST 6

prototype goal

Does defining the speed rate value domain through the flow values help achieve a constant wall thickness?

approach

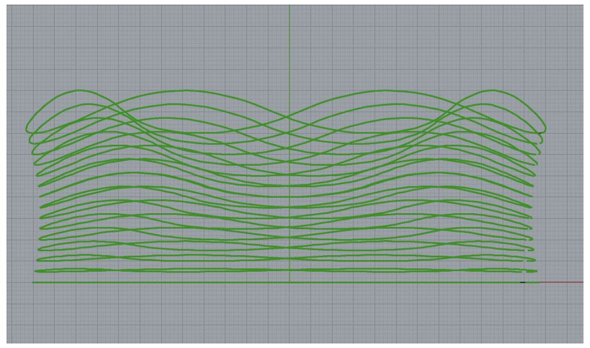
Defining the max and min speed as:
Feed=Extr/LW*LH

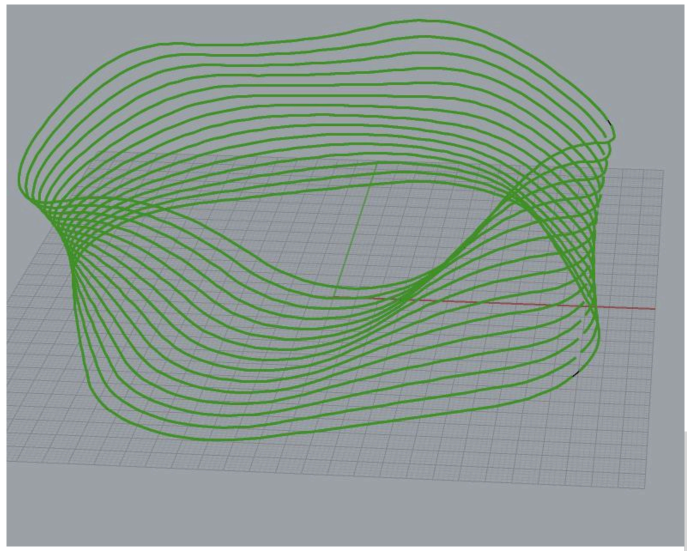
testing

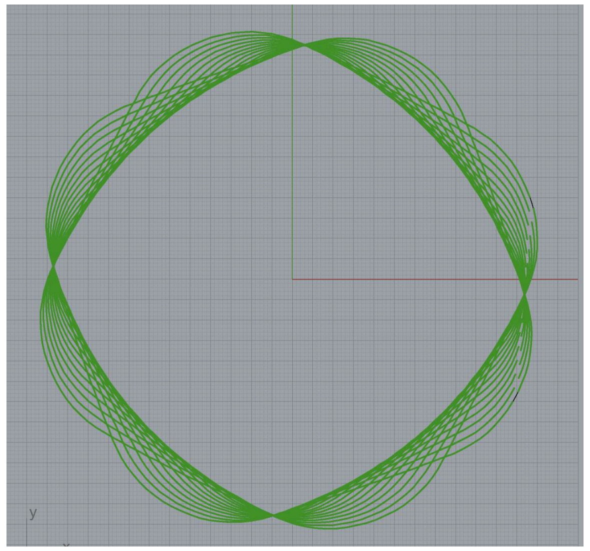
3D print non planar polyline sliced with a custom made slicer. Printed with a WASP printer

file

241211_FIXnonplanar_carmenslicer.gcode







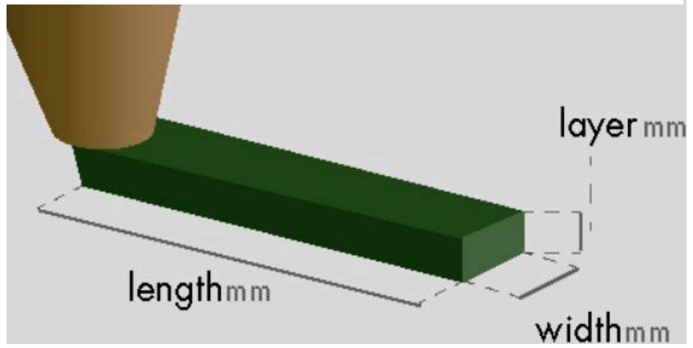
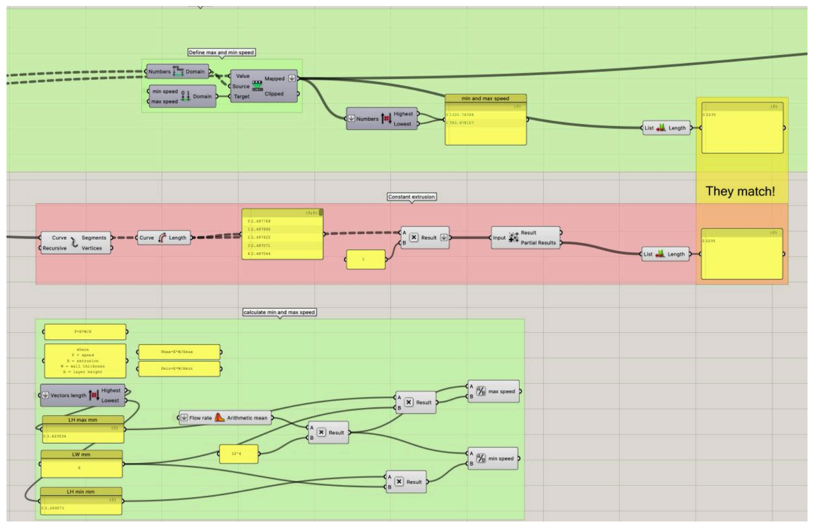
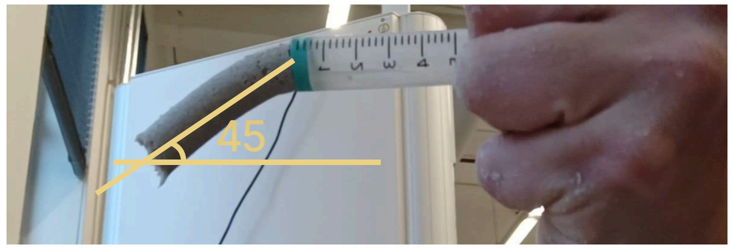


Fig. 60: Layer metrics (Ozdemir et al, 2024)



As the extrusion is defined by E=W*H*L/T, where Feed=LL/T, then we can define the the max speed as: Fmax=E/W*Hmax, and minimum as Fmin=E/W*LHmin. The layer width was set as 8mm. F = speed, E = extrusion, W = wall thickness, H = layer height, T=time, and L = layer length.



material mixture

1000ml or water plus 3 times spraying

material syringe test

45 degrees, good!

production notes

Pressure: 0.5
Nozzle: 8mm
Flow: 25 and 35%
Speed: 100%
WT: 9-11 mm

findings

The wall thickness was between 9 and 11 mm. While in the slicer it was set as 8mm. We can conclude that the speed rate is somewhat accurate as the wall thickness variance is a difference of 2mm.

FEED RATE WITH OVERHANG
13/12/24
TEST 6

prototype goal

Does defined speed rate help construct diagonal walls?

approach

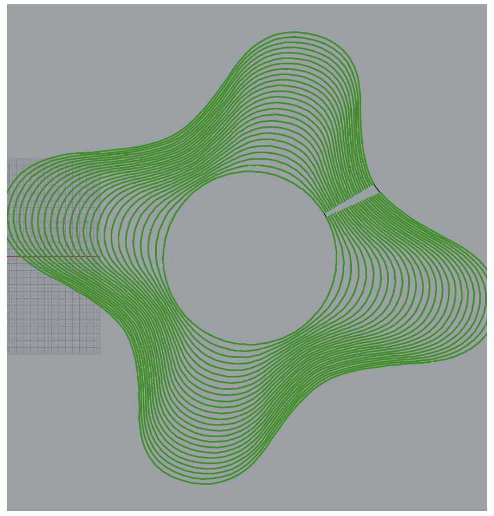
Defining the max and min speed as:
Feed=Extr/LW*LH for a eometry with 50% overhang

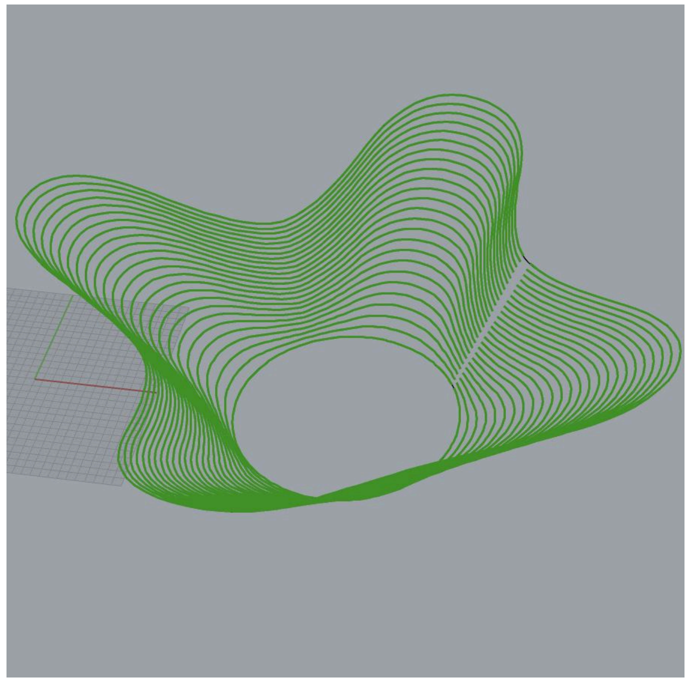
testing

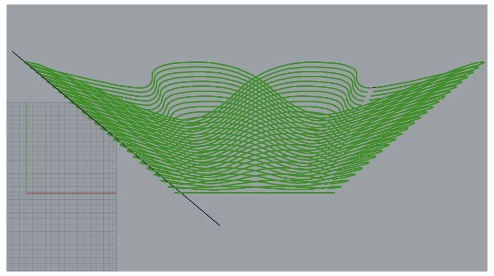
3D print non planar polyline sliced with a custom made slicer. Printed with a WASP printer

file

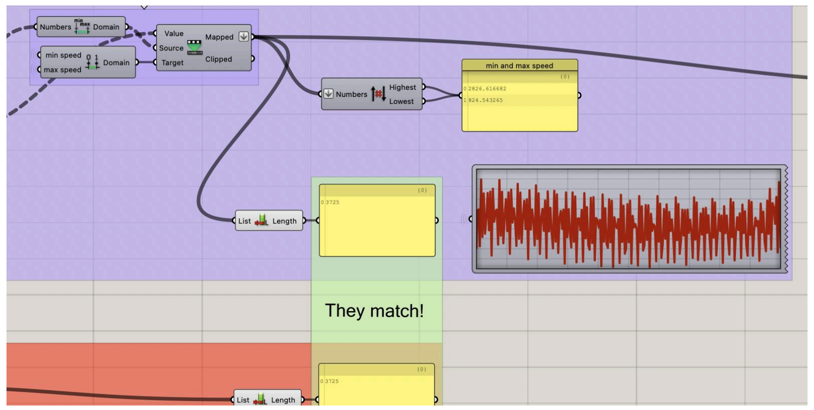
241211_complexnonplanar_carmenslicer.gcode



