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Material Research through
Sonic Fingerprints and Data Visualization

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abstract

Architectural classification has long been constrained to visual standards, defining materials as flat surfaces or static geometric volumes. Yet, when dealing with reused materials, frequently non-standard and irregular, this surface-level consideration is not enough.

To surpass this visual bias, this thesis introduces a research workflow that interrogates the hidden identity of physical materials through their acoustic characteristics. By subjecting a heterogeneous set of waste and discarded architectural materials to systematic acoustic tests, internal resonance is treated as a primary source of material reality. This provides a future theoretical model for the field of urban mining - offering a non-destructive way to evaluate salvaged resources whose structural conditions are unknown.

The sonic approach allows the material to detach from its superficial visual state, transforming physical matter into raw waves, frequencies, and numbers. From this translation, unexpected hidden physical relationships, similarities, and oppositions begin to reveal. Listening to the physical pieces transforms material analysis from an inspection into a dialogue with the material's inner structure.

The project culminates in a series of custom interactive interfaces that demonstrate the vital role of aesthetics in scientific research.

Rather than serving as passive illustrations of data, these act as filters to isolate meaningful material properties from mathematical noise. Working also with machine learning algorithms to cluster sonic fingerprints into relational patterns, these curated infographics translate chaotic acoustic signals into a legible geometric and topological language.

Ultimately, this thesis bridges the gap between raw engineering and architectural design.

By curating a multisensory framework to navigate and extract properties from our physical environment, the project expands architecture's traditional field of action, reframing the contemporary architect as also a material diagnostician.

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introduction *and* **context**

This chapter establishes the foundations for the thesis. It introduces the concept of "sonic fingerprints" and Non-Destructive Testing (NDT) as a multisensory framework to analyse salvaged materials. This section sets the stage for using hidden acoustic data to uncover the structural realities of reused building components, proving that physical matter extends far beyond its visual surface.

project *overview*

This research project focuses on the relation between reused architectural materials and their sound. The goal is to investigate the sound of each material, and what looking at each piece through its sonic ID can uncover. The use of sound, in this case, reflects the intention of exploring materiality by its true characteristics, instead of their visual characteristics. This is achieved through Non-Destructive Testing (NDT), a more hands-on approach to material testing and its organization. The results from this study are explored and expressed in a series of visual graphics and interfaces, proving the importance of aesthetics in research. Here, complex data is the gateway to creative possibilities.

Standardized materials have been reduced to concepts, due to their predictable characteristics and behaviour, and to 2D or 3D shapes in architectural drawings. But within the material reuse field, each piece needs to be analysed and treated uniquely. In the architecture industry, materials are treated mostly visually, resulting in more external-based inspections, that do not dive deeper beyond their surface. Advancing this practice, the methodology establishes a 'Sonic Fingerprint' or 'Sonic ID' for each individual component.

The Sonic Fingerprint is a concept developed to describe each piece's identity. It is the result of the sonic test- knocking the material, recording its sound and analysing its values.

The parameters, expressed by the sound waves that come from the knock, reflect the inner structure, its density, elasticity, and energy. Each piece has its own values and therefore its own identity. These values are then organized and analysed, in search of patterns and similarities, as well as contradictions to what might be expected from architectural materials.

Following this sonic test, the results show some pieces get closer to each other, and others distance themselves. Here, invisible vibrations of wasted materials are translated into patterns. The concept of material detaches itself from the physical piece and becomes sound waves, numbers, graphics, data.

This project defines a cross-disciplinary methodology that fuses data with artistic expression to reframe architectural material research. The developed set of tools spans a broad spectrum of analysis, systematically guiding the user through an incremental data ecosystem. It begins with the foundation - SonicInfo interface - which acts as the raw data ingestion layer; it then transitions into the technical evaluation of individual material behaviours via the Spectral Triangles. It then maps the piece's relationships using the Self-Organizing Map (SOM) and Hierarchical Dendrogram. Finally, it culminates in the dynamic, interactive environments of the SoundRays interfaces.

sound, architecture *and* materiality

Translating the data into infographics is where the architect and architecture come in. There are already tests to check the integrity of the materials from both the outside and the inside, but they are restricted to the field of engineering and require specialized staff to deal with the data. This methodology is an example of why the gap between material analysis and architecture should be bridged. Empowering the architect to translate raw data into infographics directly benefits the discipline by regaining control over the research process.

Infographics allow the architect to be more involved in the research process and to have more control over the data. By empowering the architect to directly manage and translate forensic data into visual expressions, the discipline regains critical agency over the overall process and data. Infographics can inspire architects with their designs, as opposed to merely analysing numerical data from conventional material tests, such as the Ground Penetrating Radar (GPR) and Ultrasonic Pulse Velocity (UPV).

The relationship between sound and architecture extends far beyond acoustics. Sound carries a spatial dimension that allows architecture to be understood not only as a static composition of materials but as a temporal and rhythmic system. Furthermore, through sounds people have the ability to locate themselves, to navigate through the physical world. Sound can lead to movement; we can guide ourselves either by what we hear when we walk or through external noise. It therefore affects how space is perceived, and also through the acoustics of space. The close relationship between these two concepts and senses, visual and sonic, should not be overlooked. On the contrary, it should raise the question of dominance of the idea that space is primarily physical, and visual. Moreover, there are a lot of sound characteristics that are also used to describe physical space. Our eyes and ears can both detect distance, texture, depth, height, structure.

This view can redefine the building as a place of relations and sensations. In this light, sound becomes a means to perceive, analyse, and organize. Architecture has recently evolved to become more considerate of touch, adding a layer of complexity and richness to a building. Including also sound to the equation, it would just contribute to a more complete architecture.

learning *objectives*

There are a lot of ways to work with sound and architecture, and this relation between is not something new. For example, it has been already explored by architects such as Iannis Xenakis and Bernhard Leitner, whose projects demonstrate (differently) how rhythm, vibration, and resonance can shape architecture through questioning our understanding of form, materiality and space. Their theoretical and practical works open the possibility of rethinking architecture, through processes of sound translation, where the spatial characteristics of sound are used to create and question physical space.

This research is fundamentally based on the spatial experiments of Iannis Xenakis and Bernhard Leitner. Their interdisciplinary works, which questioned the intersection of sound and architecture, established a theoretical basis that this study seeks to expand upon. Consequently, to address the contemporary needs of circular construction, this thesis advances that acoustic framework to investigate the hidden structural identities and relationships of salvaged architectural materials.

Sound waves are shaped by a material's internal structure, which reveals what the eye cannot see. The intention of this thesis is to use acoustic telemetry and data visualization to decode reused matter. This is guided by three research questions.

How can sound challenge the visual dominance in architecture?

What can the sound of materials unveil about them and their relationships?

How can computational interfaces and machine learning translate abstract data into interactive and intuitive, curated tools?

To answer these questions, the project develops a standardized physical testing methodology to extract acoustic data and translates it into architectural interfaces.

research *and* **literature review**

Tracing the historical intersection of sound, space, and data, this chapter provides the theoretical context for the project. It examines the pioneering works of Iannis Xenakis and Bernhard Leitner. Furthermore, it explores the evolution of sonification, establishing the historical and theoretical groundwork for the thesis's acoustic experiments.

spatiality *of* sound

While the internal resonance of a material reveals its latent structural identity, the projection of that acoustic energy fundamentally alters the definition of architectural space. Traditionally, space is delineated by static, visual boundaries—walls, floors, and enclosed volumes. However, sound operates as an active, immaterial spatial agent. As demonstrated by the pioneering acoustic environments of Bernhard Leitner, sonic frequencies possess the capacity to construct invisible geometries, defining temporal boundaries and dynamic spatial thresholds without the need for physical mass.

Within the context of this research, the spatiality of sound transitions from a purely physical phenomenon into a navigable digital topology. By extracting the acoustic signatures of salvaged materials and projecting them through unsupervised machine learning networks, sound ceases to be a fleeting temporal event. Instead, it generates a continuous spatial landscape, allowing the architect to traverse and analyse material relationships as a multi-dimensional acoustic territory.

For example, it has been already explored by architects such as Iannis Xenakis and Bernhard Leitner, whose projects demonstrate (differently) how rhythm, vibration, and resonance can shape architecture through questioning our understanding of form, materiality and space. Their theoretical and practical works open the possibility of rethinking architecture, through processes of sound translation, where the spatial characteristics of sound are used to create and question physical space.

Iannis Xenakis_ sound as stochastic mass

Iannis Xenakis, trained as both an engineer and a composer, represents one of the most important integrations of musical and spatial thinking together. His works with Le Corbusier in the mid-twentieth century and his personal explorations in mathematical music composition allowed him to see architecture as a continuation of musical logic.

The Philips Pavilion (built in 1958), designed for the Brussels World's Fair, stands as one of the most successful combinations of these two disciplines. Its concrete-made acute angles were based on the same mathematical equations used in his orchestral piece *Metastasis* (made in 1953–54). In turn, these were based on Einstein's notion of time and Le Corbusier's mathematical ideas explored in his *Modulor* books (Classical20. (2015, August 12)).

This spatial-mathematical combination converged most famously in the *pans de verre ondulatoires*, or undulating glass panes, designed for the Convent of La Tourette (1953–1961). Serving as an architectural innovation born directly from musical research, this system represents Xenakis's first explicit translation of sonic composition into a physical facade (Les Amis de Xenakis, 2023).

While collaborating under Le Corbusier, Xenakis pursued a dynamic method to regulate light and movement through the monastery's circulation corridors. He took inspiration from his orchestral work, that he was working on simultaneously, *Metastaseis* (1953–1954). In this composition he utilized arrangements and mathematical density configurations to structurally organize sound masses.

As detailed in his book *Music and Architecture*, he altered the horizontal and vertical density of concrete mullions and glass panes of varying widths, based on the mentioned musical piece (Xenakis, 2008). By grouping narrower glass panes into high-density clusters that slowly released into wider, low-density intervals, the facade functioned like a physical musical score mapping intensity, duration, and transition.

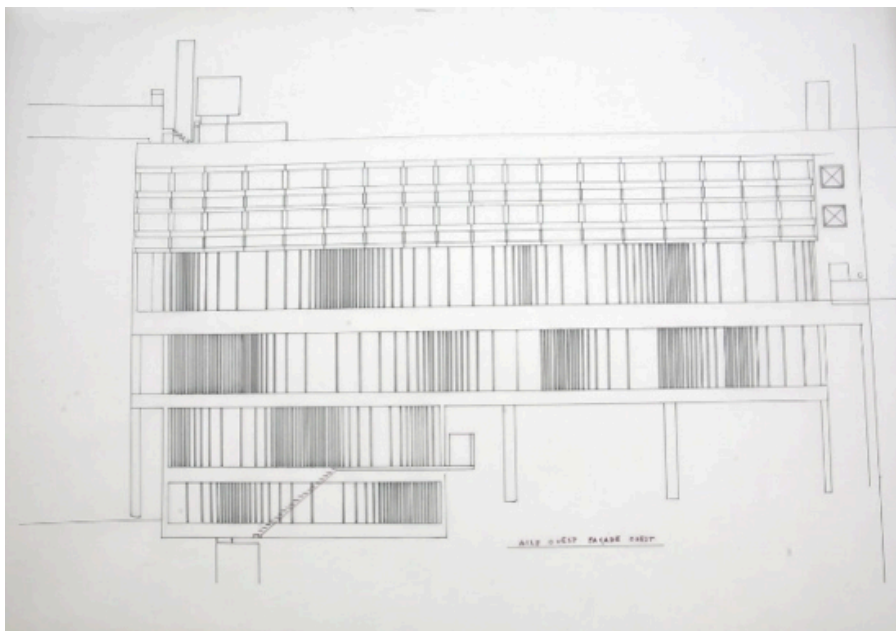


Figure 1_a

Figure 1_b



In addition to designing the building itself, Xenakis was in charge of creating the transitional piece that played between arrangements, so he developed “an electronic musical piece based on the mathematical data of the construction.” (Fondation Le Corbusier. (n.d.).)



Throughout his works, Xenakis demonstrated that sound and structure could follow the same principles (rhythm, proportion, and movement) turning architecture into “frozen music”. His architectural approach framed space as a score that unfolds over time, where design can emerge from rhythm and performance, rather than being a visual form by itself. When it comes to music, Xenakis did not compose music through conventional methods. In fact, he opposed them, considering them too restrictive. Instead, he developed an indeterminist approach to composing.

This approach allowed him to isolate sounds and therefore compose using elements external to music such as drawings and mathematical curves, or techniques such as statistics and probabilities. The result was the creation of stochastic music, which was composed upon randomness and probability rules. Everything obeyed to theoretical distribution, from duration to spacing between notes. While composing music through mathematical properties, Iannis Xenakis created systems that would generate sound, which made music the result of this process. (Xenakis, I. (n.d.)).

Figure 3_a

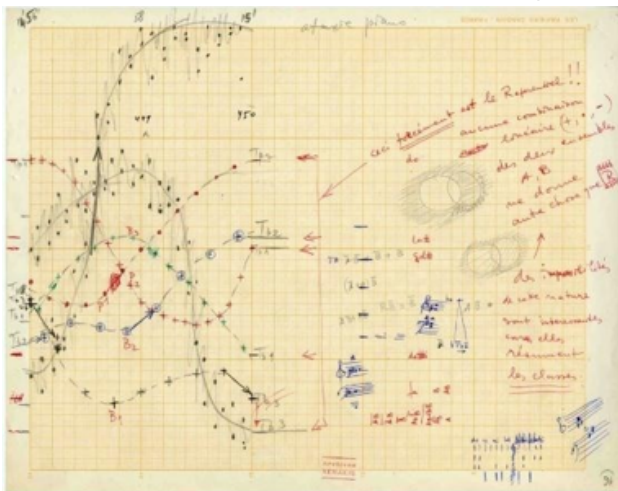
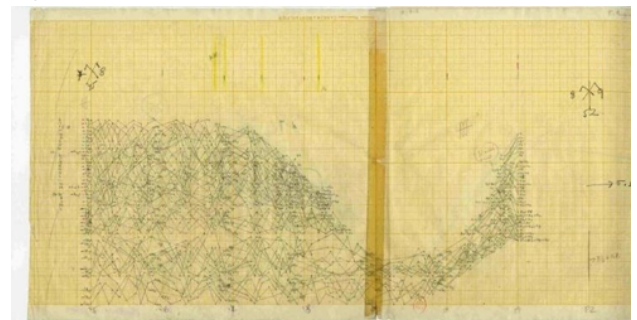


Figure 3_b



Bernhard Leitner_ sound as building material

In contrast, Bernhard Leitner (born in 1938) can be considered to have reversed Xenakis' process, constructing space from sound, and not from visual or material elements. Born in Austria, Leitner studied architecture in Vienna, before moving to New York to work as an urban designer. It was also there that he started experimenting with acoustics and space. Bernhard Leitner started treating sound as a building material, testing its physical properties to create and design space. His works range from different scales, from man-sized sound sculptures to urban installations (reSITE, n.d.).

Figure 4



Some of his projects, such as Cylinder Space (built in 1974), consist of sound fields created through carefully arranged speakers, where the listener perceives invisible walls and volumes. Leitner treats sound as a building material, defining spatial boundaries and activating body movement.

By using vibration and frequency instead of usual physical building materials, Leitner questions the dominance of vision in architecture and proposes a sensory and temporal form of spatial construction. His installations highlight how sound creates an architecture of perception, where space becomes dynamic, interactive, and immaterial. For Leitner, sound is used as a replacement to physical materials, creating and shaping space, while guiding the people who experience it (Lopez, O. (2011, September 23)).