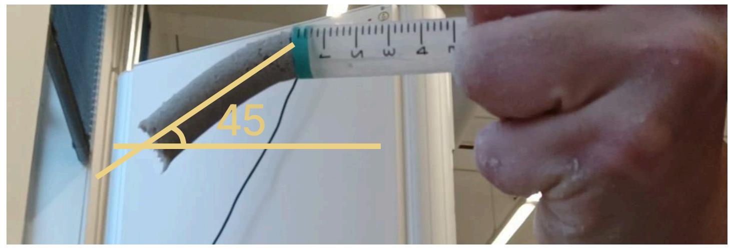




LH: 2mm
H: mm
W: mm



The graph shows the changes in speed overtime.



material mixture

1000ml or water plus 3 times spraying

material syringe test

45 degrees, good!

production notes

Pressure: 0.5
Nozzle: 8mm
Flow: 50%
Speed: 100%

findings

The layer heigh increases as it builds up since the material can not withstand the 50 degree overhang

REPETITIVE PATTERNS EXPERIMENTS

Short zig zag

Long zig zag

Wave texture

SHORT ZIG ZAG
15/01/25
TEST 8

prototype goal

Is the material roughness increased or decreased when printing repetitive patterns?

testing

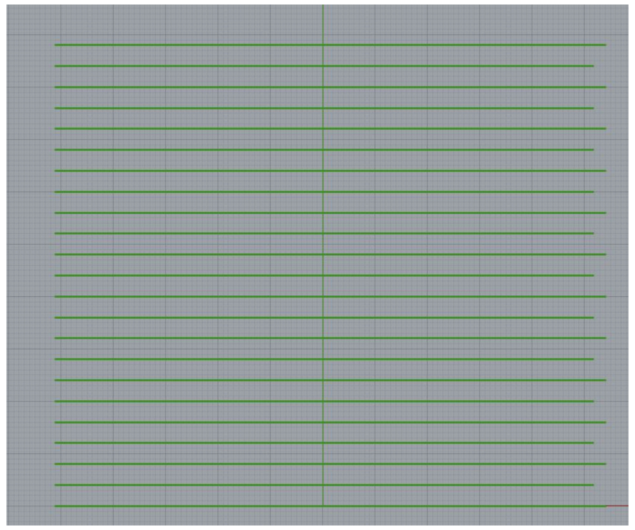
3D print custom polyline sliced using the Termite plug-in on Grasshopper. Printed with a WASP printer

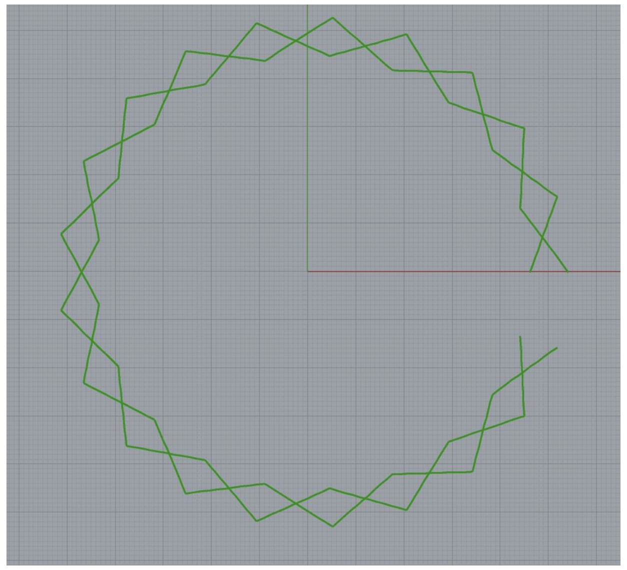
approach

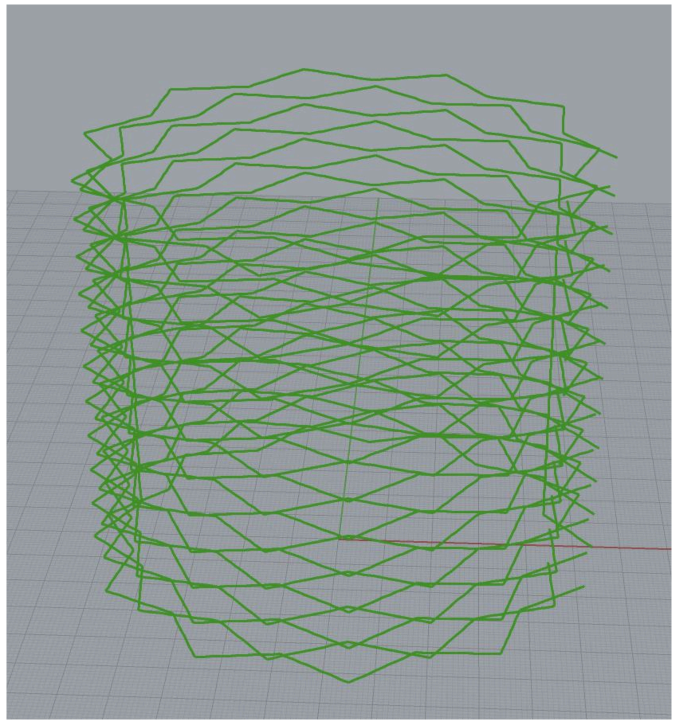
Creating a zigzag printpath

file

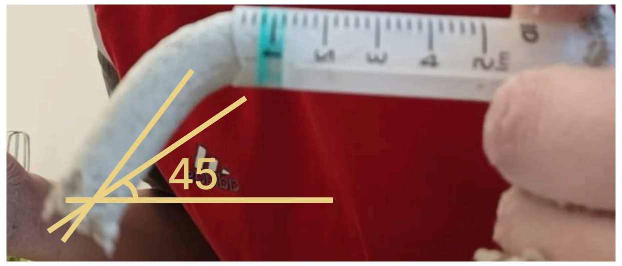
250109_zigzag.gcode







LH: 4mm
H: 90mm
W: 90 mm

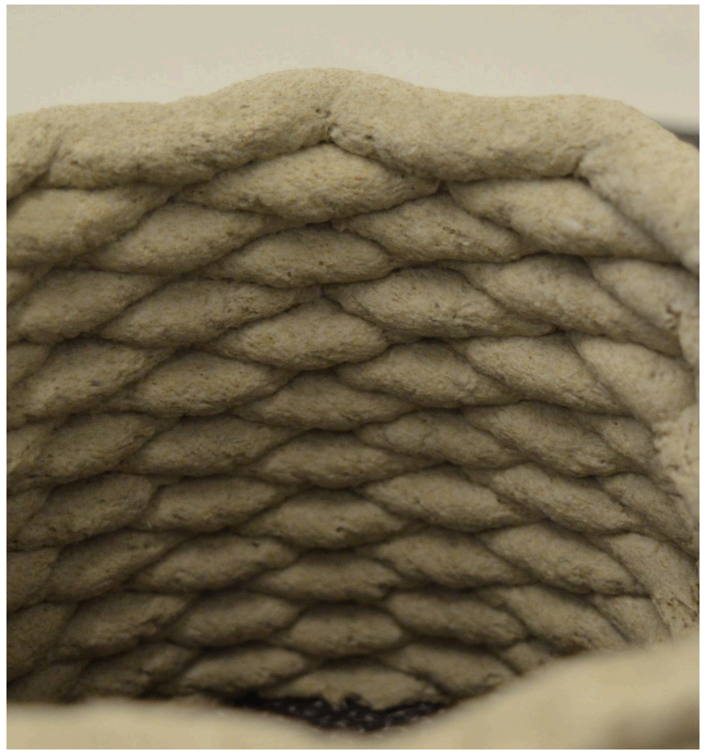


material mixture

1000ml or water plus spraying

material syringe test

>45 degrees, too soft



production notes

Pressure: 0.4
Nozzle: 8mm
Flow: 60%
Speed: 130%

findings

The roughness is slightly increased by interconnecting the layers through the zig zag.

LONG ZIG ZAG
15/01/25
TEST 10

prototype goal

Does the material roughness increase or decrease when patterns points are further appart?

approach

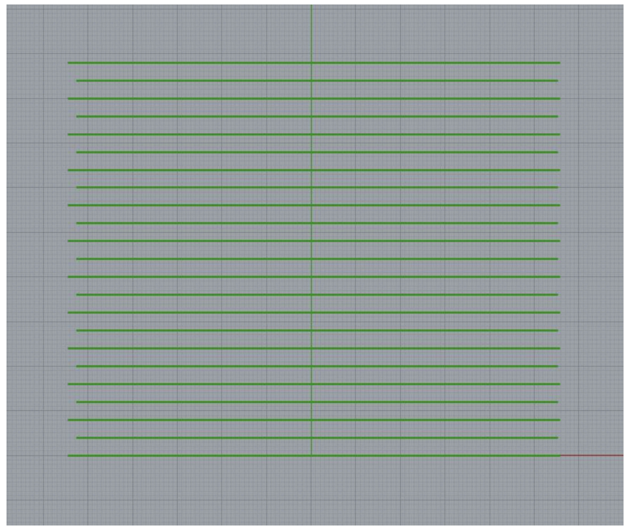
Creating a zigzag printpath where the zigzag points are further appart.

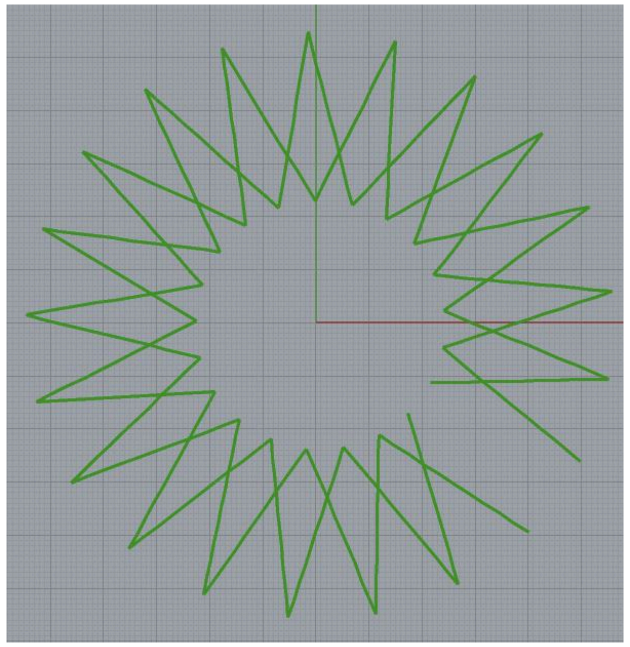
testing

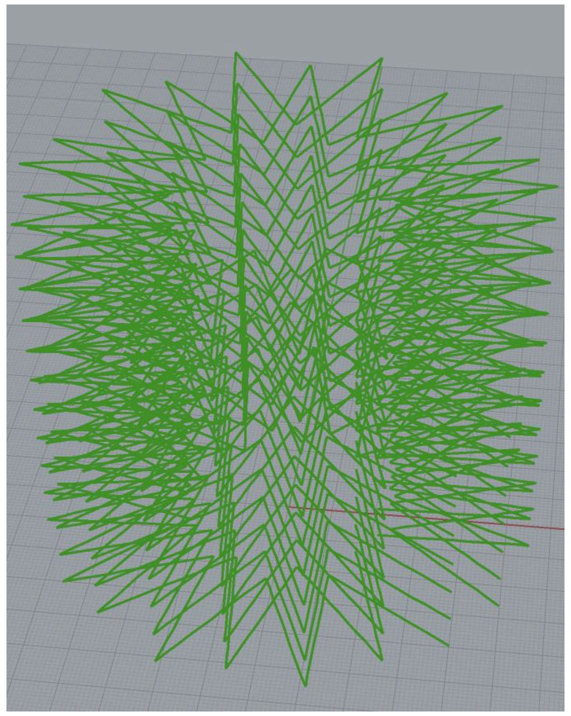
3D print custom polyline sliced using the Termite plug-in on Grasshopper. Printed with a WASP printer

file

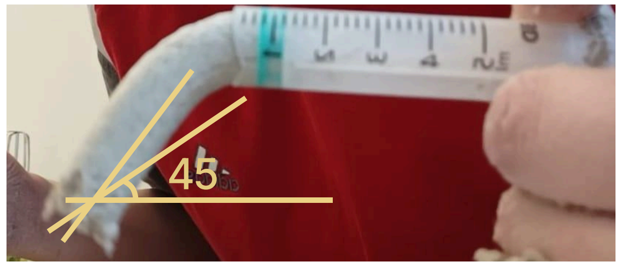
250114_spikey.gcode







LH: 4mm
H: 90mm
W: 90 mm (not taking into account the movement of the points these dimensions refer to the base cylinder geometry)



material mixture

1000ml or water plus spraying

material syringe test

>45 degrees, too soft

production notes

Pressure: 0.4
Nozzle: 8mm
Flow: 60%
Speed: 130%

findings

The layers are deposit onto each other without pushing the material and so the roughness is not increased by the layer on layer. Creases are created in the folding points of the zig zag.

WAVE TEXTURE
15/01/25
TEST 7

prototype goal

Is the material roughness decreased with a bigger layer heigh and a uniform wave geometry?

approach

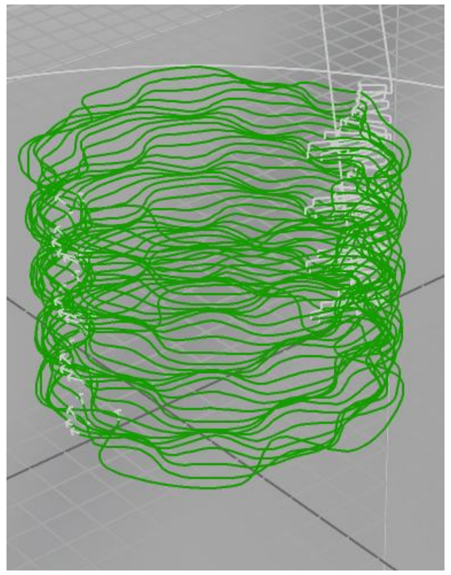
Creating a repetitive print path with 4mm layer heigh and a curvey texture.

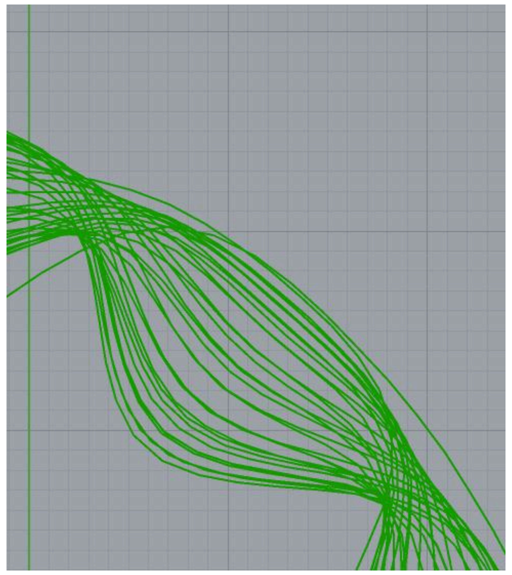
testing

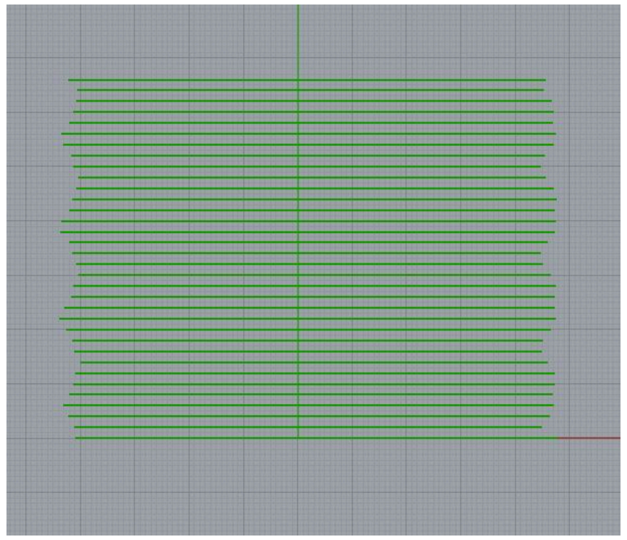
3D print custom polyline sliced using the Termite plug-in on Grasshopper. Printed with a WASP printer

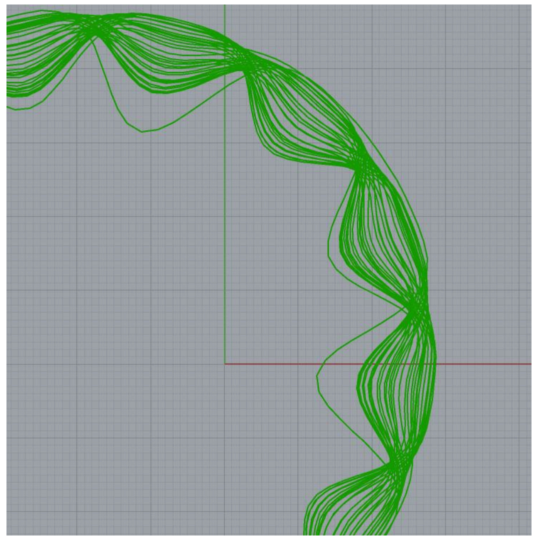
file

241215_blob.gcode

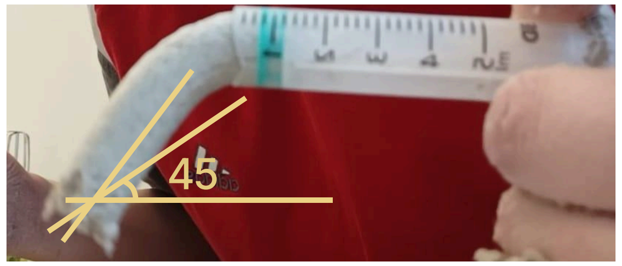








LH: 90mm
H: 90mm



material mixture

1000ml or water plus spraying

material syringe test

>45 degrees, too soft

production notes

Pressure: 0.4
Nozzle: 8mm
Flow: 60%
Speed: 130%

findings

The texture accuracy in relation to the model is quite accurate. With the movement of the nozzle following the defined geometry, the material fiber becomes more visible.

ADDED TOOLPATH NOISE EXPERIMENTS

Increasing the layer height

Perpendicular and tangent noise

Perpendicular smaller noise

Noise direction changes

INCREASING LAYER HEIGHT
15/01/25
TEST 11

prototype goal

How does the material roughness change at different layer heights?

testing

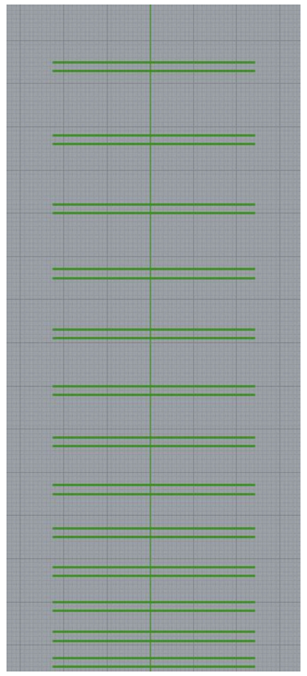
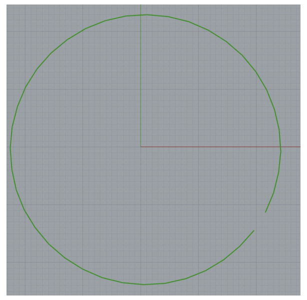
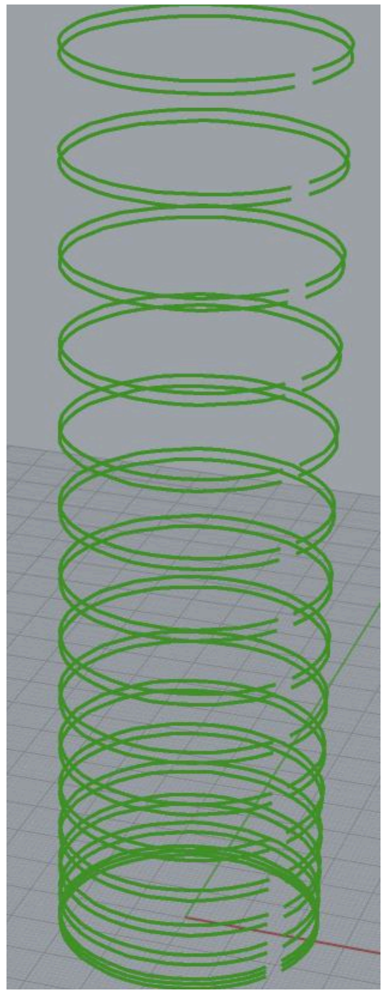
3D print custom polyline sliced using the Termite plug-in on Grasshopper. Printed with a WASP printer

approach

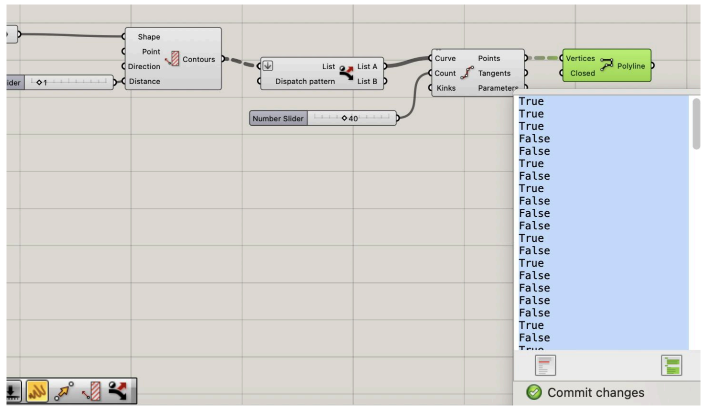
Make a dispatch pattern for a cylinder with contours 1mm apart where fro every layer jump the layer height increases 1mm.