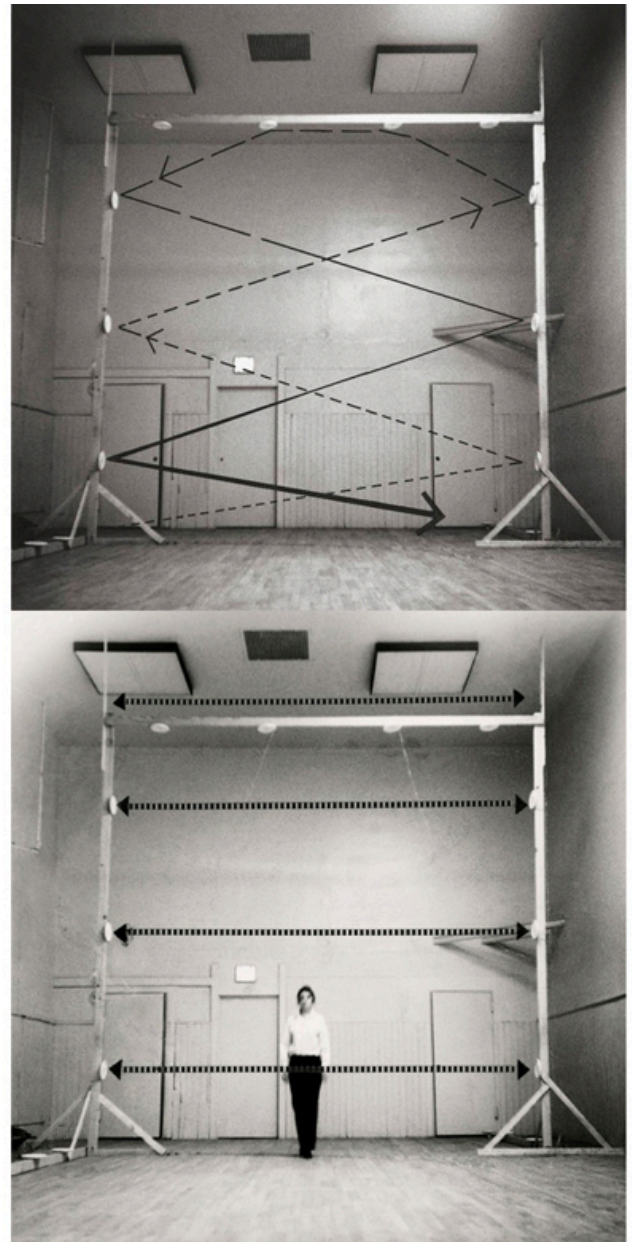


Figure 5

Cylinder Space is originally formed by 8 poles placed in a circular shape, each on with 2 speakers in its ends. The listener experiences sound travelling in different directions, as shown in Figure 6. This project stands as one of the only that was translated to built architecture in Parc de la Villette, Paris (built in 1987) (reSITE, n.d.). The loose poles with speakers, that originally shaped the structure, got hidden in a circular concrete structure.

Located in a valley, the structure is torn apart by an alley that attracts the visitor on one side and frees him back to the park in another one. The 5m round walls rise to the same height as the upper part of the valley, in which the visitor stands. Listening to the sounds from a distance but not being able to fully comprehend the structure makes the visitor intrigued. Going down the long staircase, the isolating double concrete walls and the round shape all get together to create an immersive space.

Additionally, given its scale and shape, the listener is invited to focus on the structure, the sky ceiling and himself. All these properties, plus the involving surrounding sound travelling around the listeners, contribute to a more introspective experience (Lopez, O. (2011, September 23)).

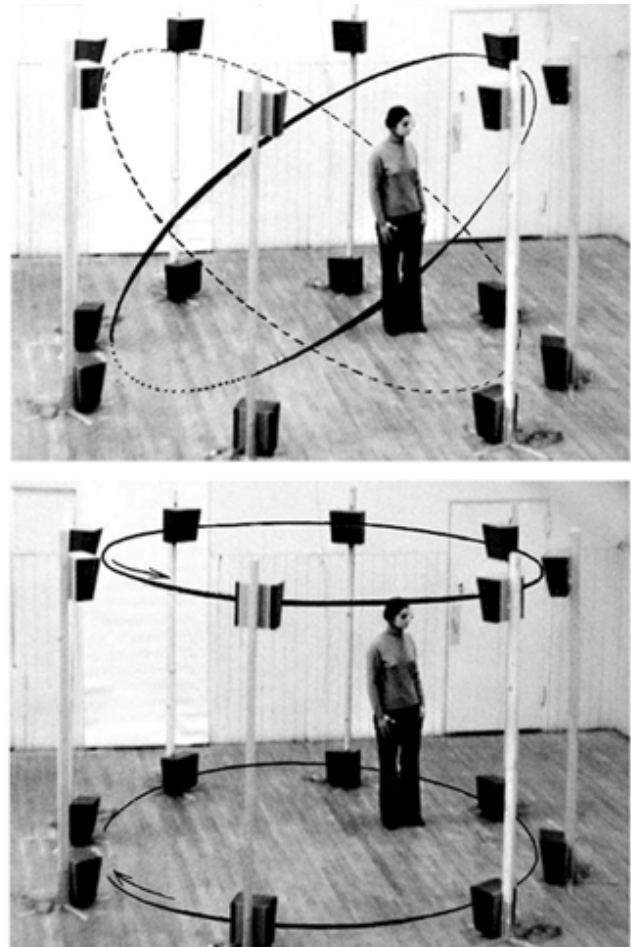


Figure 6



Figure 7

Bernhard Leitner also produced diagrams that explain his vision in all its fronts. These pieces are often a mixture of structural photographs with drawings, representing scale, structure and sound as well. Some drawings are somewhat abstract, also showcasing the music, composed by himself, for the projects. These usually show how sound travels through space and how it interacts with the listener, offering a visual representation of the installations. This type of drawing can also be understood as the formalization of sound. They represent another way to connect architecture with sound and other disciplines—a less physical but equally important way.

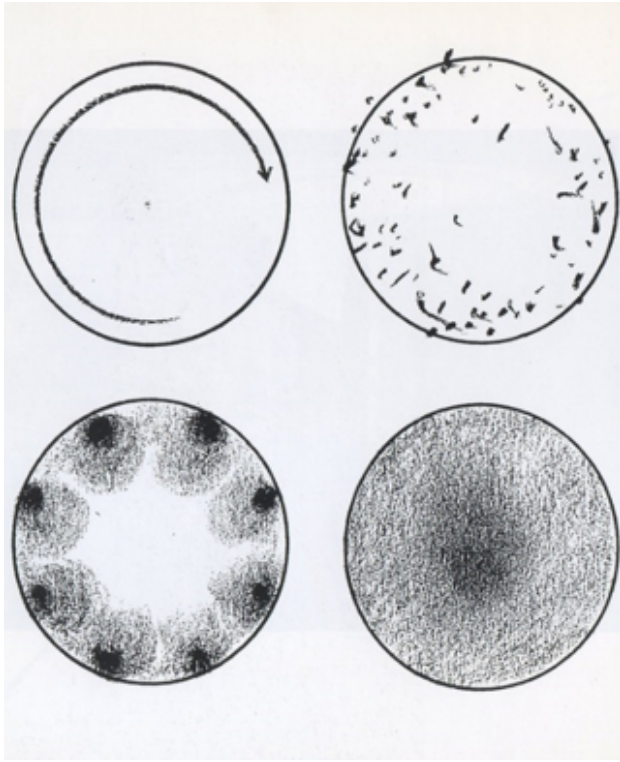


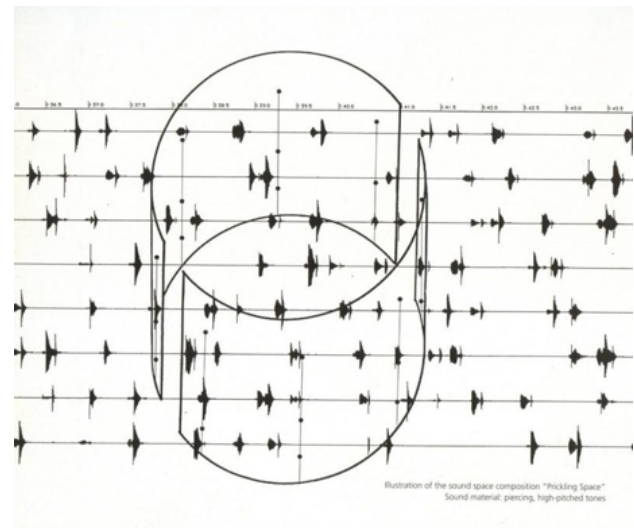
Figure 8_ a

Furthermore, they stand as a good example of how good representation, while simple, can influence the way an idea is expressed and perceived, acting as a bridge between the creator's complex ideas and the interpreter's successful understanding of them.

spatiality of sound

The combination of these disciplines with architectural purpose proves "[...] the potential for a new architecture which brings together the experience of the architect, the art of the composer and the determining will of the sculptor." (Lopez,O. (2011, September 23)). These projects show different relations between architecture and sound, and what benefits can come out of it.

Figure 8_ b



Both Xenakis and Leitner open pathways for rethinking how architecture can emerge from rhythm, sound, and sensory translation. Xenakis operates from music to material form, while Leitner operates from sound to spatial experience. Altogether, they establish a relation between the physical and the perceptual, showing that sound is not merely a consequence to architecture but can also act as a structural and compositional principle. Besides, both these examples show how architecture benefits from a multisensory approach, taking away emphasis from the visual stimuli and giving it to sonic receptors. In the current world and technological state, it makes sense to push both their approach and discoveries to a new level that would also meet the current society's needs.

Although this thesis does not follow exactly Iannis Xenakis' or Bernhard Leitner's approach, it takes concepts from their methods and works and applies them in different ways- always with the goal of highlighting the relationship of architecture and sound. Xenakis' use of stochastic and mathematic rules is here evident in the Self-Organizing Map, which works based on mathematical rules. On the other hand, Bernhard Leitner approach of treating sound as a construction material, inspired to look at sound from a different perspective, and to treat it as the main material and topic within this work.

sonification

Sonification is the use of sound to comprehend data, usually signals or images. Through data mapping, this process takes properties from the study object and matches them with sound parameters. This method helps breaking down complex datasets, exposing patterns that are easier to notice and process by hearing rather than by conventional visual information (Accessible Oceans. (n.d.)). Because sound is processed by the brain in a different part than visual information, this technique allows scientists to uncover information that otherwise would stay hidden in these complex datasets.

Sonification is a very useful and good alternative to processing complex data visually. While this method has been proved innovative and helpful, it has been established that to get better results it is better to combine sonification with visual processing of data, making this a better complementary technique rather than a replacement (NPR, September 21, 2025).

This method was invented in 1908 by the German Johannes (Hans) Geiger, an experimental physicist. He created the Geiger counter, which is a detector for ionizing radiation. The device functioned by emitting an acoustic click each time an ion was detected. In the beginning, the device was only capable of detecting alpha particles, but later, and working with Walther Müller, the counter was improved to



Figure 9

It is important to notice that the sounds are not meant to be created. Each extracted parameter is matched with a different instrument, which will play different tones depending on the amount of data. These sounds create patterns or loops so that variations stand out.

More recently, this method gained recognition after being used by Wanda Diaz-Merced. Wanda was born in Puerto Rico and lost her eyesight during her university times. To follow her lifelong dream of becoming an astronomer, she started using sonification to translate cosmic data into sound, after hearing a live audio of a sunburst. Using this method, she was able to analyse the energy emitted by Jupiter, which led to scientists discovering that there was information that could be unveiled with sound, such as stars' characteristics.

With sonification astronomers were able to search for patterns and information unbearable to process visually, given the amount of data received. Following the application of this method and its outcome, Wanda started working with NASA, creating a program to support and attract visually impaired people to astronomy. In collaboration with a team of scientists and musicians, NASA developed xSonify, -alongside Wanda, Anton Schertenleib and Robert Candey- a software to create sound from x-ray data from space (NPR, September 21, 2025).

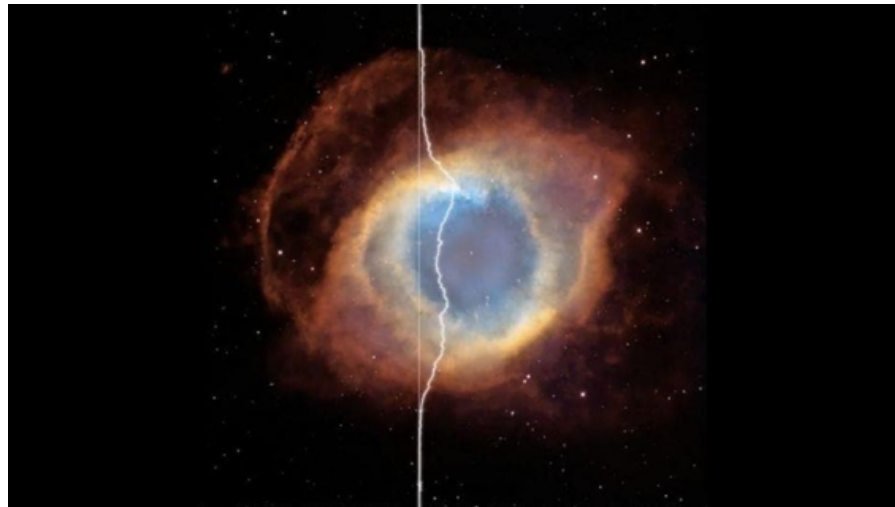


Figure 10

Turning energy flashes emitted by the fusion of stars into sound, allowed astronomers to better understand them. Since then, sonification has been also used in different fields, from science to arts and even technology. Across these different disciplines, the methodology differs but the goal is always the same- to make data visible and easier to process through sound.

Despite not being a very common practice in architecture, there are already some sonification experiments, such as the sound analysis of the Barcelona Pavilion (built in 1925), designed by Mies van der Rohe and Lilly Reich. At the heart of this project is Spanish architect Bea Goller, who is also a long time researched of the relation between sound and architecture. She believes that turning a building into sonic data can lead to a new understanding of it. So, a 5,5min audio referring to the analysis of the building's plan, from left to right, unveils the building's anatomy. Its element's repetition, the relation between spaces, solids and cavities, the spatial and material relation prove that translating material into sound changes the understanding of space.

By assigning each material to a specific sound, it is possible to understand the timing of the materiality of the building, and its variations; through sound it's possible to understand where there is a wall, a window, a column (2015, October).