file

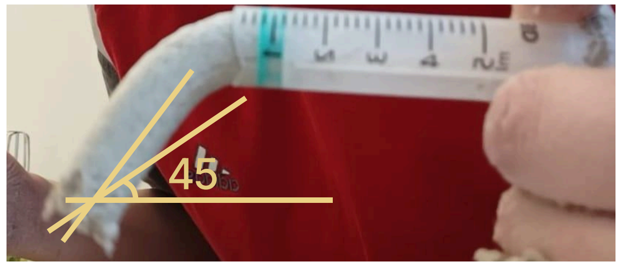
250114_increasingLH.gcode

H: 165 mm
W: 50 mm



The dispatch pattern was defined so every two layer the layer height increases by 1mm



material mixture

1000ml or water plus spraying

material syringe test

>45 degrees, too soft



production notes

Pressure: 0.4
Nozzle: 8mm
Flow: 60%
Speed: 130%

findings

The material goes from very visible fibers making a rough finishing for the smaller layer height, to a smooth finishing as the layer height increases.

PERPENDICULAR AND TANGENT NOISE
10/12/24
TEST 4

prototype goal

How does the look of the walls change when creating noise in the printing path?

testing

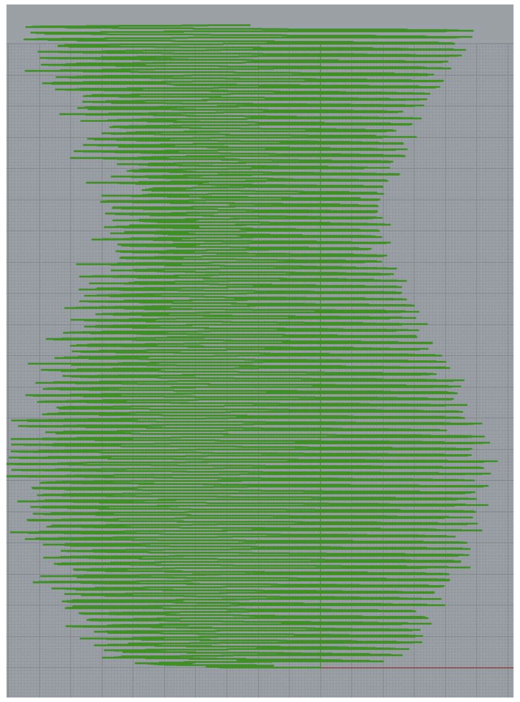
3D print custom polyline sliced using the Termite plug-in on Grasshopper. Printed with a WASP printer

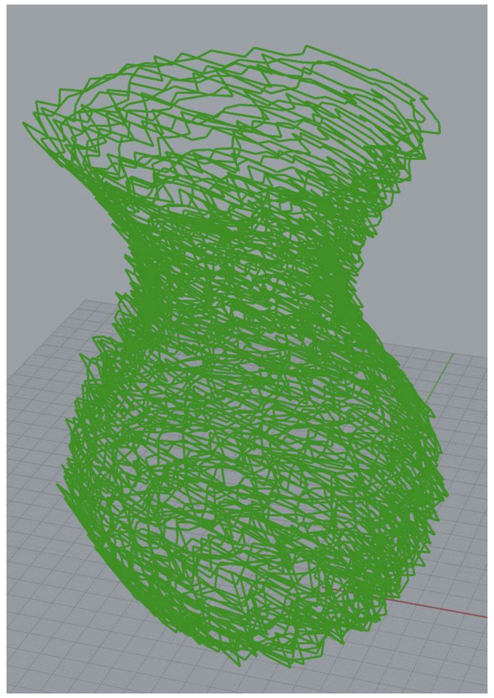
approach

Creating a printing path where the curve points are moved a different directions and distances so the nozzle moves constantly while printing every layer. But using smaller distances than test 3

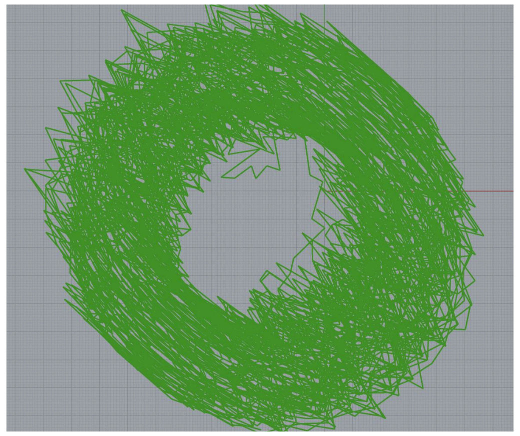
file

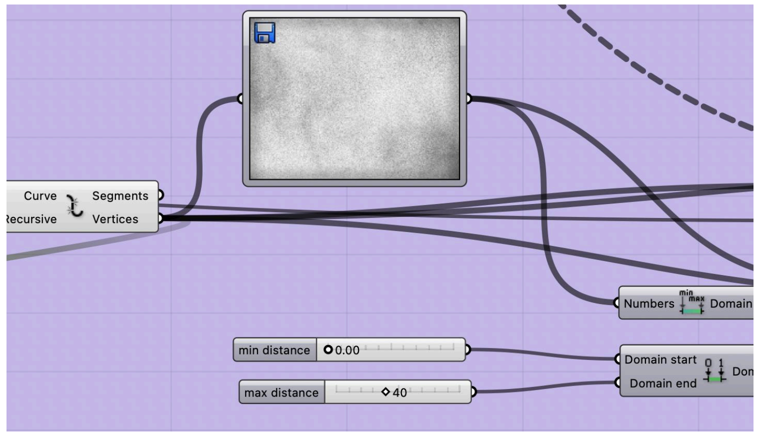
241210_noise.gcode



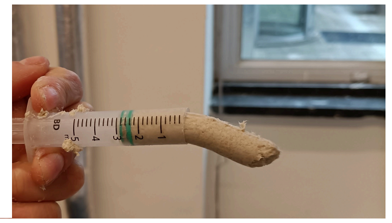


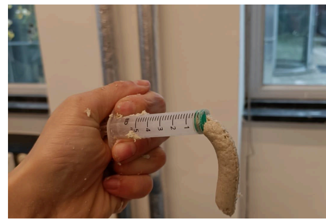
LH: 2mm
H: 205 mm
W: 137 mm





The noise was generated trough image mapping. For this example a grainy image was used. The point movement distances were mapped to a maximum of 40mm. The point movement is outwards on two sides and tangent on the other two to est out the difference. To hide the seam, the prototype´s polilyne was spiralised using 40 points for the precision ramp.



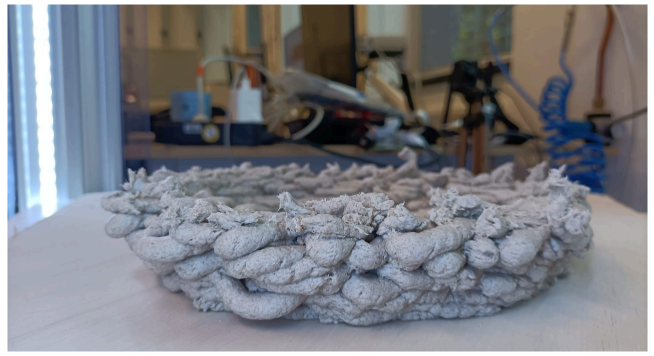


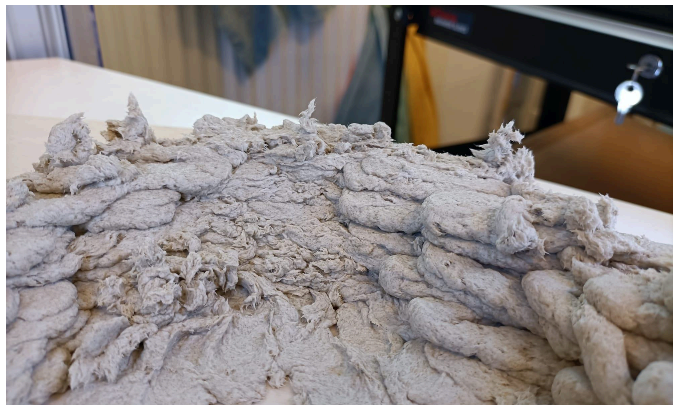
material mixture

1000ml or water, stored fro 4 days and 2 cups of water

material syringe test

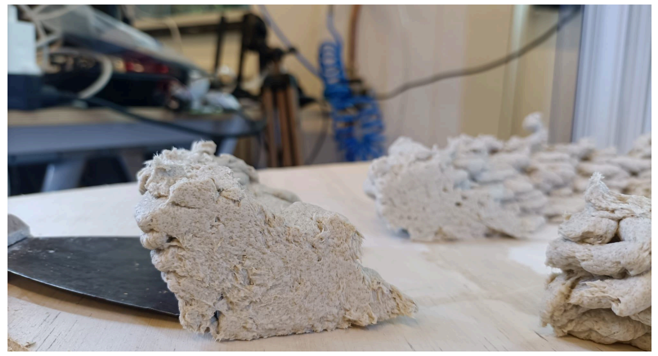
>45 degrees, too soft





production notes

Pressure: 0.3
Nozzle: 8mm
Flow:50%
Speed: 100%
WT:



findings

The material rough look becomes even more noisy. At parts where the previous layer is pushed and the extruded material is stretched, the material looks quite fibre-ish. Both perpendicular and tangent noise increase the material roughness, tough the fibers become more visible for long perpendicular noise as the material is pulled.

PERPENDICULAR SMALLER NOISE
10/12/24
TEST 5

prototype goal

How does the look of the walls change when creating noise in the printing path?

approach

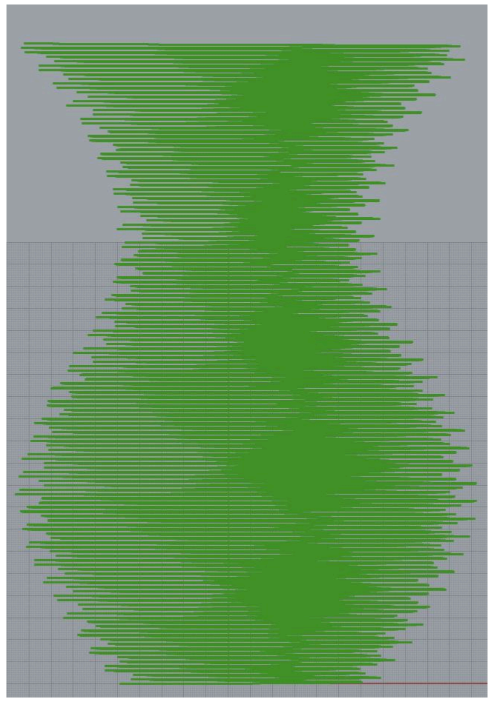
Creating a printing path where the curve points are moved a different directions and distances so the nozzle moves constantly while printing every layer. But using smaller distances than test 3

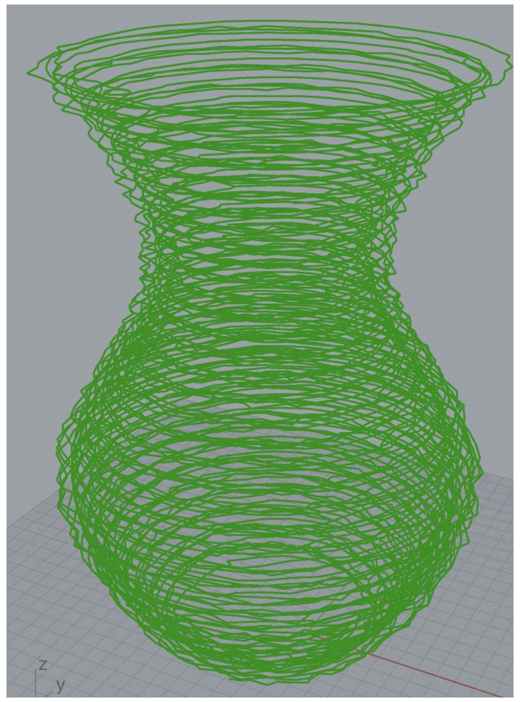
testing

3D print custom polyline sliced using the Termite plug-in on Grasshopper. Printed with a WASP printer

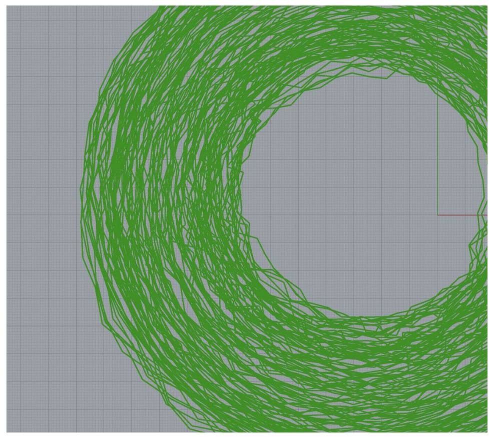
file

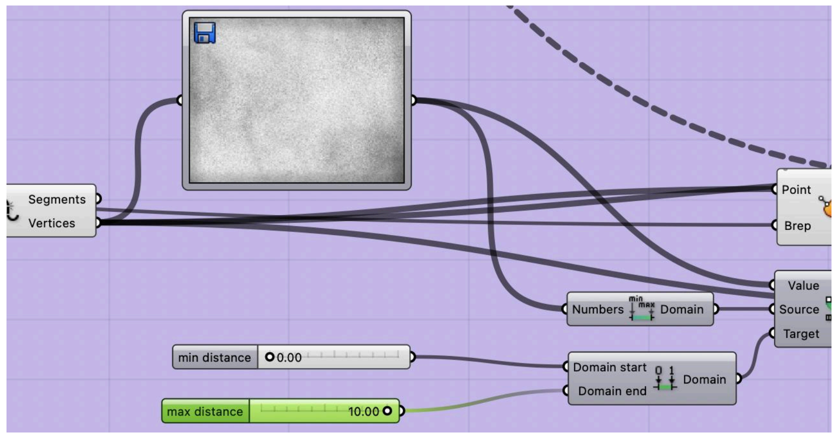
241210_noise_v2.gcode



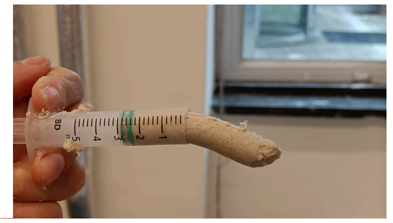


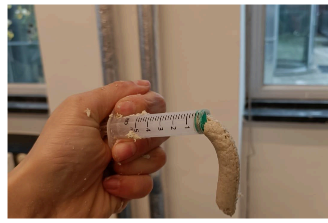
LH: 2mm
H: 205 mm
W: 137 mm





The noise was generated trough image mapping. For this example a grainy image was used. The point movement distances were mapped to a maximum of 10mm. To hide the seam, the prototype´s polilyne was spiralised using 40 points for the precision ramp.





material mixture

1000ml or water, stored fro 4 days and 2 cups of water

material syringe test

>45 degrees, too soft

production notes

Pressure: 0.3
Nozzle: 8mm
Flow:60%
Speed: 70%
WT: 9mm

findings

The layers look unorganised. The material bonding is really good. The material roughness is increased.

NOISE VECTOR DIRECTION CHANGES
15/01/25
TEST 12

prototype goal

How does the material roughness vary when the points moved to add noise are moved not only horizontally outwards?

approach

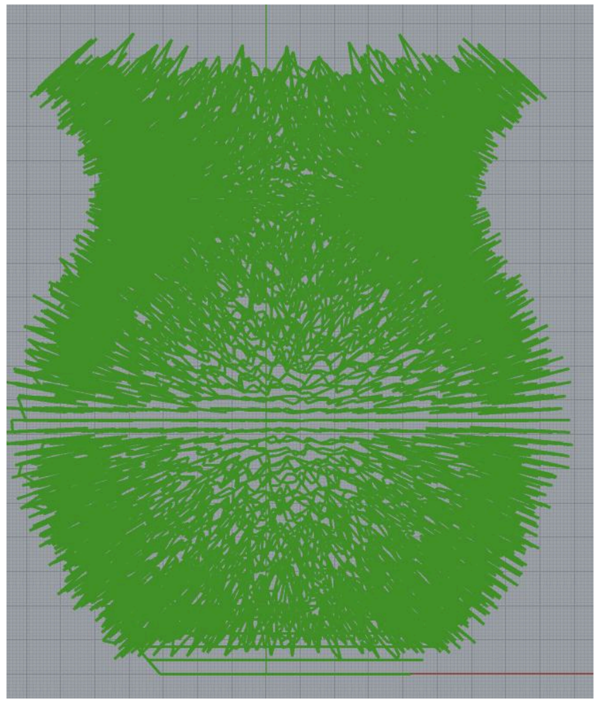
Creating a printing path where the curve points are moved following the normal vectors from the vase geometry.

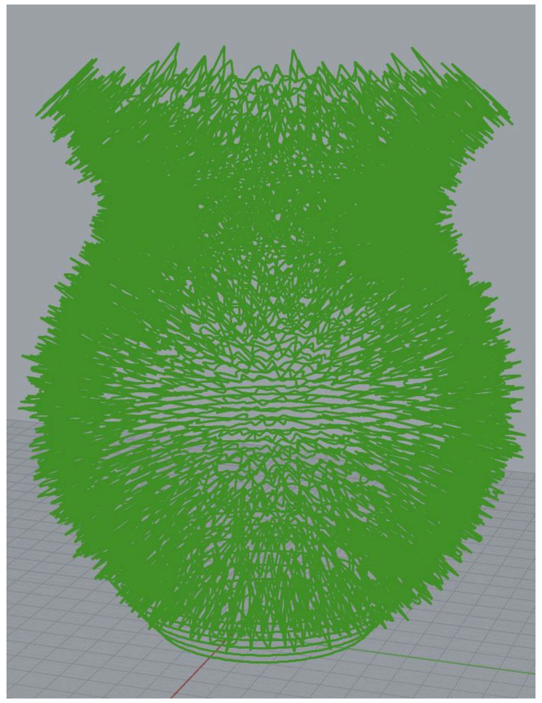
testing

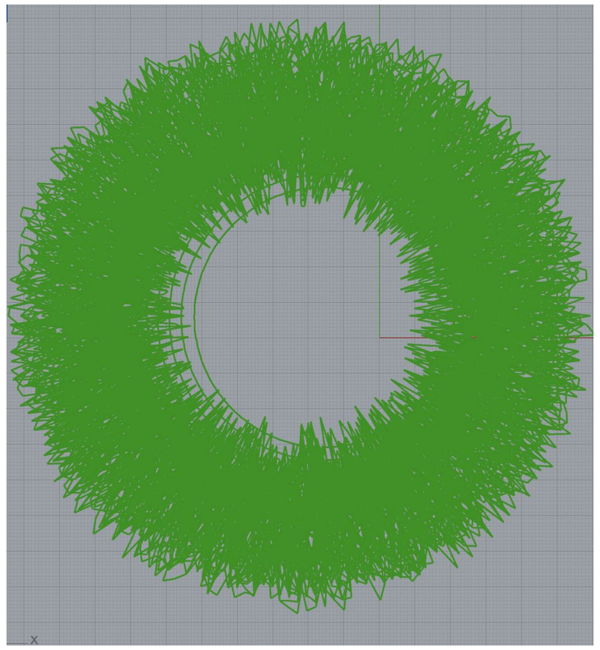
3D print custom polyline sliced using the Termite plug-in on Grasshopper. Printed with a WASP printer

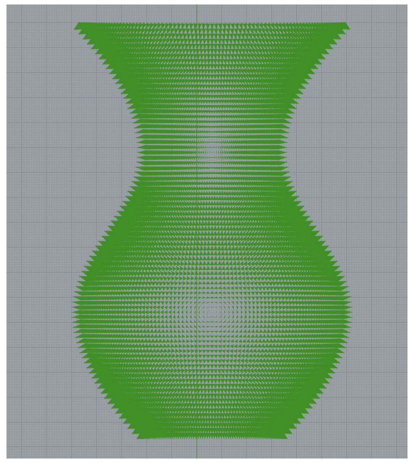
file

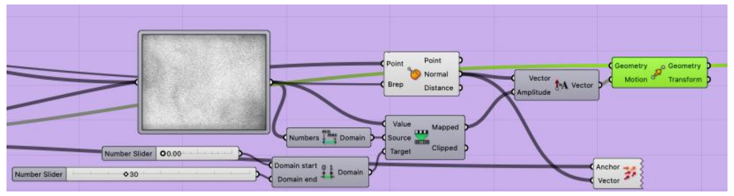
250114_noisedirectionvectors.gcode



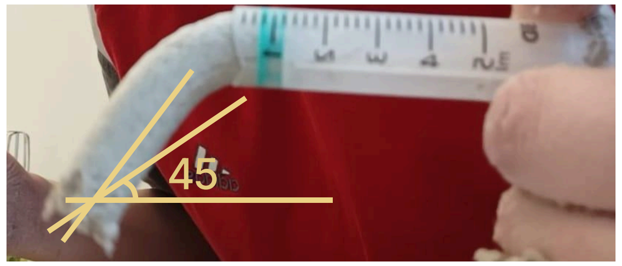








The normal vectors from the geometry were used as the directions to move the points according to the remaping from the image mapping.



material mixture

1000ml or water plus spraying

material syringe test

>45 degrees, too soft

production notes

Pressure: 0.5
Nozzle: 8mm
Flow: 60%
Speed: 130%

findings

The layers are pushed into each other in a way layers are no longer visible. The printer pushes and pulls the material in a way that the fibers and wholes become very visible.