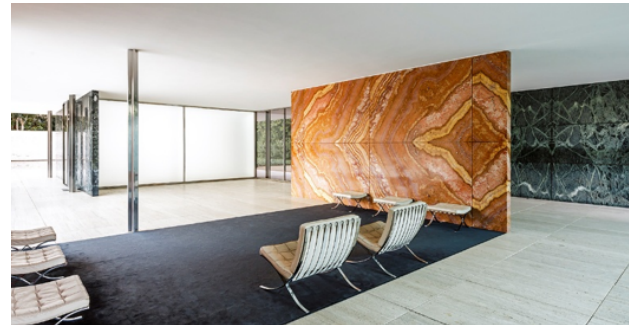


Figure 11_a



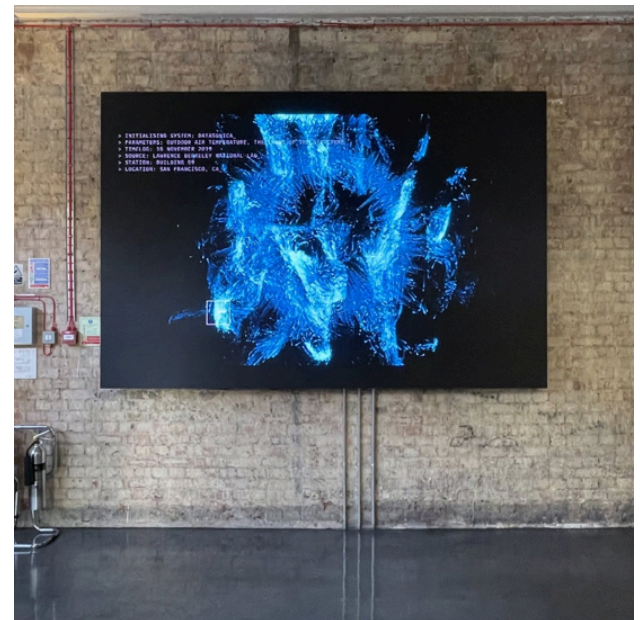
Figure 11_b

Shifting from basic analogue monitoring, where an isolated acoustic click signifies a single particle impact, paved the way for current data managing techniques. As computational processing developed, sonification also evolved into multi-layered, generative digital environments; complex environmental and physical datasets are synthesized into continuous harmonic systems. Tiziana Alocci establishes her work within this contemporary framework of complex data curation. Alocci's DATASONICA moves beyond passive information layout to graphic design and sound synthesis. These operate simultaneously, and prove that dense, multi-layered data becomes easier to comprehend when processed through coordinated, multisensory stimuli.

In this experience, it is possible to visualize environmental data from the sensors located inside and outside a building. These sensors are capturing humidity, temperature, and solar radiation, and turning it into data. The numeric chain that resulted from these measurements is then translated into frequency, which is later paired with visual data. This process's outcome is a soundscape representing the life of the building (and its variations) through time. Once again, this analysis is easier to comprehend when paired with visual representation, so different parts of the brain can interpret and process diverse types of sensory information. To make this easier to understand in this project, Tiziana explores a dynamic form of representation.

Here, the designer chooses a visual always flowing circle of matter to represent the changes, which suffers several alterations depending on the data input from the sensors (Tiziana Alocci, n.d.). By combining data with both audio and visual information, the expression of this project becomes richer, and easier to comprehend. This project stands as a great intersection of these different types of media, showing how data analysis can benefit from being treated with care visual and sonically.

Figure 12



The translation of environment and structure into sensory architectural output shifts from localized testing to building observation through the investigation of dynamic, data-driven systems. A project that binds sound, infographics, and architecture into a singular, immersive outcome is DATASONICA by information designer and artist Tiziana Alocci. Rather than treating a building as a static physical container, or static structural assembly, this interactive experience tracks and visualizes real-time environmental metrics captured by sensor networks positioned across both internal and externally in the building. These register shifts in humidity, temperature, and solar radiation, outputting data that is mapped onto acoustic frequencies. The resulting soundscape acts as a sonic manifestation of the building's atmospheric metabolism over time, giving a distinct auditory presence to invisible environmental and spatial variations.

To process this dense influx of data effectively, Alocci pairs the sonified environment with a generative, dynamic infographic structure, emphasizing the vital role of aesthetics in transforming raw data into legible information. Embracing such a dynamic mode of representation, the interface displays an ever-evolving, fluid circle of matter that distorts and alters its graphical properties in direct response to the incoming sensory data (Alocci, n.d.).

By combining visual and sonic stimuli, this multisensory framework enables diverse regions of the brain to simultaneously decode complex, multi-layered data. This relation of both audio and visual information makes the project richer. Furthermore, the data becomes highly comprehensible to people outside specialized scientific fields due to its expressive medium of communication.

DATASONICA ultimately stands as a critical intersection of media, demonstrating how architectural data analysis can reveal the living, temporal reality of the built environment when treated with forensic and aesthetic care. This framework offers an open-ended model for how multisensory, and curation can increase data expression and consequently understanding.

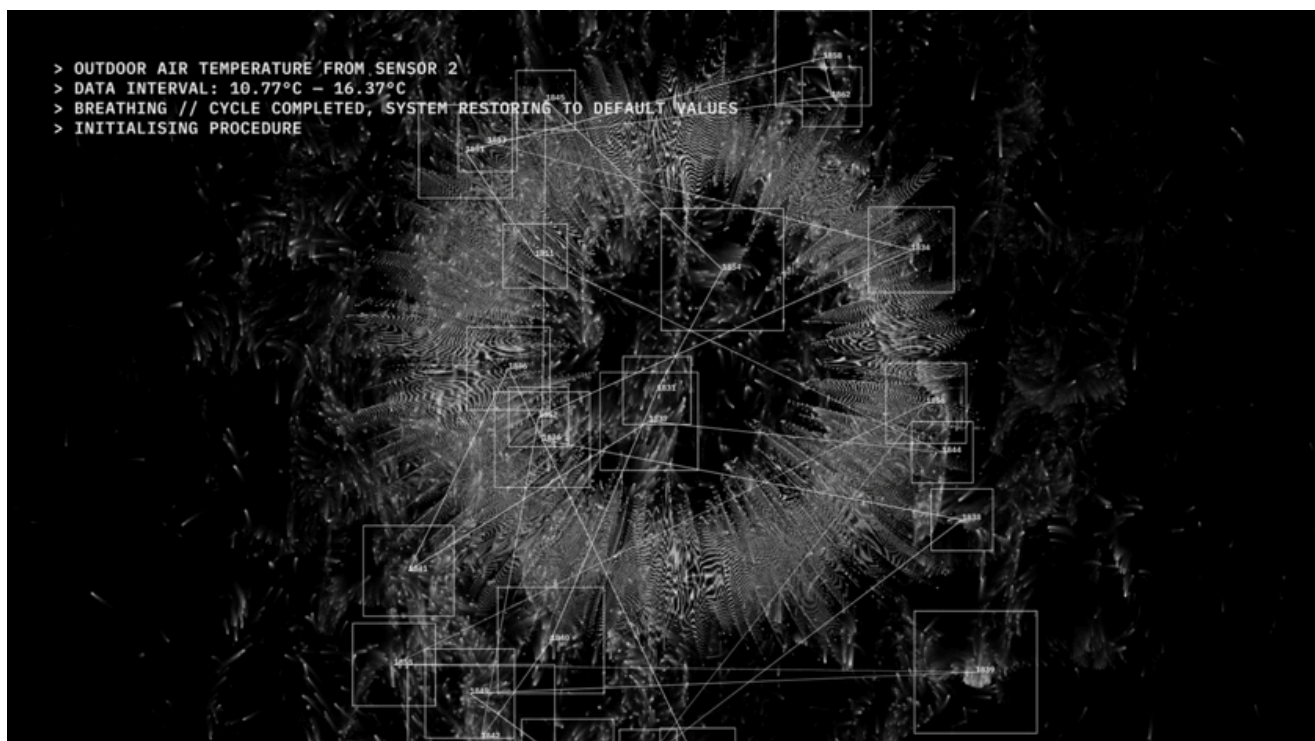


Figure 13

material *theory*

Architecture is currently one of the most polluting industries in the world, being responsible for around 40% of carbon emissions around the world. (World Green Building Council. (2021, September 15)).

Architecture is undeniably a necessity for mankind and therefore it cannot be discarded. Some methods for changing the impact architecture currently has include, for example, rethinking materials used, making architecture more energy efficient.

Most architecture digital tools, such as CAD and BIM, rely on standardized materials, predictable in shape and performance, while reused materials often show irregularities and signs of use. The use of waste creates a knowledge gap due to the uncertainty of its performance. It is therefore necessary that each piece is analysed, external and internally, in order to understand its current state and possible use. Through Non-Destructive Testing, it is possible to create a digital library of waste materials, and to analyse each piece.

Because the project focus on the study of materials, and to follow the current effort to practise a greener architecture, only reused materials have been used. Although this topic is not directly related to construction, it is still architecture and therefore it also respects its commitment to sustainability. Consequently, there was a brief investigation about places around Lund or Malmö that could supply discarded materials. After talking to the representatives of those places, two of them ended up being the source for the collected pieces. These materials came mainly from two places, both in Malmö. The bricks and tiles origin from Malmö Återbyggdepå, while the other materials, such as the woods and metals come from the Varvsstaden AB material bank.



Figure 14_a



Figure 14_b



Figure 14_c

The search for discarded materials to use repurpose them has been influenced by contemporary architecture firms such as FOJAB and Lendager, which exemplify how architectural design can evolve through the reuse and reassembly of existing materials. Their work challenges the modern linear model of construction — extraction, use, disposal — by introducing cyclical processes of transformation and adaptation, as well as an innovative approach to the design process (Overstreet, K. (2020, July 17)).



Figure 15_ b

Figure 15_ a



FOJAB's Mobilitetshuset Hyllieäng in Malmö reinterprets a parking structure as an urban material experiment. The façade combines reused glass and metal panels in a rhythmic composition that carefully balance ventilation, light, and texture. This project reveals how architectural expression can emerge from systematic reuse, where material irregularities and historical traces become part of the building's identity. FOJAB's method is essentially multidisciplinary: it integrates material research, digital design and sustainability into a coherent framework, never forgetting about aesthetics and surroundings (FOJAB.(n.d.)).

Similarly, the Lendager Group in Copenhagen has established itself as a pioneer in circular architecture. Their projects, including Upcycle Studios (built in 2015) and Resource Rows (built in 2020), incorporate reclaimed concrete, wood, brick and glass from demolished structures, reassembled through digital coordination. Lendager's approach not only reduces embodied carbon but also creates an expressive architecture of continuity. Each reused component carries a fragment of the material's memory (Lendager Group. (2015)).



Figure 16_b

Figure 16_a



One big problem noted while exploring the «form follows availability» approach regards material storage. (Jenning, P. (2024, February 7)). This was a major issue for FOJAB's Mobilitetshuset Hyllieäng. Because they used metal sheets from the metal industry, that were discarded weekly, they could not predict its shape at the time the project was being built. This is because, in this case, metal and the construction industry have such different tempos.

This makes it more difficult to plan how a building will actually end up being, so a different approach to the process is needed. Some changes include designing with more flexibility—something that has been more frequent in architecture in recent years— and also keeping close contact and dialogue with the planning office, as described by Petra Jennings. This last initiative makes it better to adapt and react to any unforeseen events during the process, such as differences in materials from the planning to the construction phases.

All of these projects can inspire architecture—not only built architecture but the whole range of it—to seek different approaches and answers to today's challenges. These project's commitment to inclusivity happens on two parallel levels: the material and the human. On a material level, this workflow embraces “non-standard” waste—the irregular, the worn, and the discarded fragments that traditional systems often exclude due to their lack of predictability.

On a human level, utilizing sound to think of architecture converts the process into a more inclusive and human experience. Drawing inspiration from the works of Wanda Diaz-Merced, who used sound to study the outer space, complex data can be interpreted in an easier and more complete way by using other senses.

Architecture is historically visually focused, prioritizing visual form above all other sensory receptors. In contrast, by making sound the central piece, this project takes inspiration from the sustainability committed and approaches material research from a different take. For this practice, discarded materials are sourced for their sonic parameters, and each piece is looked at as a data-rich foundation.

material nomenclature

Another part of the process that raised a lot of questions was when naming the pieces, to organize them before starting the test. This uncertainty derives from their composition being unknown, so it became difficult to give names that would make them easily identifiable. Not only this problem posed questions about the materials' origin but also made me reflect on what makes each material's ID. Is it indeed their composition, their shape, their functionality?

To overcome this problem, new ID's were given to each piece, based on their composition. For the materials in question, they are either be classified as 'mineral' (min), 'organic' (org) or 'metal' (met). This classification is followed by a number, which us the number of te material tested, and then which test they were subject to. In the name there is always either a k (knock), or a p (pendulum). Although both tests were made with the pendulum, k means single knock and pendulum multiple knocks. This way, the reformed name for the first single knock brick tested, for example, becomes min.01.k. The new ID name helps looking at each material primarily based on their composition, discarding function or shape. In a dataset of about 30 materials, such as the library one in question, this is enough to lose track of the physical piece attached to the sound heard.

Although the pieces cannot be fully separated from physical form and their name, they are connected to images for analysis purposes. Nonetheless, for data processing, it seemed better to disconnect the conventional name from the piece, so they can be interpreted unbiasedly.



physics of acoustic sounds

To understand this topic and define the acoustic fingerprint of each piece, it is necessary to examine certain sound characteristics and how they relate to physicality. Rather than treating these features as isolated sonic properties, they are processed as indicators of inner structure, density, elasticity, and energy of the matter.

First, amplitude represents the maximum displacement, or height, of a sound wave. It relates directly to how loud a sound is, and physically, it translates into how elastic a material is (Accessible Oceans, n.d.).

Secondly, frequency tracks the number of sound waves per second; within this thesis, it measures how hard or soft the material's structure is (Accessible Oceans, n.d.).

This analysis isolates the peak frequency, which is the exact highest frequency value achieved by a sound wave. A high peak frequency means the material is stiff and lightweight, while low values indicate elasticity and heaviness (ScienceDirect, n.d.). In terms of physical energy behaviour, a high peak frequency indicates that the material has low internal damping, allowing high-frequency structural vibrations to propagate freely rather than being immediately absorbed by the contact, whereas a low value signifies higher absorption.

Finally, the temporal dissipation of the signal is captured through peak duration, defined as the interval of time a sound or signal stays near or at its maximum level of energy (NDT.net, n.d.). When measuring materials, a sharp sound creates an instant thud, meaning the peak duration will be short. Conversely, when the acoustic energy is successfully sustained by the material's internal structure, the peak duration will be significantly larger

methodology

This chapter details the step-by-step physical and digital processes of acoustic data acquisition. This framework ensures that the extracted sonic data accurately captures the true structural identity of the architectural materials.

methodological *framework*

Starting this project, the initial idea was to gather the materials needed, record them under constrained circumstances, and start working on the digital workflow with the collected data. Despite this, delays with getting the materials forced the process to be inverted. The digital part of the project was built first, using non-accurate recordings of different materials as samples to test the workflow and its results. The recordings were made on different occasions and settings, but were rigorous enough to start analysing these different materials.

Background noise and purity of the materials, as well as accuracy in the knocking were taken into consideration, and were kept as precise as possible. Despite this, and later analysing the recordings, it is possible to notice some lack of equality on them. The recordings include materials and objects that come close to architectural materials such as lamps, tables, windows, walls, bricks, which translate into samples of metal, wood, glass, concrete, ceramics.

initial **data acquisition**

At a later stage, a simple pendulum was built to make the recordings more accurate. Though the first test knocks were made with a fingernail knock, the pendulum ensures the same piece always hits the different materials, with the same velocity and strength. This translates into stability in intensity, which makes the reproduced sound waves purer in transmitting the real identity of the piece.