Appendix 3: Reliability Analysis of Measurements

Appendix 3: Reliability Analysis of Measurements

As the achieved roughness is not replicable and every sample will have cavities and inconsistencies at variable locations and sizes, it is important to test the repeatability of the recorded absorption coefficients. To test the repeatability of experimental measurements it is essential for each sample to repeat the measurement multiple times to then perform a reliability analysis (Aslan & Turan, 2020).

The main issue with the reliability of a scale relates to the scale's internal consistency, which indicates how well the items within the scale are connected (Pallant, 2020). And thus, it is essential to examine whether all items are measuring the same underlying concept. To do so, the degree of relationship between various tests or measurements conducted for the same scenario should be analyzed (Aslan & Turan, 2020). To assess the repeatability of the experimental measurements, each sample was measured three times.

Mid-low frequencies

For very tightly fitting samples, the specimens were less prone to vibration, and so the deviation from one measurement to another was very small or even null.

Nevertheless, for samples that did not fit perfectly and were as well very thin, specimens were more prone to vibration. Accordingly, replacing the same sample and measuring a second time, produced a notable deviation as well as peaks in the results due to sample vibration.

As shown in Figure xx, a samples with layer height of 4mm and so a thin wall thickness of 10 mm, which was produced at a feed rate twice as fast as the rest of the samples, led to a thin and weak sample that did not fit tightly in the impedance tube as so deviated notably from one measurement to another.

Considering this notable deviation for thin and less flat samples, the absorption coefficients discussed in the results include the average measurements.

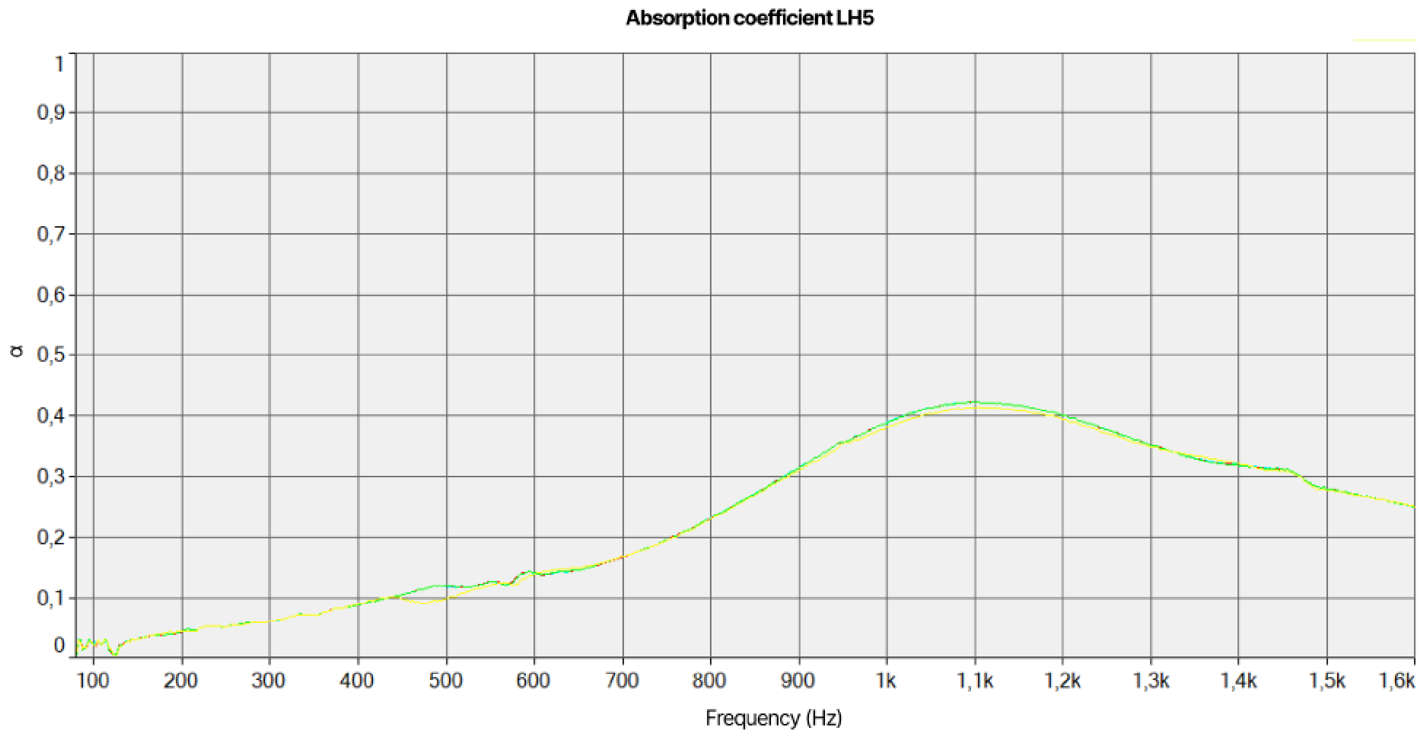


Figure xx: Comparison of absorption coefficients of the same sample (LH5), replacing it in the tube for every measurement (tighly fitting sample)

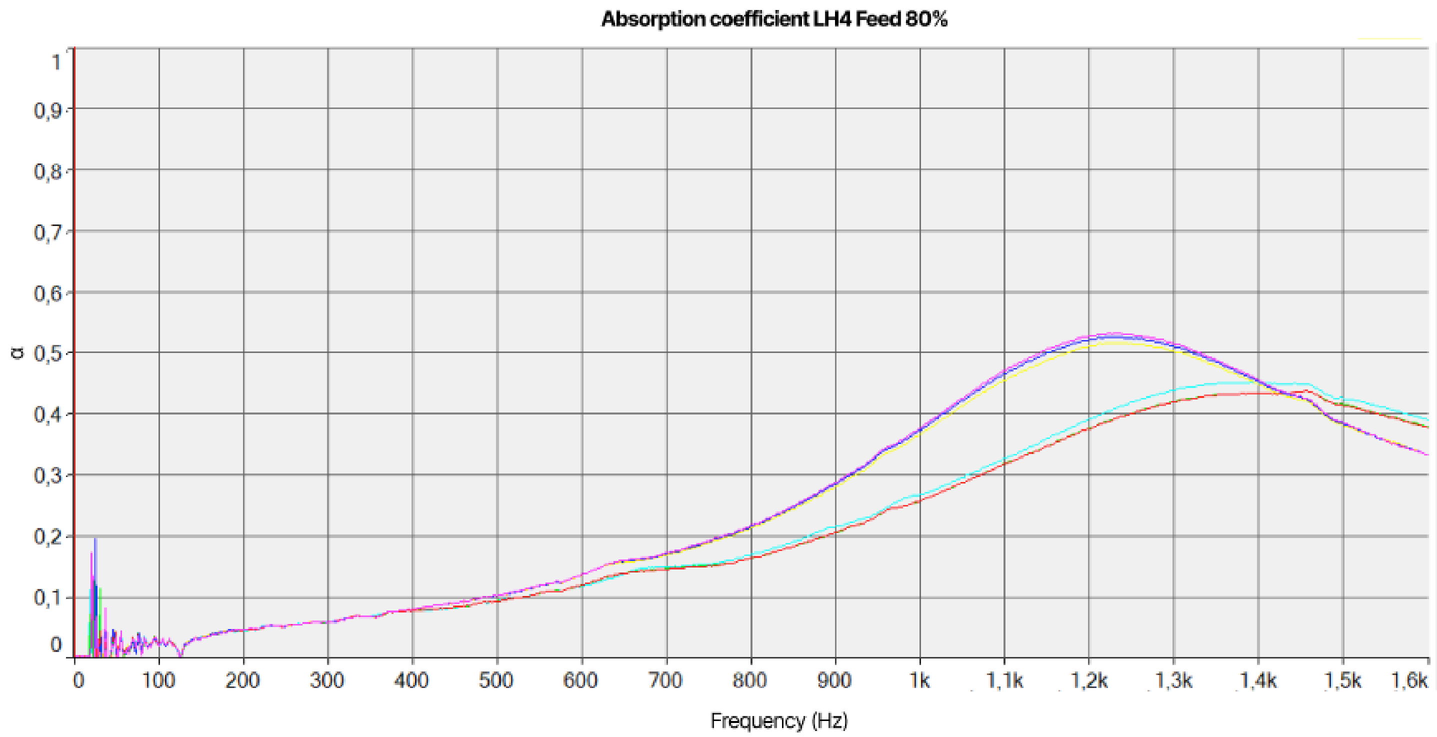


Figure xx: Comparison of absorption coefficients of the same sample (Feed 80%), replacing it in the tube for every measurement (thin loose sample)

Appendix 3:Reliability Analysis of Measurements

Furthermore, to test the ability to replicate the achieved absorption coefficients, specimens were produced with exactly the same settings and material batch, to then be measured and compared.

Figure xx shows the recorded absorption coefficients for two samples with LH3, same feed, flow and from the same material tank and humidity conditions. In the graph it is visible that the deviation from one sample to another is quite small and thus the internal consistency of the results is quite reliable and indicates almost the same acoustic behavior.

Figure xx: LH3 specimens

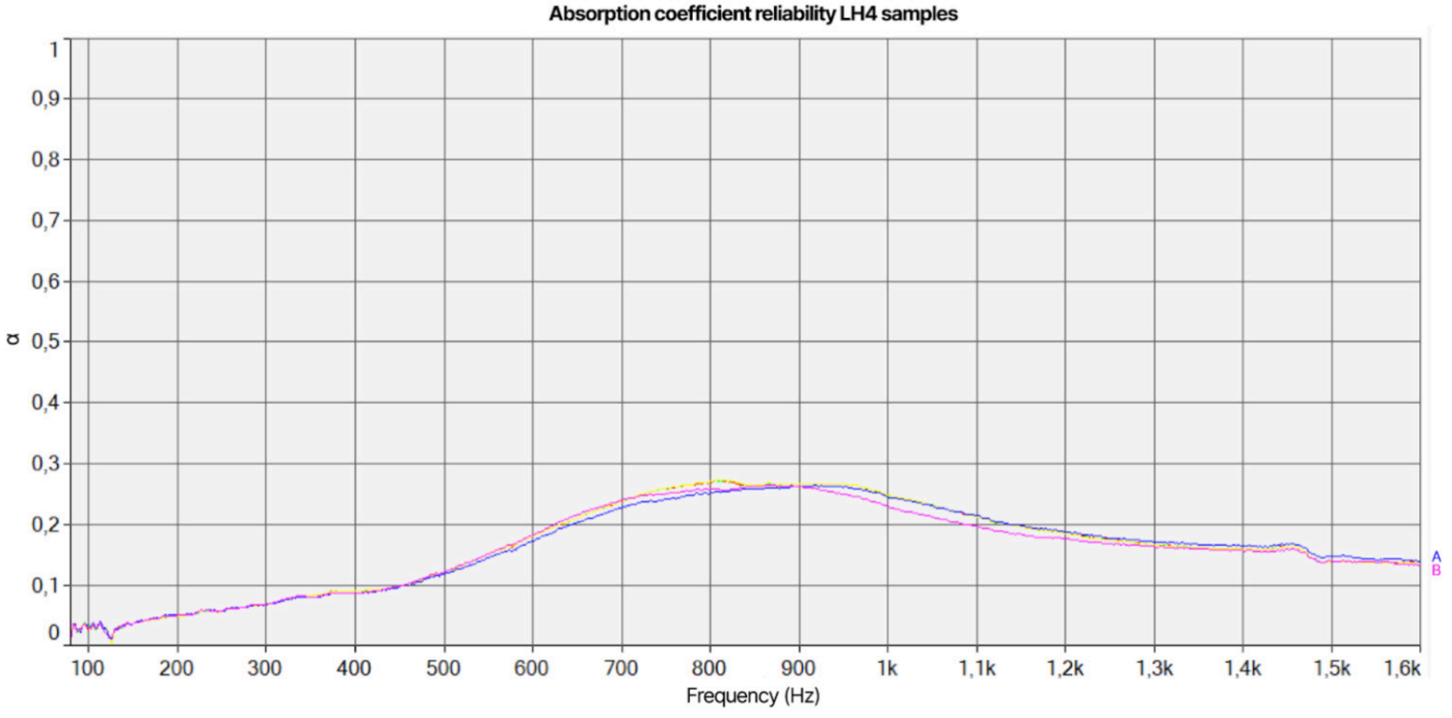


Figure xx: Comparison of absorption coefficients of three LH3 mm samples

Appendix 3:Reliability Analysis of Measurements

In the other hand, Figure xx shows the recorded absorption coefficients for three samples with LH4, same feed, flow and from the same material tank and humidity conditions. Here, the deviation from one sample to another is visibly big, indicating that the internal consistency of the results is rather questionable, and the deviation of the measurement results from one sample to another underlines the poor replicability of the samples. If only samples A and C are compared, we can see a deviation of around 50Hz, which is still considerable but the internal consistency would still be considerable. Nevertheless when inclusing also specimen B, the deviation is too high.

One reason why there is a big gap in reliability from samples produced with a 1mm layer height difference is due to the achieved sample thickness. Samples produced with 3mm layer hight achieve a wall thickness of 14mm, contrarily to the 4mm layer height ones being 10mm wall thicknesses. These makes the samples less rugged and lighter, and therefore more bunerable to deformation during post-processing and drying. Consequently, these specimens are not fully flat as well as light making them more prone to vibrate while testing them in the Impedice tube. These vibrations explain the recorded high peaks shown in the graphs for thinner samples.

Figure xx: LH4 specimens

Figure xx: LH4 specimens

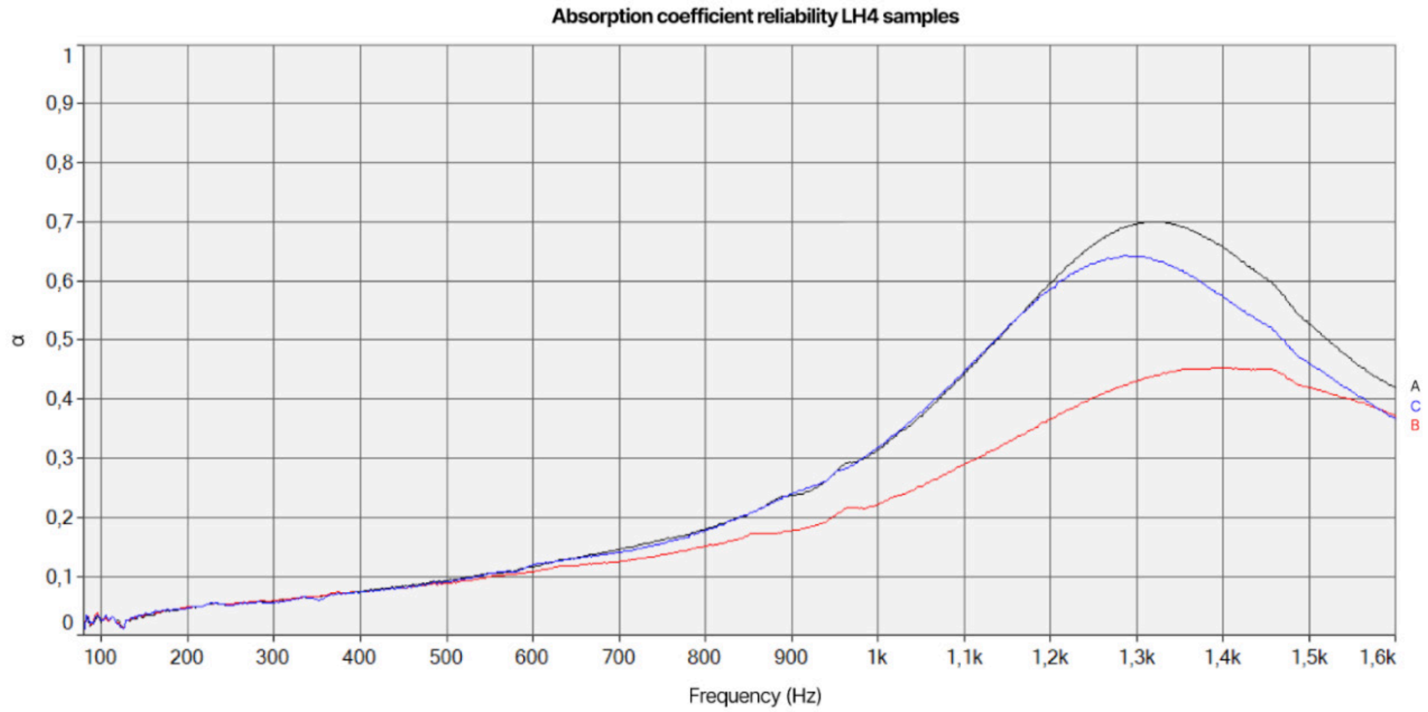


Figure xx: Comparison of absorption coefficients of three LH3 mm samples

Appendix 3:Reliability Analysis of Measurements

High frequencies
As shown in Figure xx, replacing the same sample and measuring a second time, produced a notable amount of peaks in the results. Nevertheless, the underlining behavior is rather constant with a few around 100Hz deviations.

Looking at the absorption coefficients of two samples with LH3 and with the same feed and flow, there is not as a strong coherence as with the samples for mid-low frequencies.

On the other hand, Figure xx shows the recorded absorption coefficients for three samples with LH4, the same feed, flow and from the same material tank and humidity conditions. Here, the deviation from one sample to another is visibly big, indicating that the internal consistency of the results is rather questionable, and the deviation of the measurement results from one sample to another underlines the poor replicability of the samples. If only samples A and C are compared, we can see a deviation of 500 Hz, in which case the internal consistency would still be considerable. Nevertheless, the absorption coefficients of specimen B show many peaks that are not replicated by the other samples.
A difference which could be due to sample vibration.