Figure 18

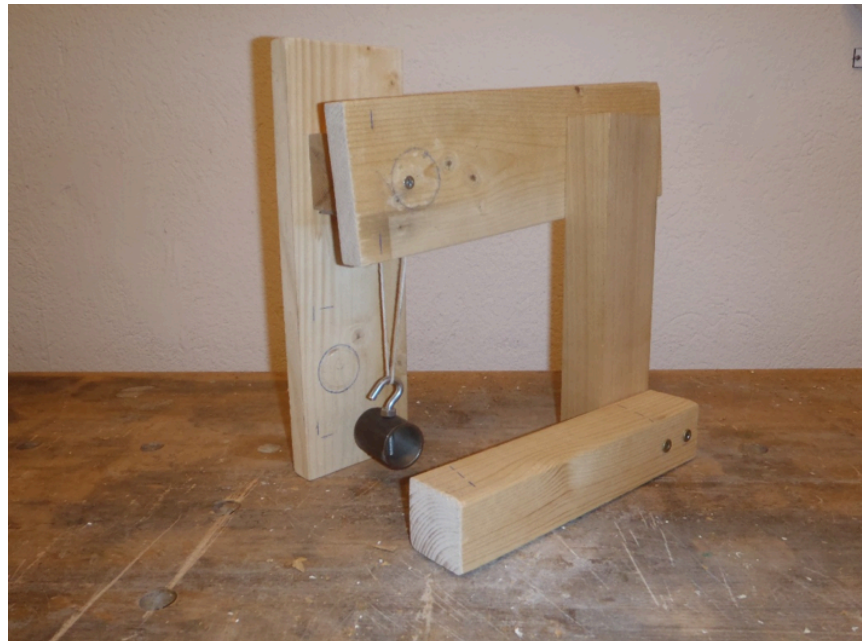




Figure 19

The pendulum is a simple wooden structure, built from leftover wood, that is supported by two unaligned vertical pieces. These are placed diagonally to each other to add stability to the piece and are held by a horizontal wooden piece at the base, which also serves as support for the recording device. This way the recording suffers less interference from outside noise.

The chosen hitting piece is a baseless cylinder metal piece, which reduces the metallic eco and gives space for the materials' sound waves to be recorded with less interference. This piece is hung by a rope, which produces no additional sound when moved and gives flexibility to the metal cylinder during the knock. The length of this rope is always the same, so the intensity and velocity of the knock stay stable.

data *visualization*

Serving as the analytical core of the thesis, this chapter translates invisible acoustic data into legible forms. It describes a custom digital pipeline: from the raw ingestion of sound waves, to parametric geometric filters, and into unsupervised machine-learning tools. The chapter concludes by exploring the rematerialization of this data through 3D printing.

digital *exploration*

At the start of the digital workflow is Pure Data, which was used to process the sounds by measuring and converting the sound parameters into MIDI values. That MIDI data was sent to TouchDesigner through Open Sound Control (OSC), which is an open network massaging format developed for “communication among computers, sound synthesizers, and other multimedia devices.” (Open Sound Control, n.d.)

In TouchDesigner, the data is processed, and the values extracted from Pure Data were associated to XYZ coordinates. This locates each material piece into space (X=Amplitude, Y=Frequency, Z=10 to ensure space between the squares). The outcome for each piece is a square, that depending on its values it gets bigger or smaller, darker or lighter. Another outcome from TouchDesigner is a table with each value for each parameter of each material.

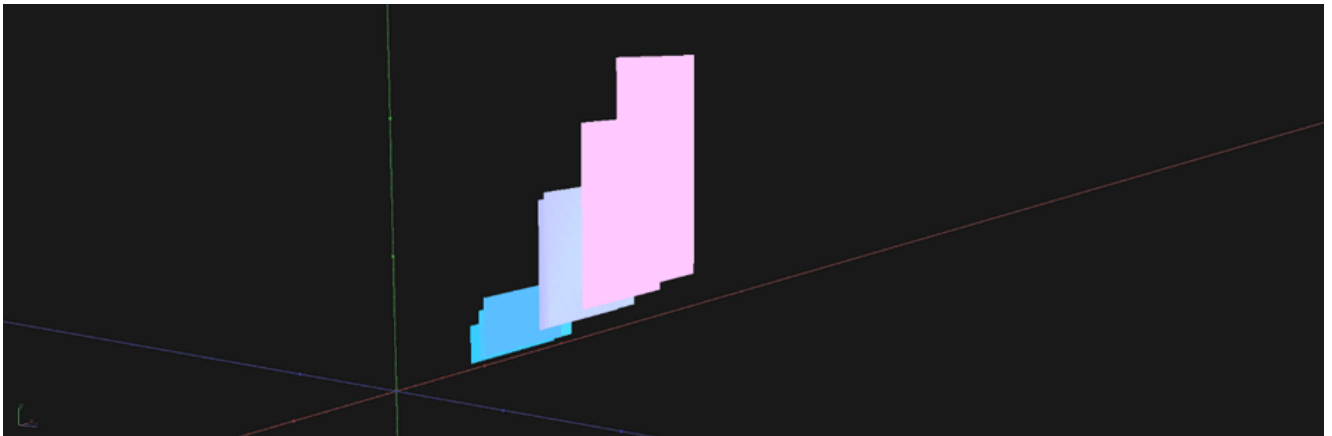


Figure 20

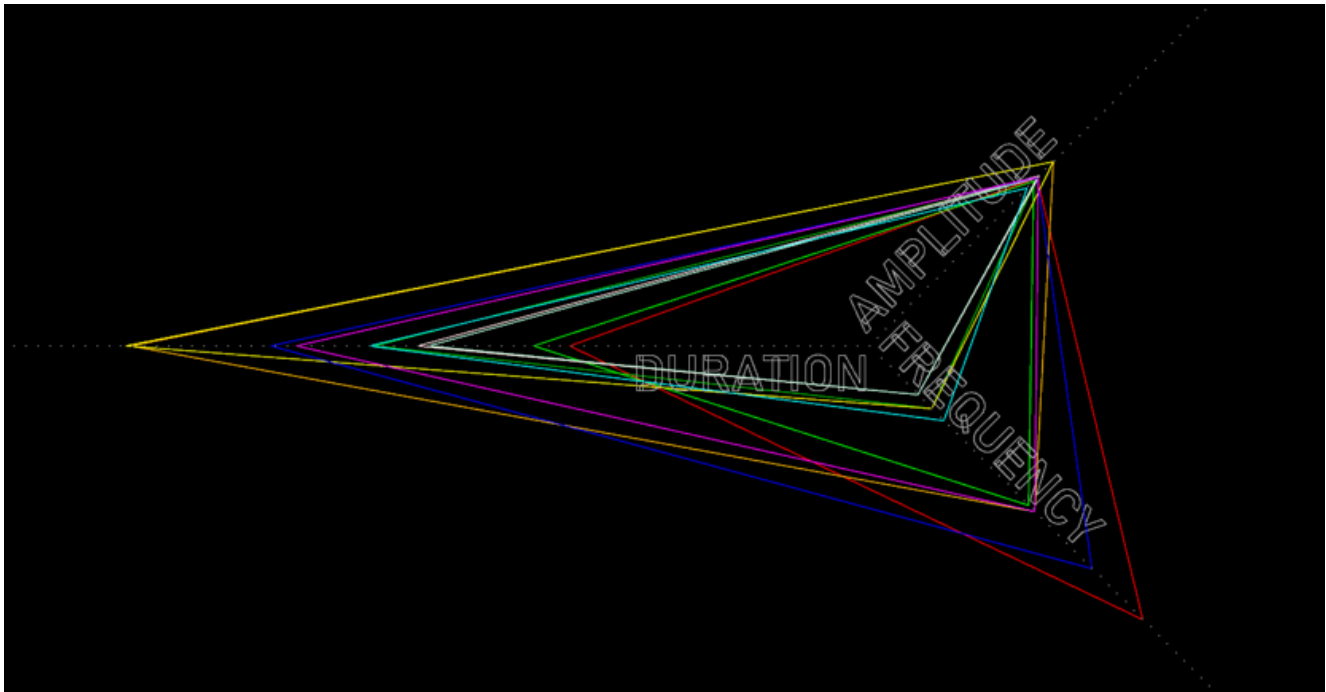


Figure 21

Despite this developed workflow, obstacles with it and time constraints led it to be adjusted. For the processing of the final recordings, both Pure Data and Touchdesigner's steps of the process were eliminated and, to connect each piece's sonic data to the creation of the triangles in Rhino, *soundInfo* was directly connected to Rhino. Each material's sonic numbers were exported into a table containing their name, amplitude, frequency and peak duration values, which was directly fed into Grasshopper's script.

The sound samples collected at the beginning located into space. The sounds were translated into squares, in which the size is connected to the frequency, and the colour to amplitude. This way, the harder the material, the bigger the square. And the louder the sound, the darker the colour.

This table was then exported to Grasshopper, to create the triangle graphics that explore the relations between Amplitude, Frequency and Peak Duration, allowing an easy understanding of these characteristics for each piece, and an easy comparison between them.

soundInfo_ sound processing

To help studying each sound and its characteristics, an interface was created using Python. This interface, *soundInfo* reads and displays the sound characteristics from the selected file. It is possible to analyse the amplitude, frequency, peak frequency, peak duration and timbre of each sound. On a later stage, some thresholds were defined to classify each sound based on their structural characteristics. There is also an option to listen to the selected sound, as well as to show its spectrogram. For this interface to show the sound parameters, a *.json* file was created for each sound. This file contains the characteristics mentioned above, obtained through analysis of the *.wav* file recording.

Figure 22_a

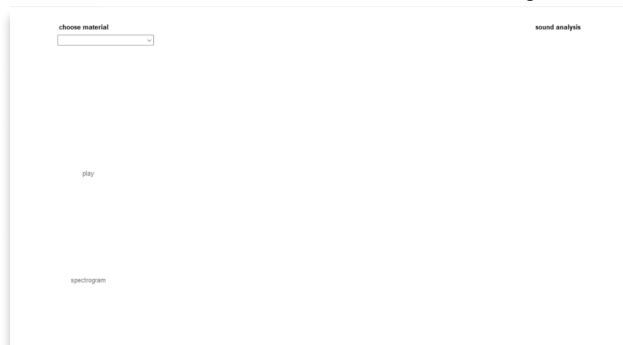


Figure 22_b

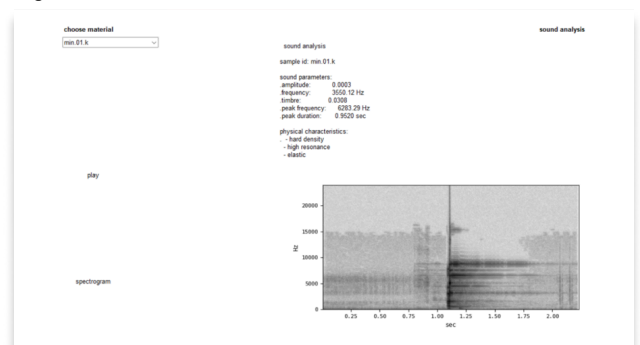


Figure 23_ a

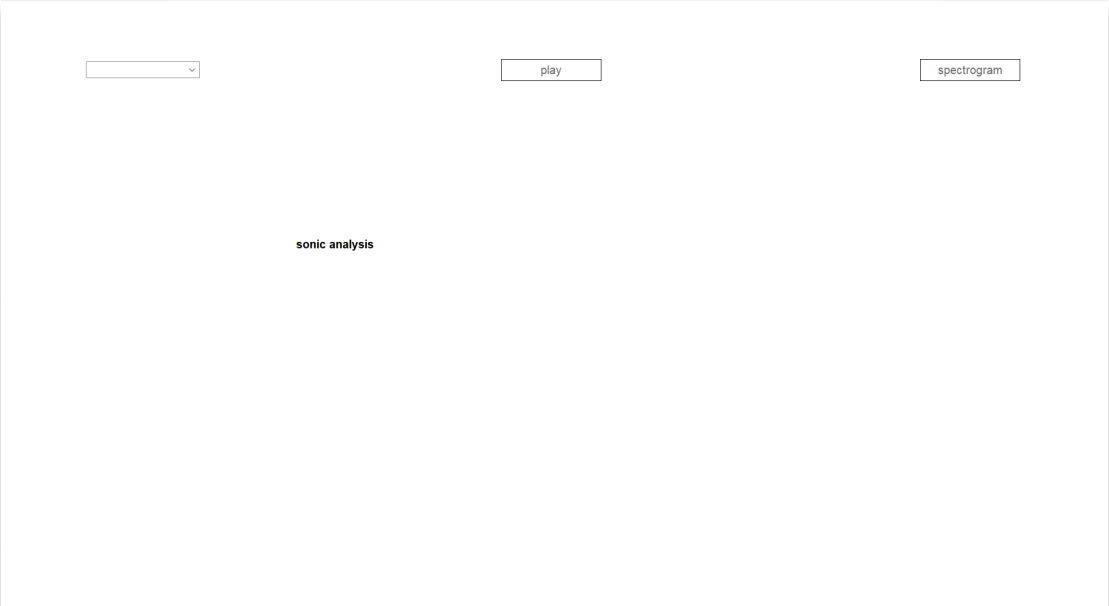
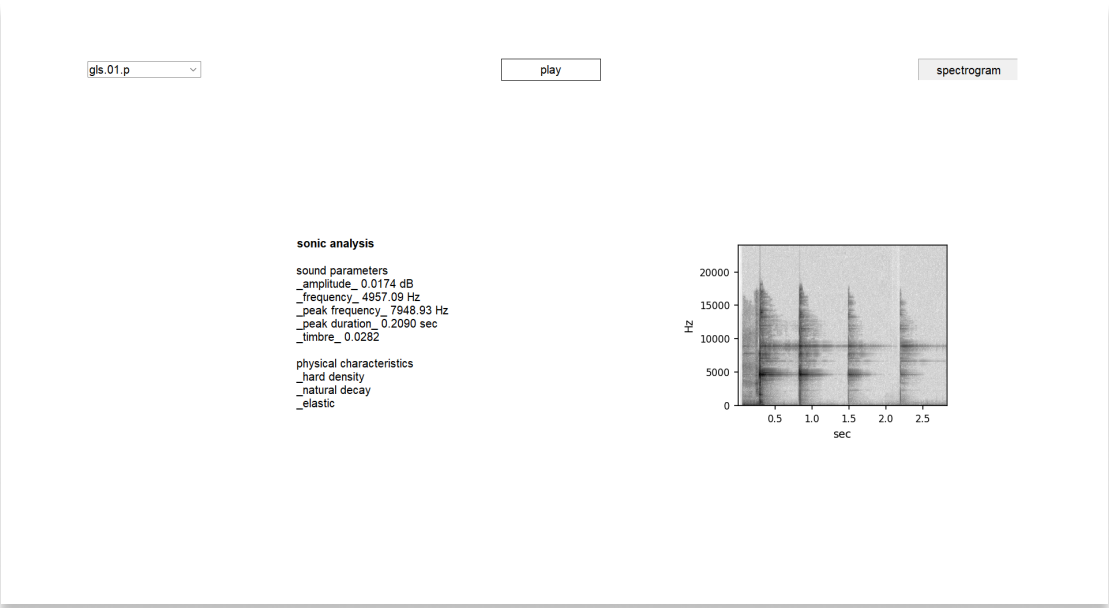


Figure 23_ b



spectralTriangles_ analytical design

While the *SonicInfo* interface extracts precise acoustic parameters, raw numerical tables lack intuitive understanding. To bridge this gap, the extracted data (amplitude, frequency, and peak duration) is exported to Grasshopper and translated into spectral triangles. The values are normalized and mapped onto a custom tri-axial coordinate system: amplitude on the positive x-axis, frequency on the positive y-axis, and peak duration along a diagonal vector into the -x-y quadrant. Connecting these vertices forms a closed polygon, turning each material's acoustic signals into geometric shapes.

These triangles were then presented in three different ways: the individual graph containing each triangle and name, for analysis and comparison of each piece; the individual hatched triangles stripped away from any graphic, scale or nomenclature, relying entirely on visual processing to communicate material behaviour; the overlapping composition of every piece, both in a graph, for an overview, and blurred - to understand which values are mostly present in the materials. By evaluating these geometries, architects can rapidly assess structural properties: a large, symmetrical triangle signals high density, and a skewed shape reveals internal friction or fatigue. This visual expression transforms raw data into legible architectural language.

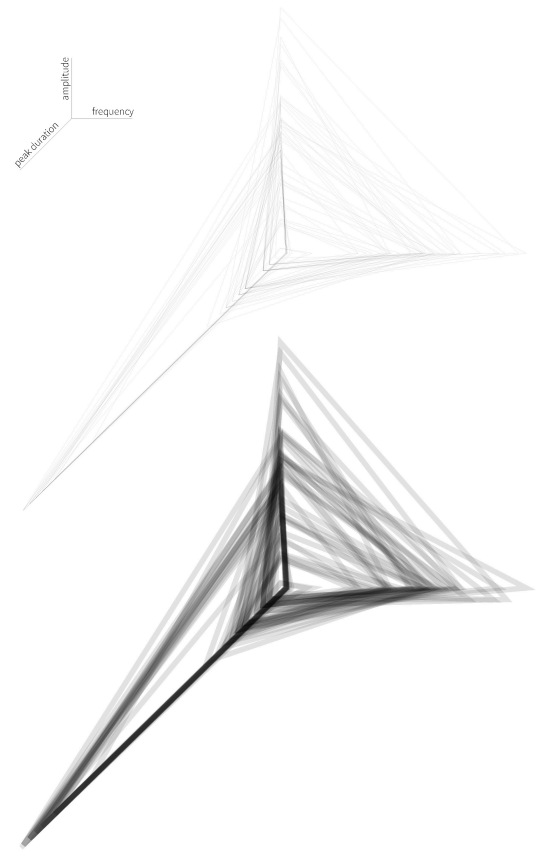


Figure 24

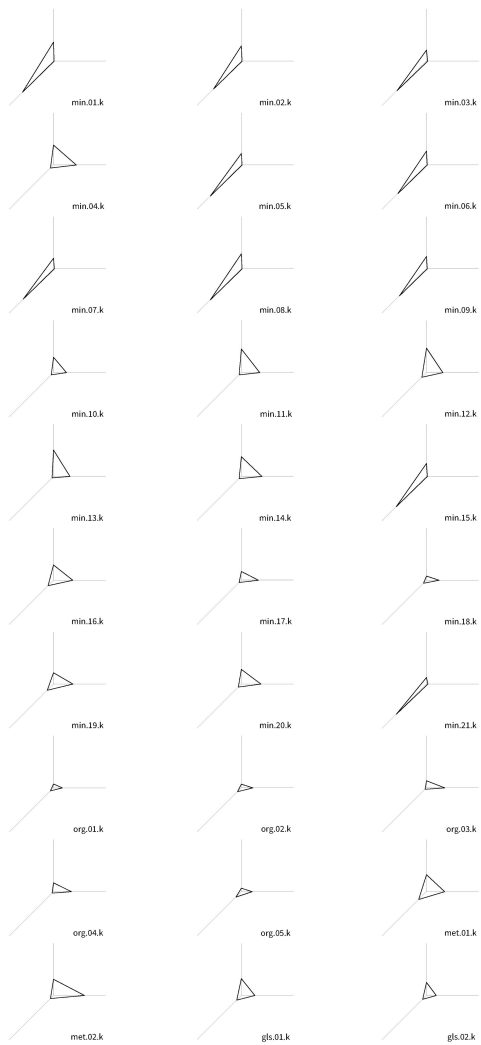


Figure 25_a

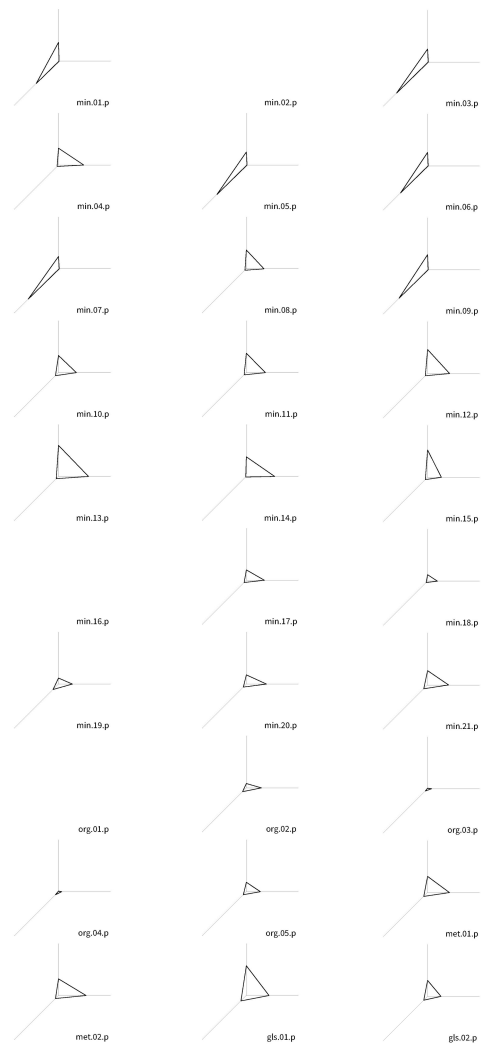


Figure 25_b

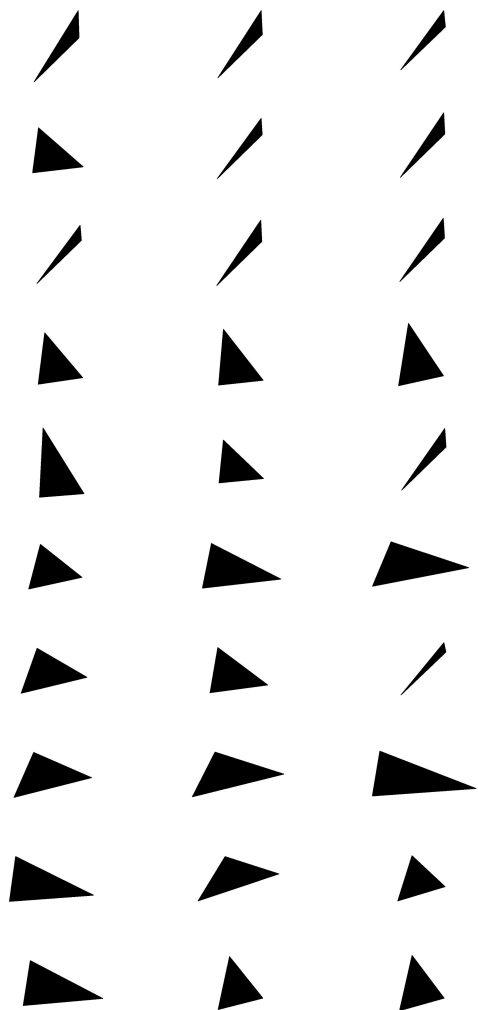


Figure 26_a

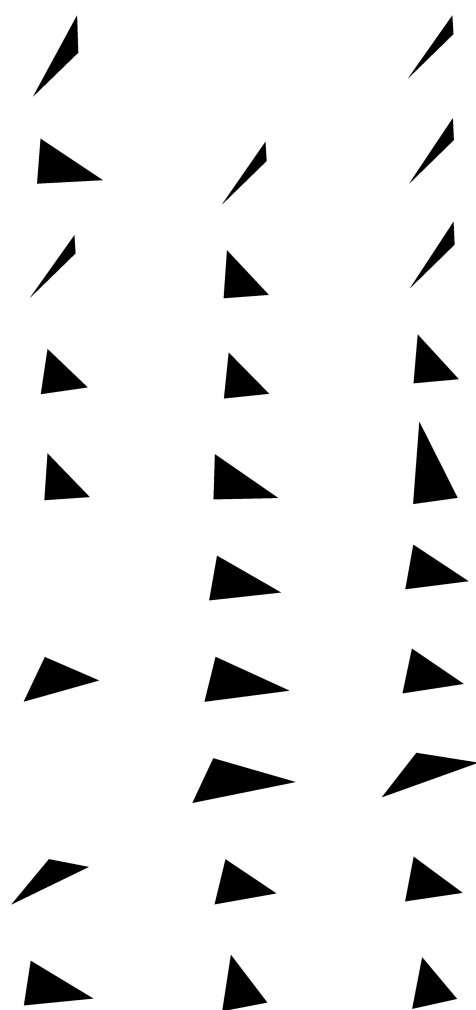


Figure 26_b

self-organizing map_ material organization

The Self-Organizing Map, (SOM) is an unsupervised artificial neural network designed to perform non-linear dimensionality reduction, effectively translating high-dimensional data into a low-dimensional, typically 2d, topological map (MathWorks, n.d.). The algorithm operates through competitive learning. During training, complex input vectors are introduced to a grid of artificial neurons. For each input, the network identifies the Best Matching Unit (BMU), which is the node whose weight vector is mathematically closest to the input space, typically calculated via Euclidean distance. The weights of the BMU and its immediate topological neighbours are subsequently adjusted to resemble the input more closely, causing the network to organically organize itself into a continuous spatial landscape where similar data points congregate into visual clusters (IBM, n.d.).

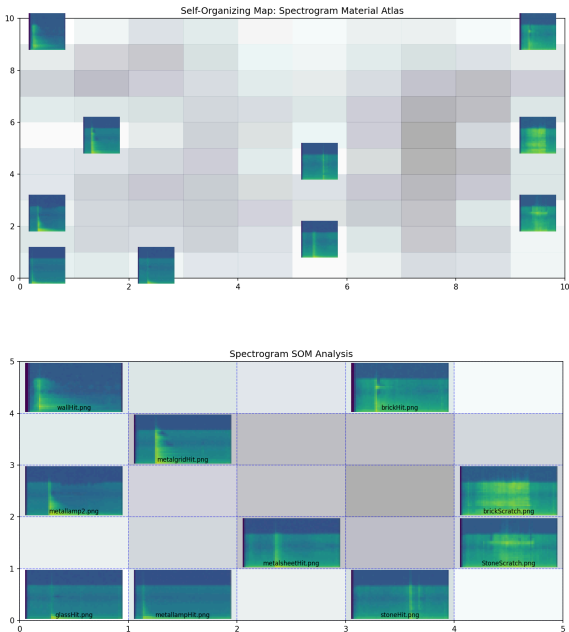
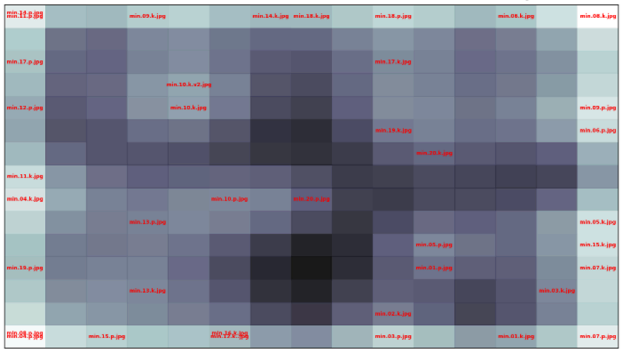


Figure 27_ a



In the context of architectural material research and acoustic forensics, the SOM aligns directly with spatial design thinking. Instead of forcing physical materials into rigid, predefined categories, the SOM projects a fluid relational canvas. This allows the architect to visually identify "neighbourhoods" of material resonance and harmonic texture, facilitating the intuitive discovery of structural similarities across disparate salvaged materials without relying on their common name or historical origins.

Figure 28_ a



Figure 28_ b



Figure 28_ c



Figure 28_ d

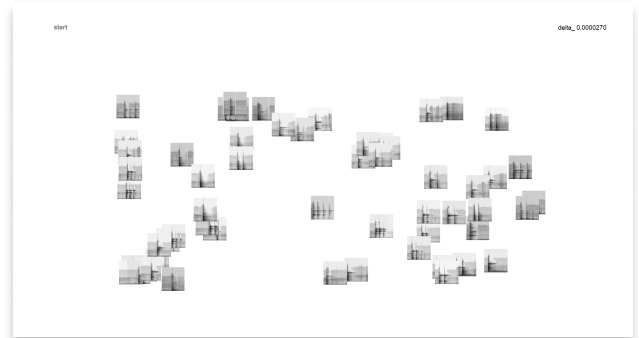
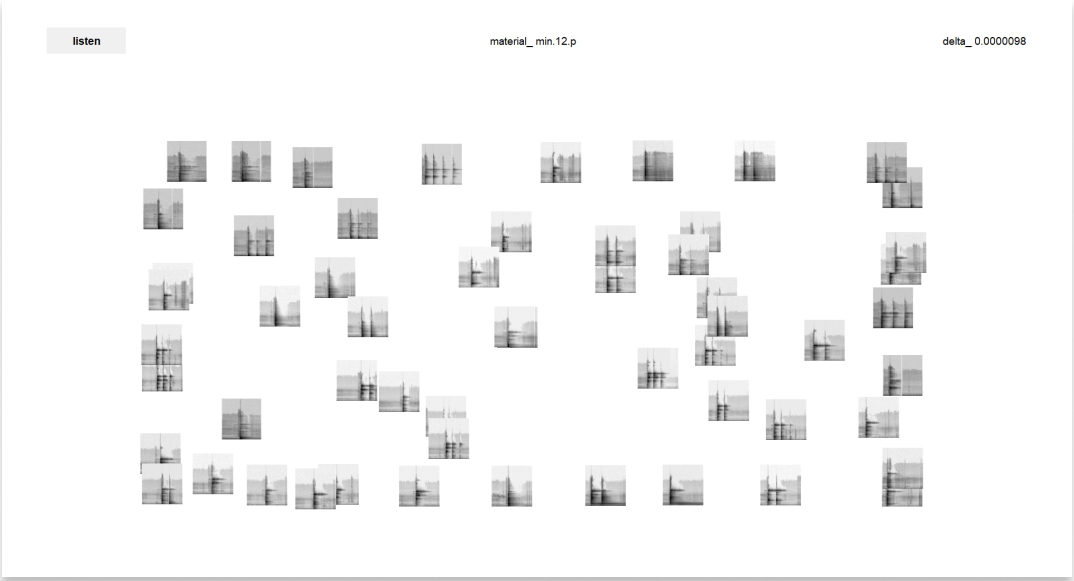


Figure 29_ a



Figure 29_ b



hierarchical dendrogram_ material classification

Agglomerative hierarchical clustering is a bottom-up unsupervised learning algorithm that constructs a rigorous, nested taxonomy of data, visually represented as a branching tree structure known as a dendrogram (Scikit-learn developers, n.d.). The computational process starts by treating every single data point, such as an individual material's acoustic signature, as an isolated cluster. The algorithm then computes a pairwise distance matrix to evaluate the structural dissimilarity between all clusters. Through successive iterations, the two clusters separated by the shortest mathematical distance are merged into a higher-level node.

This continuous combination is done by a linkage principle, Ward's minimum variance method, which ensures that each consecutive merger results in the smallest possible increase in total within-cluster variance (IBM, n.d.). In this architectural research, the dendrogram actively challenges traditional, visually biased material classifications. By organizing a material corpus exclusively through acoustic characteristics, the dendrogram generates an objective, performance-based structural hierarchy. This objectively maps the true physical elasticity and internal damping of salvaged waste, demonstrating precisely how non-standard resources relate to one another, regardless of their surface degradation or previous architectural function.