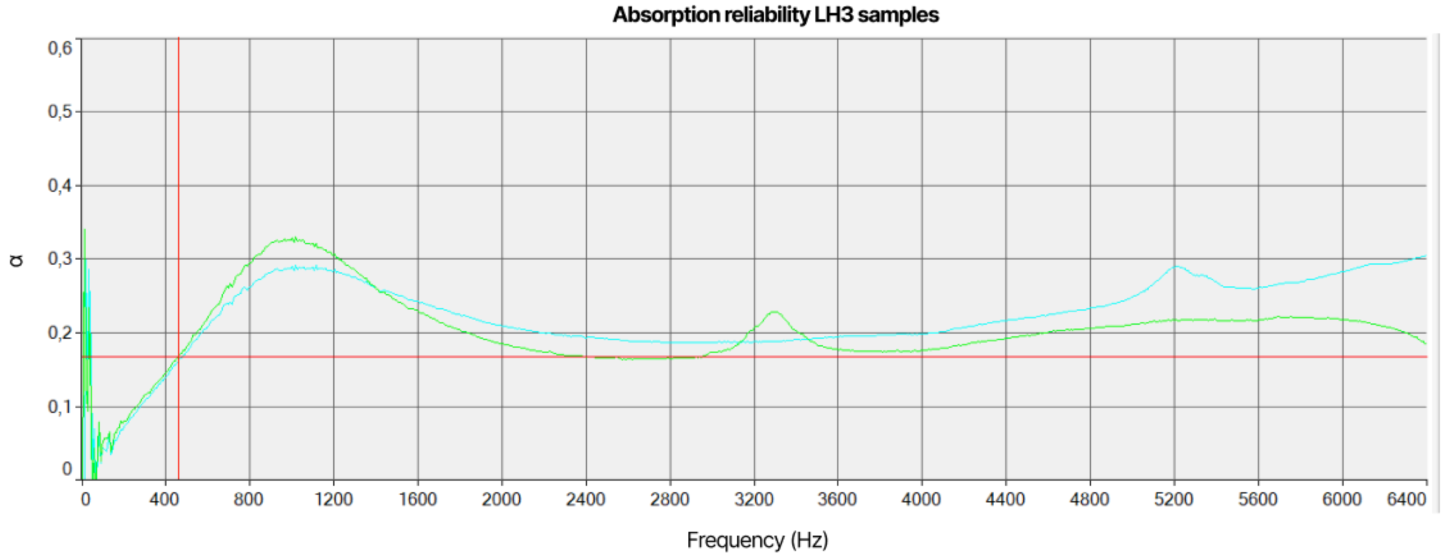


Figure xx: Comparison of absorption coefficients of two LH3 mm samples

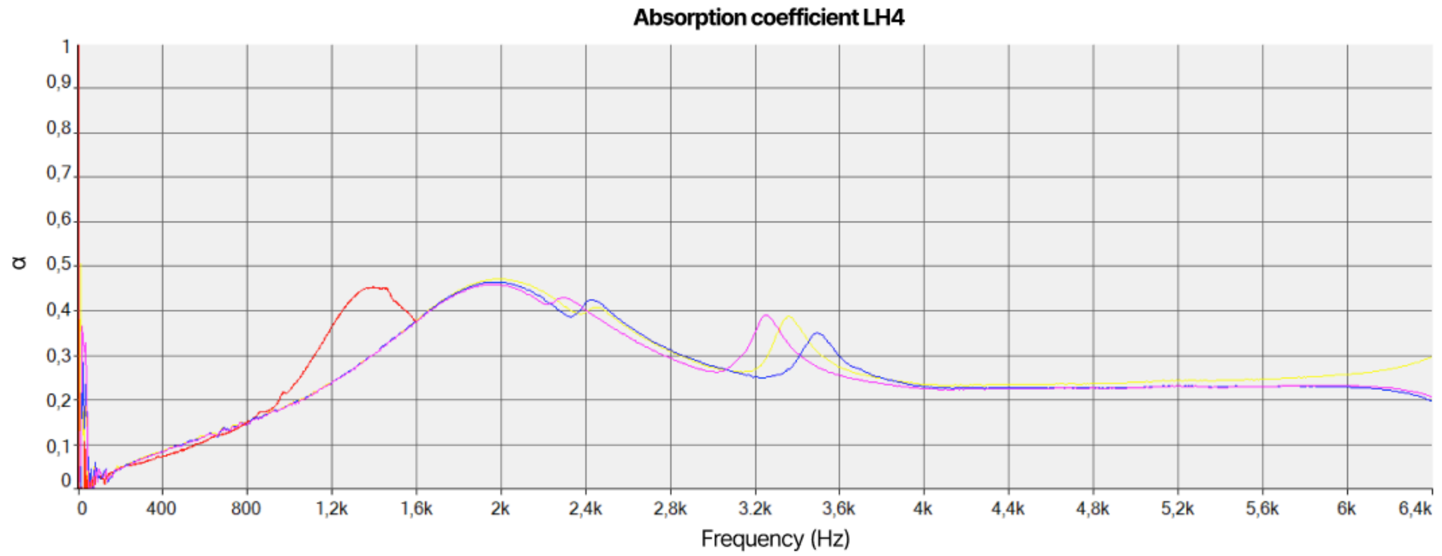


Figure xx: Comparison of absorption coefficients of the same sample (LH4), replacing it in the tube for every measurement

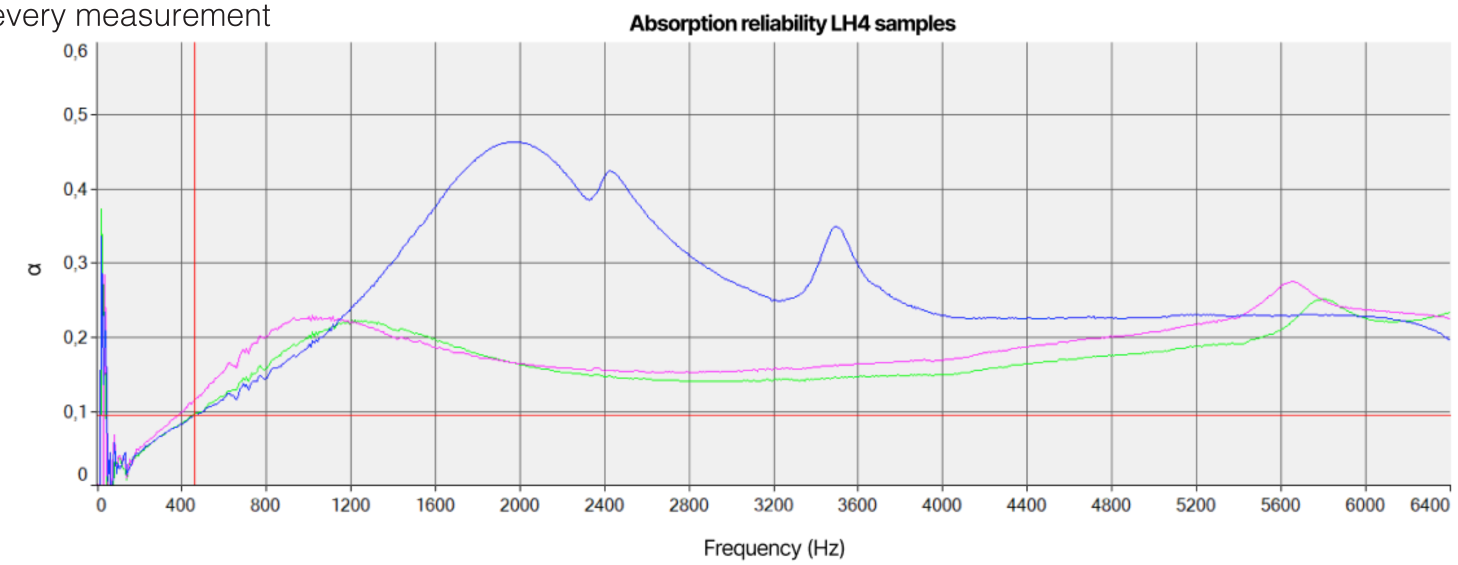


Figure xx: Comparison of absorption coefficients of three LH4 mm samples

Appendix 4 - Project Brief

Personal Project Brief – IDE Master Graduation Project

TU Delft

Name student Carmen

Student number 5619793

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Exploring large scale 3D printing with bio-circular materials

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

With a startling 37% of worldwide emissions, the building and construction sector is by far the largest emitter of greenhouse gases (UN Environment Programme, 2023). Materials like cement, steel, and aluminium have a large carbon footprint during manufacturing and use. Omlab is a research and design studio that develops infranature and nature-friendly buildings without minerals such as cement or clay, and using only ecologically responsible chemistry (Omlab, 2024). This way, Omlab offers a potential solution to the environmental impact of the construction industry by making waste materials extrudable and implementing them in construction.
While production with bio-circular materials provides a smaller embodied carbon footprint, they come with increased handling complexity since they are anisotropic and heterogeneous, when compared to standard industrialized materials (Rossi, 2023). Studying their behavior, characteristics, performance and 3D printability, can push for bio-circular material adoption. Digital fabrication tools yet need to be further studied with bio-circular materials in order to ensure the material's structural performance when 3D printed.
This project explores the potential of biodegradable materials in the field of 3D-printing. By adopting a material and technology-driven approach, the project seeks to study the performance of 3D printed bio-circular materials, and identify 3D printing process that allows to design material behavior. With the material and prototyping-driven design approach, emphasis is placed on understanding the material performance when 3D printed, to then shape a design vision that integrates the opportunities of 3D printing with bio-circular materials. This experimental research conducting iterative loops through 3D printing, can allow to generate knowledge in terms of 3D printing with bio-circular materials addressing multiple 3d printing features.

Note: The "bio-circular material" used in this project refers to the material developed by Omlab. The material is composed of 98% of waste and 2% biobased organic matter. The raw materials are by-products and residual flows from sewage treatment. The material prototype is cement-free and contains no minerals, fossil resources or chemicals nature can't deal with. The material has the strength of gypsum concrete, but is lighter and locally produced.

➔ *space available for images / figures on next page*

introduction (continued): space for images

click to add picture

image / figure 1

image / figure 2

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

While 3D printing with bio-materials holds promise, boundaries occur in terms of possibilities in shape, printability, materiality, architectural performance and contextual degradation. Experimental research conducting iterative loops through 3D printing can allow to generate knowledge addressing multiple 3d printing features. These can include different printing mediums, variable layer qualities, nozzle geometries, geometries, infills, designed material behavior or non-planar printing.

The main challenge is to through printing and slicing settings, allowing a poorer material to perform in high quality. Through thoroughly understanding the material and reviewing the technology, a range of possible results this material can achieve is gathered. This process through 3D printing iteration, pushes the limits of performance of the material to generate a new outcome defined by a designed printing process.

The main contribution of this project is 3D printing knowledge in the field of bio-circular materials. By exploring the potential of biodegradable materials for 3D printing, a relation between 3D printing parameters and material behavior is identified and developed to be able to monitor material behavior as a designed part of the printing process.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design/Investigate/Validate/Create) a (what will be the deliverable -> prototype/ roadmap/process/ intervention/approach/ guideline/strategy/…) to (what should it do -> create/ understand/evaluate/validate/improve/execute/analyse/…)
(the objective -> experience/ value/process/product/…) for (whom -> target group/ client/…) in (what context).

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

Investigating a printing process to design material behavior for bio based materials.

The project will be conducted following a material and technique-driven approach. This will be conducted through prototyping based research, aiming to gather a knowlege base of the behabior of the material when 3D printed.
This experimental research conducting iterative loops through 3D printing aims to generate knowledge addressing multiple 3d printing features. These can include different printing mediums, variable layer qualities, nozzle geometries, geometries, infills, designed material behavior or non-planar printing. To be able to conduct a prototyping approach, the 3D printing productions will be done at the LamaLabs in the TU Delft Architecture faculty. This lab provides large-scale 3D printing facilities that include a robotic arm and Wasp clay printer.
It is important to empathize the equal importance of material and technique in this design process, as the constraints in material properties, 3D printability, and 3D printed behavior, are equally important to identify the opportunities of 3D printing with bio-circular materials for construction. Furthermore, the used material for the research is currently printed with a cartesian printer, and yet needs to be tested with additive manufacturing machinery with further degrees of freedom.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	12-11-2024
Mid-term evaluation	28-01-2025
Green light meeting	31-03-2025
Graduation ceremony	29-04-2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	✔
For how many project weeks	25
Number of project days per week	5

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

In my graduation thesis I want to put to practive my skills in design for 3D printing and robotic printing, achieved by working at The New Raw.

After generic plastic, flexible materials, ceramics and recycled plastics, I want to keep expanding my additive manufacturing knowledge while getting ivolved in a practice that does not use fossil, chemical additives, or produce further waste. Accordingly, I want to gain experinece in biobased 3D printing. For this, I want to learn to follow a material driven design process that includes the technology as part of the material experience.

Furthermore, I want to expand my Grasshopper parametric coding skills. As well as learn more about slicing and gcode hacking for 3D printing architecture.

Appart from techincal skills, as a project conducted from brief to final output fully on my own, and having to coordinate with mentor chair and external client, I want to bettern my project management and communication skills.

MAY 2025

MASTER THESIS
Integrated Product Design | Industrial Design Engineering | Delft University of Technology

AUTHOR
Carmen Enríquez Comendador

CHAIR
Dr. ir. E.L. (Zjenja) Doubrovski |
Department of Sustainable Design Engi-
neering

MENTOR
Ir. E.J.L. Noordhoek |
Department of Human Centered Design

IN COLLABORATION WITH
Omlab