Figure 30

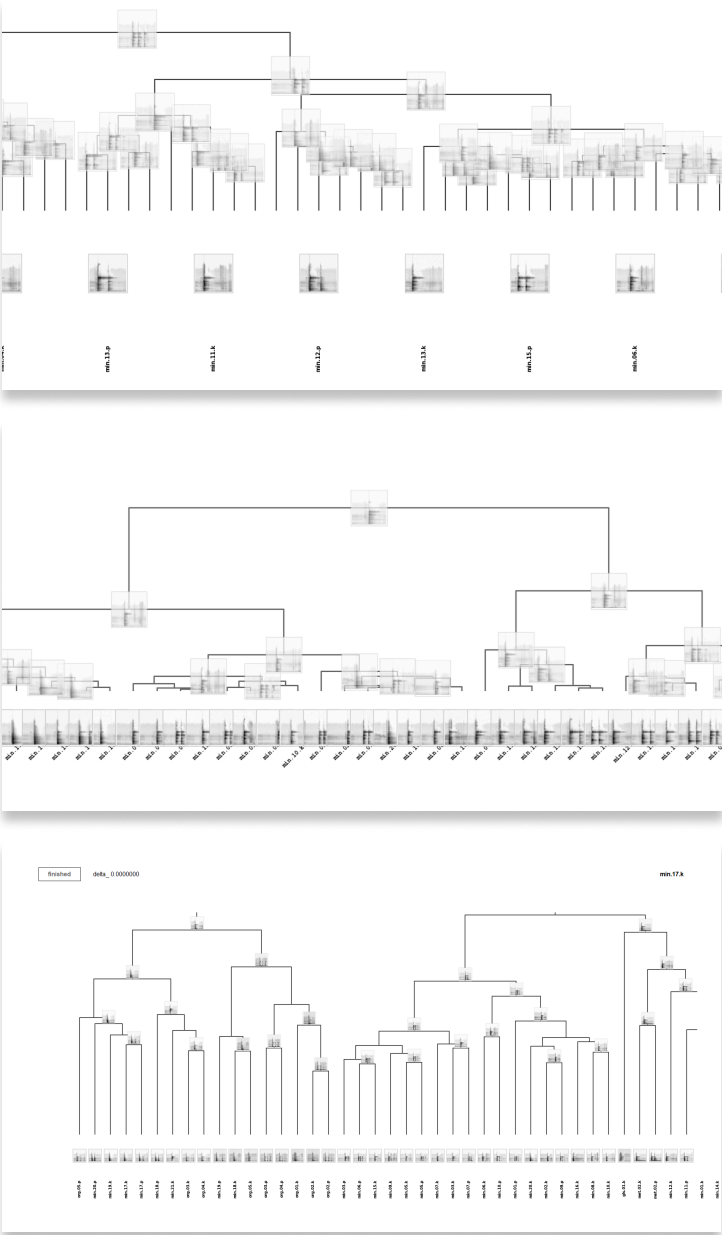
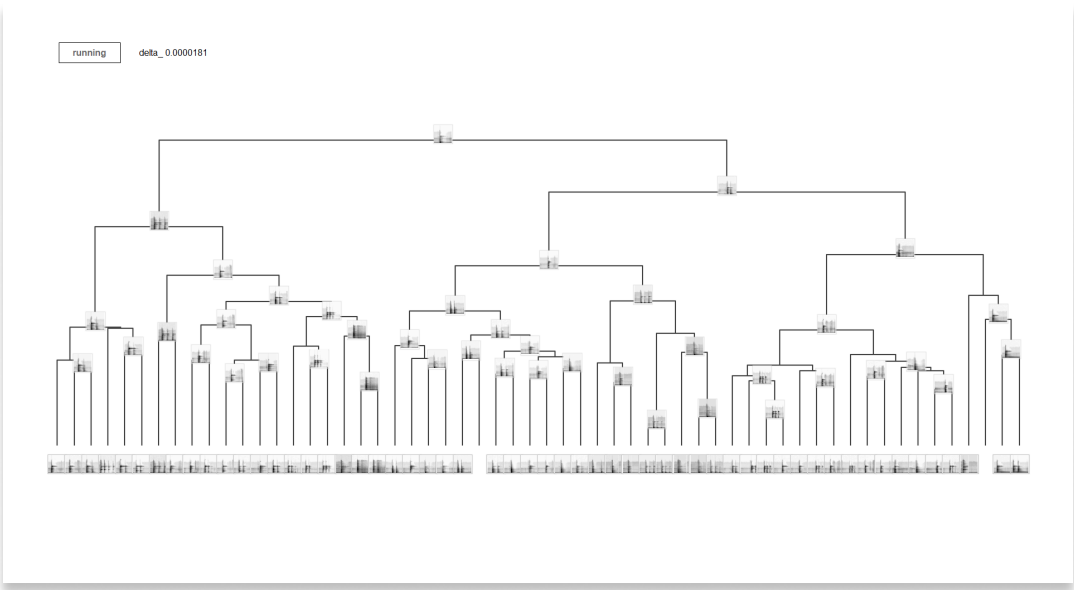


Figure 31_ a



Figure 31_ b



soundRays_ relation and diagnosis

At a later stage, and also using Python, another interface was created- *soundRays*. This tool was initially thought to be completely interactive, where people can manipulate each material, using its own characteristics. This allows the user to approach each material initially through its sound rather than by its visual attributes. The interface starts with all the materials displayed by lines and cantered to the same point. After selecting a piece from the dropdown, the sound of this same piece is played, and it is possible to choose to activate its amplitude, which curls the line, its frequency, which changes the length of it, or its duration peak, which makes the line zig-zag. Here, the bigger the amplitude, the bigger the curl, which translates the material elasticity; and the bigger its frequency, the bigger its length, which indicates its hardness; and the bigger the peak duration, the bigger the zig-zag, which is related to the number of physical wave cycles before running out of energy.

There is also a 'play' button, so the selected material can be heard at any time. On the other hand, it is also possible to select a ray, whose name is indicated in the dropdown bar. Despite not being completely direct, since any visual information about the material is missing, that is what makes this tool interesting. The user is invited to explore it by the sounds it hears, and just after that it can link the coded name of the material to its photo, from a photo-based material library made to link the two senses.

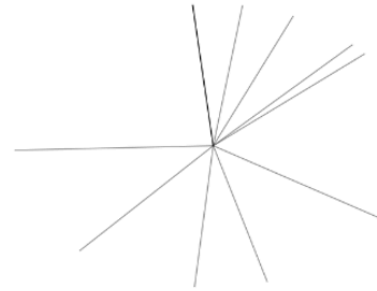


Figure 32_ a

Figure 32_ b



Although *soundRays* is a good interactive tool for sound exploration, it needed some alterations to be used as an analytical tool. For that reason, some changes were made: the interface becomes less interactive, as it starts with all the sound attributes activated and it is no longer possible to manipulate them. In this version, for the selected material, its image is displayed on the side. These changes allow the user to connect more easily each sound to each material and make it faster to explore its attributes. Here the goal is not the interactivity part and the discovery of each sound, but a direct connection of each sound to the real piece and its sound analysis.

After having the sounds characterized and analysed, the next step was to find a way to explore and manipulate the sounds. This way, and to approximate data to form, the idea came up for creating an interactive interface that allowed the user to mess with the sound parameters of each piece, creating different shapes. *soundRays* stands as an intersection between data and interactivity.

Figure 33_ a

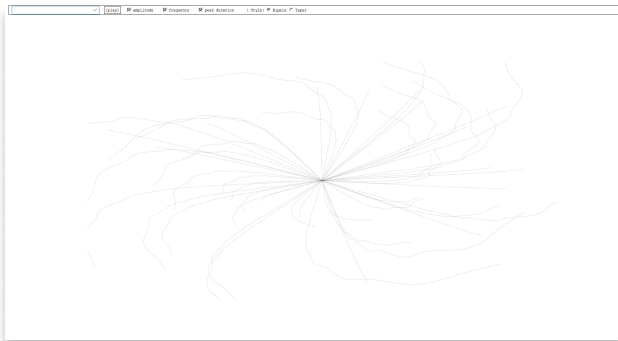


Figure 33_ b

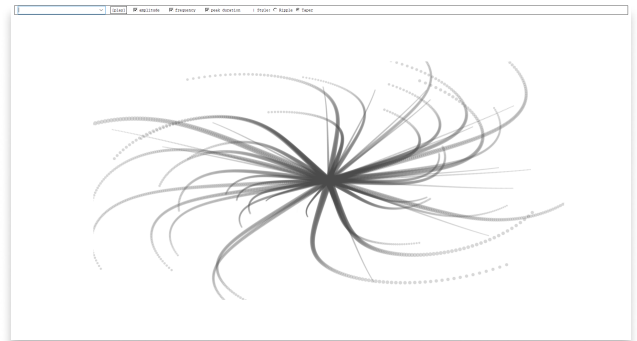


Figure 34_a

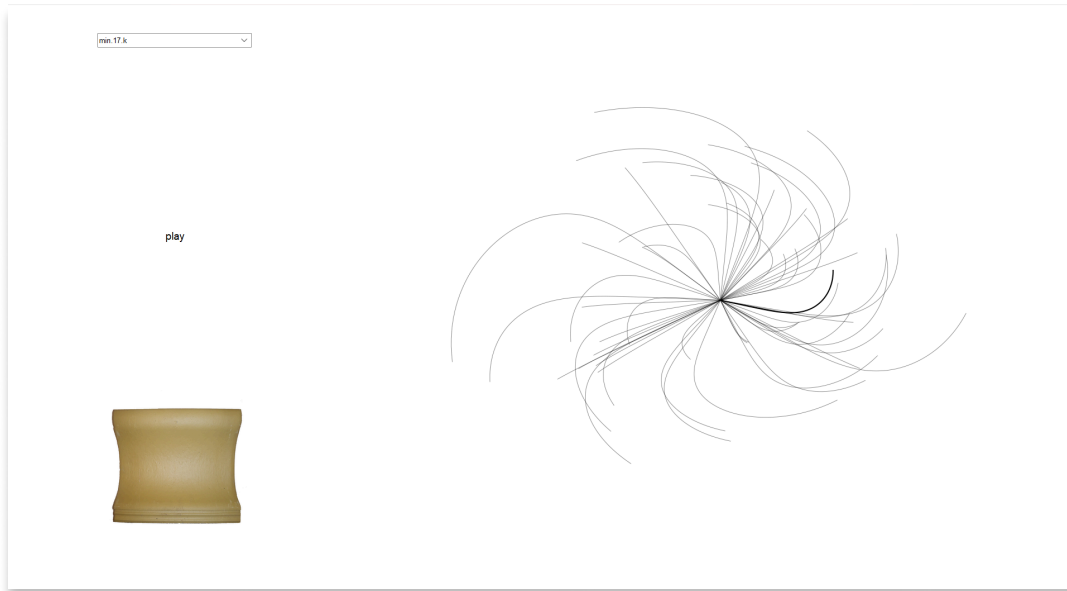


Figure 34_b

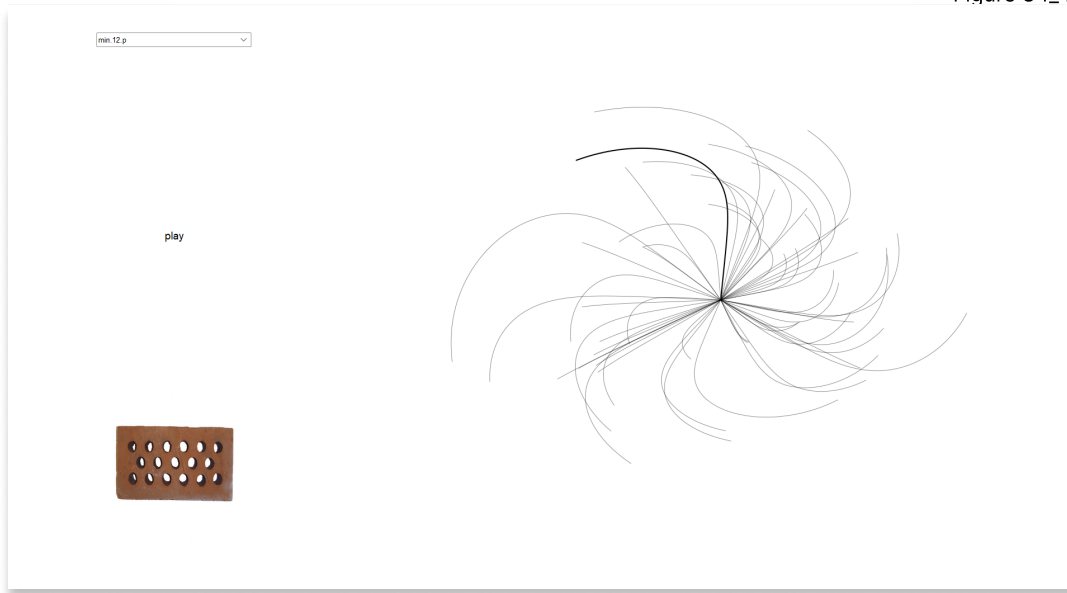


Figure 35_ a

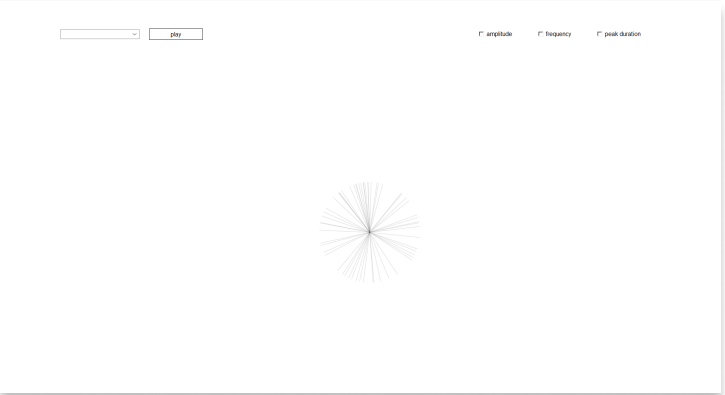


Figure 35_ b

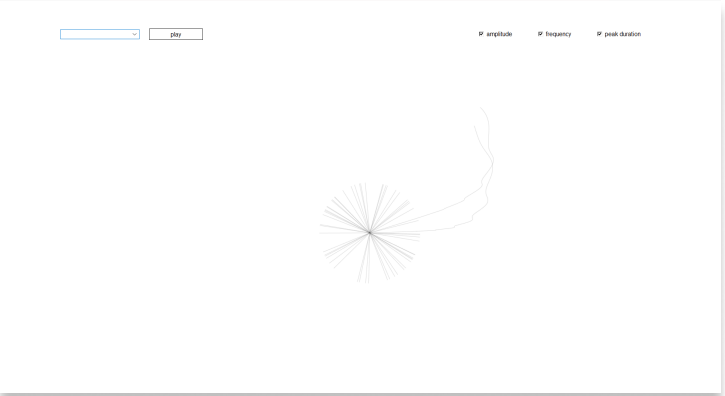
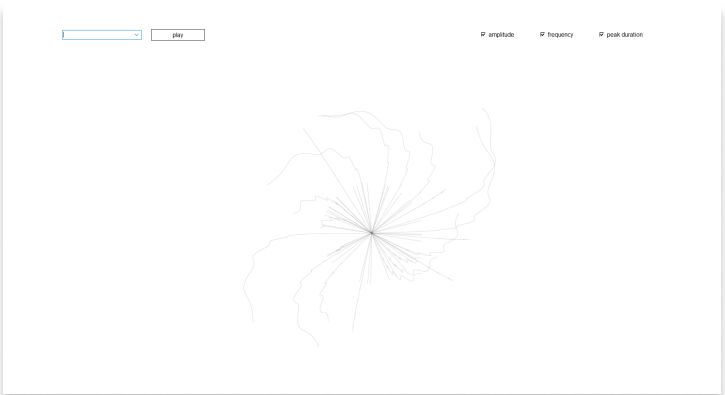


Figure 35_ c



analysis of results

The thesis functions as a curated series of graphics and custom interfaces designed to actively challenge both the traditional role of sound in architecture and the conventional ways engineering data is presented. The generated material can be categorized across a diverse, multi-layered range – shifting from static geometries to interactive interfaces; and from strict technical analysis to open-ended artistic exploration. By organizing these tools to address both individual material characteristics and organizational libraries, the workflow successfully blends apparent opposing design concepts. Ultimately, it strips away the cold, unyielding nature of raw data, translating it into a deeply intuitive visual mode that effortlessly aligns with human cognitive processing.

The exploration of these tools allowed to study the properties of sound, define which one's suit the project better, and correlate them to physical and visual properties. These graphics, although different in form and objective, all stand as comparative tools for results. *soundRays* depicts sounds as lines, *spectraltriangles* does it through geometric graphs. They both express the same sound characteristics, allowing direct comparison between the materials, their sound and their representation.

By converting raw numbers into an accessible graphic language, infographics make complex data easy to understand for people with little context or knowledge on the matter. They turn dense mathematical charts to engaging intuitive visual processing graphics. Ultimately, this approach highlights a key role for the contemporary designer: handling data with aesthetic care to create clear, collaborative tools.

These make hidden physical realities immediately legible. For his project, the aesthetic language goal was to keep the graphics simple and clean. Inspired by classic computer aesthetic from the 1980s and 1990s, which combines primarily white and black colours with some grey annotations. The interfaces' squared shapes are meant to contrast with the long curvy lines. In this case, these choices are also meant to cause no distractions when the user is interacting with the interfaces. Thus, these tools become easier to navigate and interpret.

Although *spectralTriangles* has aesthetics as a central characteristic, it is fundamentally an analytical tool. It provides a more traditional reading of the values registered and consequently the materials. The viewer can immediately register structural stiffness through the posture of the triangle, transforming an otherwise invisible quality into an unmistakable spatial expression.

On the other hand, *soundRays* is a modern and interactive interface, which enables the user a direct way to compare the material's behaviour through their graphic expression. It introduces a temporal, fluid layer to representation, translating the nuances of internal structure and mechanical decay into expressive, rhythmic lines. This dynamic tool brings legibility to complex structural noise, transforming wave frequencies into visible movement and texture.

Both of these are tools developed to express the material's qualities and to represent each piece individually. Ultimately, they can also serve as a comparing tool, leaving room for personal interpretation. To close this interpretational gap, the two machine learning tools were also developed. These explore the relation between all the selected pieces and cluster them, unveiling relationships that visually would have not been made.

These curated infographics democratise specialized forensic data, turning raw numbers into design knowledge. By translating the hidden interiority of each material into a unified, accessible visual language, these tools activate intuitive human cognition that standard engineering charts leave unused. Variations across the material components become immediately comprehensive. This aesthetic accessibility establishes a new framework for interdisciplinary collaboration, whether involving architects, craftsmen, or researchers. It proves that when the designer curates visual information in a data-rich environment, otherwise complicated physical realities can be instantly understood.

Rather than viewing engineering testing and artistic expression as conflicting ideologies, they are treated as deeply complementary parts, where scientific data directly feeds creative generation. The implementation of the SOM and the hierarchical dendrogram perfectly embodies this fusion; they arrange technical algorithms to organize the material corpus and find structural relationships, yet their outputs are consistently displayed as interactive, artistic visual soundscapes. This ideology equilibrium allows *spectralTraingles* to handle the precise, technical representation of core sonic qualities, while *SoundRays* represent fluid, interactive lines to better get the information across. The entire workflow relies on this highly scientific process, using creative visualization as the primary instrument to make complex data immediately comprehensible.

Figure 36_a

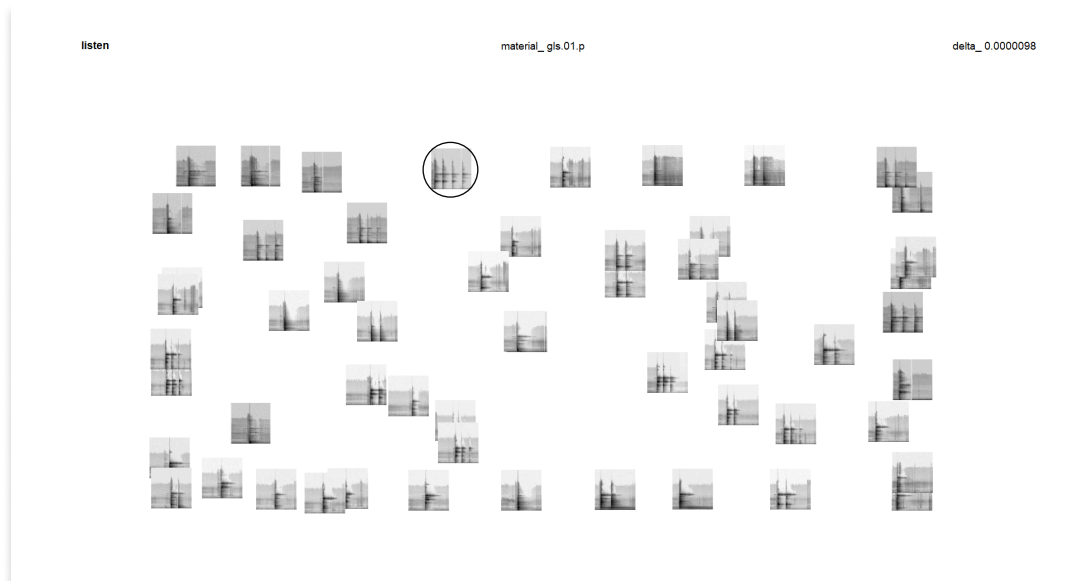
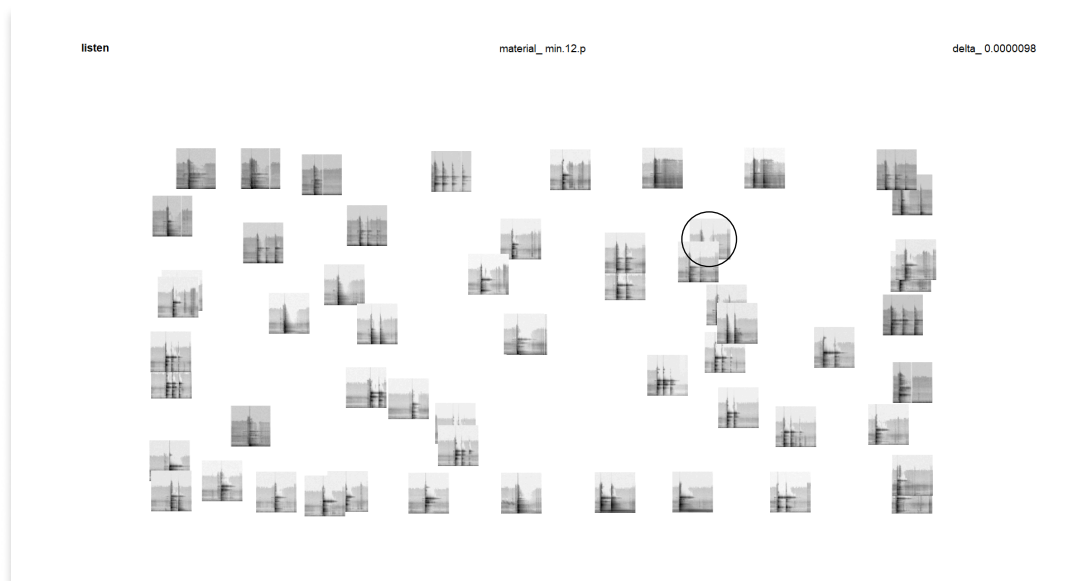


Figure 36_b



A major finding of this research lies in how the diagnostic interfaces respond to different layers of material variation. While some materials perform expectedly, there are some relations that uncover new relationships. On one side, this methodology reveals sonic similarities between differently composed materials. For example, there are wood and brick pieces that clearly sound the same. On the other side, there are materials that might not sound very much alike but still share characteristics when compared in the developed tools. This applies for materials with distinctive look and sound, but that have, for example, similar looking lines in *soundRays* – meaning they share sonic parameters.

The comparative analysis of samples gls.01.p and min.12.p exposes the need for implementing a multi-scalar diagnostic practise. When observed through the *soundRays* interface, both materials exhibit highly similar dynamic behaviours, indicating that their baseline energy dissipation rates and internal damping coefficients are closely matched. This structural affinity is further corroborated by the Hierarchical Dendrogram, where their clustering paths intersect closely. This suggests a shared root in overall mechanical elasticity and broad statistical resonance. However, their projection onto the SOM reveals a stark divergence. Because the SOM clusters materials based on the visual textures of their spectrograms, it places them far apart on the grid.

This multi-interface discrepancy reveals that while gls.01.p and min.12.p absorb and release kinetic energy at almost identical speeds (as seen in the *SoundRays* and dendrogram), the actual harmonic chords generated by their respective micro-structures are distinct. It proves that a material's temporal decay and its harmonic texture are decoupled properties, requiring distinct tools and visual lenses to fully comprehend.

Figure 37_ a

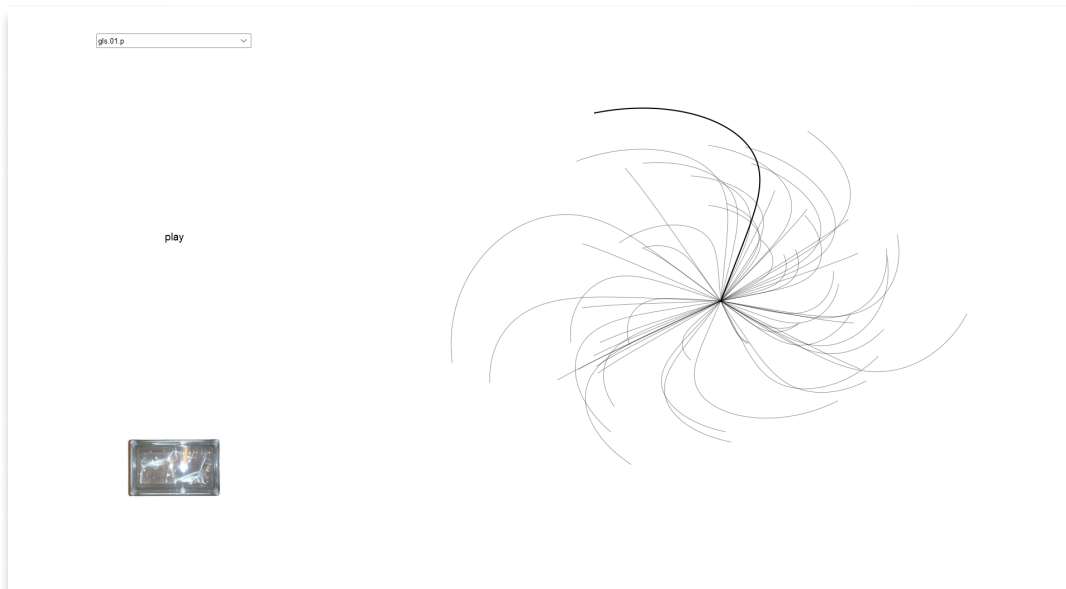


Figure 37_ b

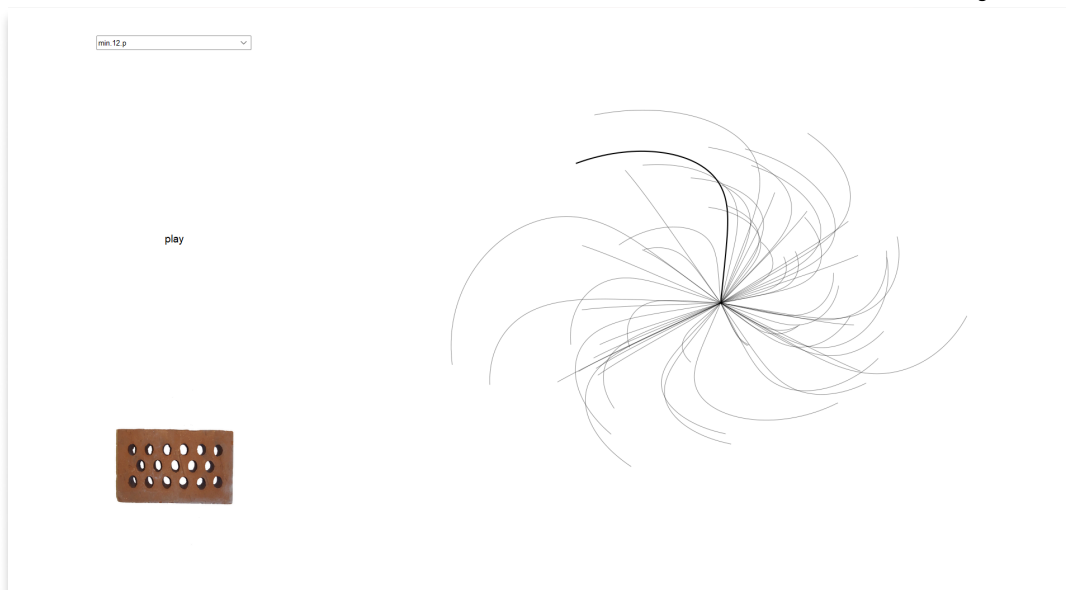


Figure 38_a

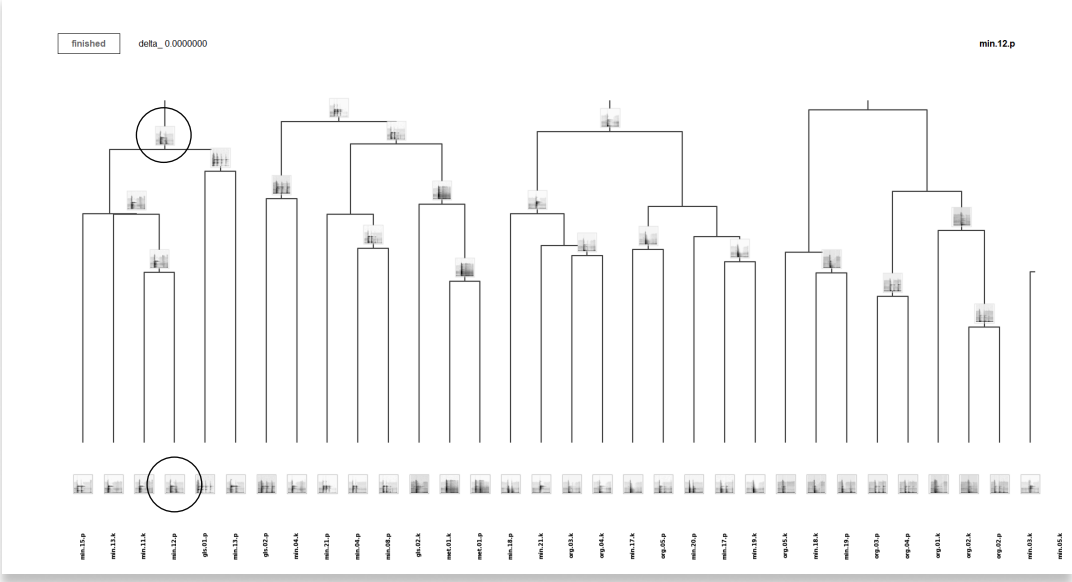
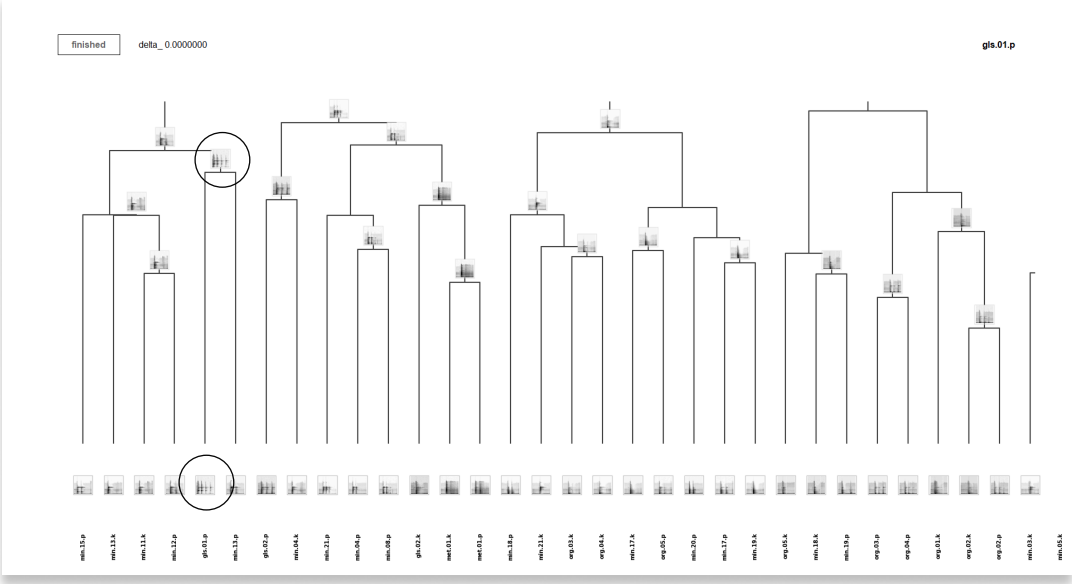


Figure 38_b



initial **data acquisition**

Due to the extensive digital focus of this project, opportunities for physical exploration were limited. Nevertheless, to investigate the physicality of sound, two specific steps of the workflow were 3D printed: the spectrograms obtained by *sonicInfo*, and the curved lines produced by *soundRays*. These elements were selected because they benefit the most from three-dimensional representation. Both the spectrograms and the lines become significantly more comprehensible and expressive when physically materialized.

Furthermore, exploring these physical translations revealed valuable secondary architectural attributes. Although these findings are secondary to the project's primary objectives, they offer worthy reflections.

The 3d-printed spectrograms can be interpreted as a rematerialization of the original salvaged material, translated through its sonic ID. By gaining physicality, the 3d spectrogram essentially becomes a new material itself, existing in parallel with the original. This duality challenges the traditional definition of a material, as two structurally distinct physical objects now represent the exact same.

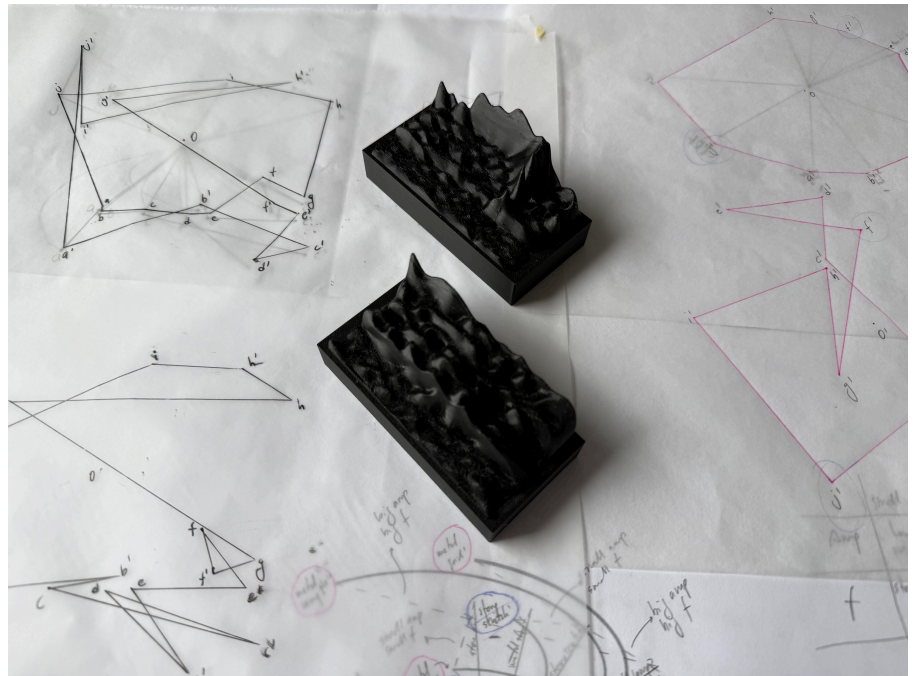
The 3d-printed *soundRays* hold significant graphic and architectural form value. In a two-dimensional format, they provide a direct, aesthetically compelling method for interpreting and comparing the sonic properties of various materials. However, when translated into a 3d physical object, the foundational acoustic parameters become more intuitive to read, allowing the geometry to visually embody its architectural origins.

3d print_ spectrograms

Spectrograms were translated into 3d form using Rhino's *Heightfield* command, and later 3d-printed to better understand them. Instead of having just a 2d representation of the sound, this object allows better comprehension of the material. It stands as a projection of the material from its original form into an object. It separates it from its normal state through its sonic identity and properties and helps visualizing both material expressions.

At an initial stage of the process, the placeholder materials were 3d-printed as tests. These are represented in Figure 29 and represent elevation of the loudest (lighter) points of each sound. The final prints, which relate to the final recordings, were produced contrarily. Here the sound causes a depression of the volume, as observed in Figure 30.

Figure 39



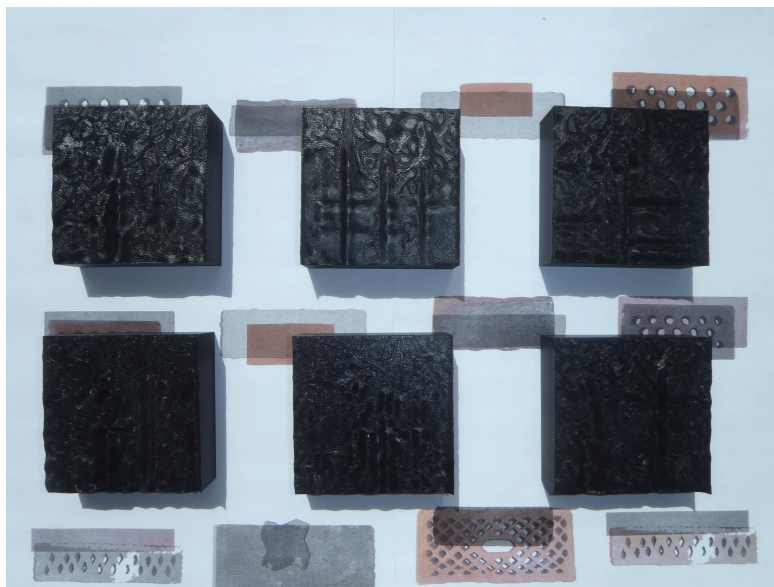
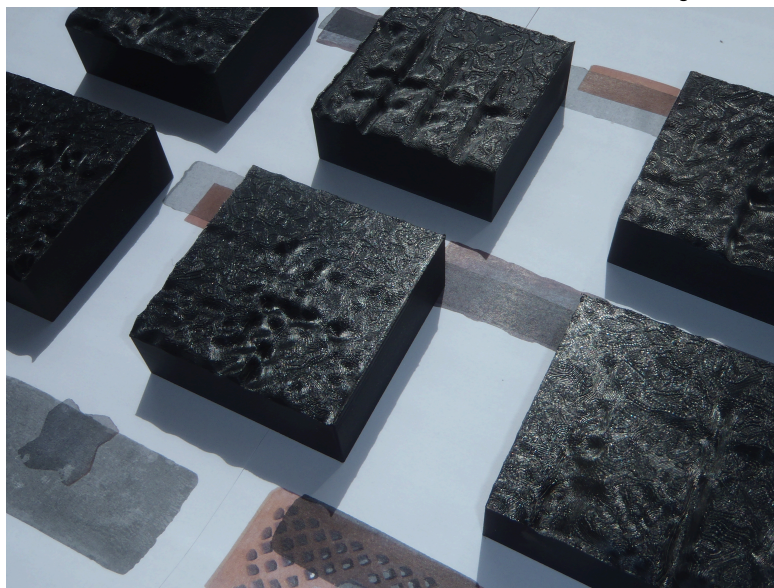


Figure 40_ a

Figure 40_ b

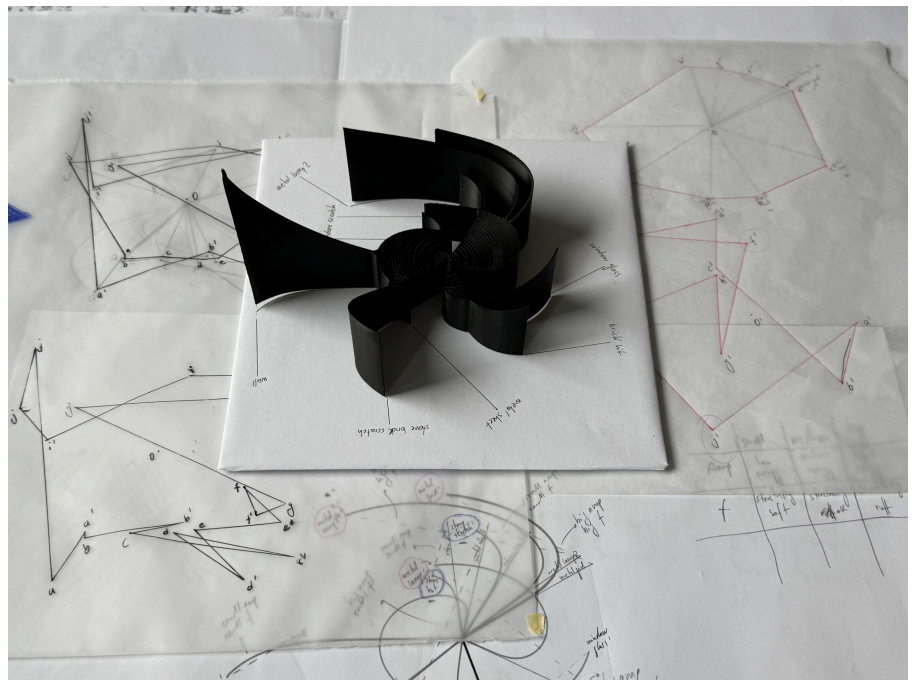


3d print_ *soundRays*

Following the digital development of the *soundRays* interface, a spatial investigation of its generated geometries was conducted. The analysis focused on the vectors' directions—specifically the relationship between their point of origin and their final resting coordinates (before and after the parameters were activated).

This exploration began through manual sketching and progressed into physical cardboard modelling, testing the architectural implications of these terminal vector paths. While the initial purpose of the physical model was strictly to map spatial relationships, the three-dimensional structural qualities of the rays naturally originated speculative design modifications and architectural experimentation.

Figure 41



analysis of results

While sound is the main study object for this thesis, the importance of vision for everyday life and architecture is not to be questioned. After all, it is through the dominance of vision that the human being has lived ever since. Despite this, at the centre of this work stands the belief that vision should be complemented by other senses. These physical objects are the intersection of senses, and help looking at architecture materials from a different perspective - through a more sensory lens. The 3d spectrograms, for example, are a way to both look and feel each material differently. They are not only visual, but also sonic and tactile. Furthermore, they incite the comparison between digital and physical forms, which can be an important reflection to make as an architect nowadays, when dealing with materials.

To fully comprehend this work, the distinct emotional and atmospheric qualities that these interfaces evoke, particularly through their sonic projections, must also be considered. There is a magical quality to this continuous back-and-forth between heavy, physical matter and lightweight digital media - a process that completely abstracts things that are inherently tactile and structural. Under this lens, dense material pieces separate themselves from their physical and visual states, transforming into sounds, lines, numbers, triangles. Interacting with these custom tools makes it impossible not to look at the physical environment differently, forcing the viewer to abstract away from a raw pile of waste matter and see it instead as an information and data-rich body full of hidden energy.

conclusion *and* **future direction**

The final chapter synthesizes the research findings and projects the developed methodology into a real-world architectural context. It reflects on the evolving role of the architect and proposes a speculative, practical future theory for the project: shifting the focus from broad inter-material mapping to intra-material verification.

reflections

The concept of this methodology follows Xenakis's work, which demonstrates that chaotic, mass-statistical noise could be organized through mathematical and geometric parameters to create a new formal order. In this thesis, the processing and transition from raw acoustic signals to structured graphical outputs functions as a contemporary manifestation of Xenakis' composition techniques. Rather than composing musical scores from abstract probabilities, this workflow extracts the latent, stochastic mathematics already embedded within the physical structure of materials and visualizes them as architectural materials.

While Xenakis provides a technical foundation, Bernhard Leitner provides the inspiration for the curated, experiential presentation format of this research. Leitner's work elevated architecture from an auditory sensation to a primary material capable of defining and shaping physical space. By presenting this thesis's findings within a highly curated, artistic approach, the research shifts from data reporting to a sonic-spatial installation. The physical models and digital interfaces help to allow the viewer to experience the sonic properties of the materials as physical, spatial and sonic pieces.

Transitioning from speculative digital workflows to processing real, live data introduces a shift in the designer's process. Unlike purely digital methodologies, where data can be retroactively smoothed, or mathematically adjusted, physical acoustics are completely raw and must be processed in its purest form. Despite having the digital workflow prepared, working with live material recordings revealed to be more demanding than initially thought.

The results from the digital process tests, using the sample materials, turned out to lead to different directions than the final recordings. This can be explained by differences in rigour while recording the sounds, as well as differences in the number of recordings. The number of samples used for testing and the final number of analysed sounds also impacted the project, both the process and the visualization of results. It is very different to work with, and represent, 10 material recordings, or 60. Therefore, it is also worth acknowledging the importance this for future studies.

While the materials produced for this research successfully validated the acoustic-to-graphics framework, it also demonstrated that capturing the true "Sonic ID" of architectural materials requires the elimination of environmental variables, as well as better recording set-up. To achieve proper scientific rigour, future iterations of this recording protocol should be made in a more controlled environment, such as in a recording studio, and using a microphone.

future *direction*

This methodology should not be viewed merely as an isolated test, but as the foundational diagnostic framework for automated Urban Mining. In an ideal circular construction workflow, this acoustic-aesthetic framework should function as an intelligent screening gateway for reclaimed resources. As materials arrive at a sorting yard, they should automatically pass through this non-destructive testing sequence. By integrating automated mechanical impacts with real-time audio analysis, the system replaces human guesswork with objective structural profiles. Instead of downcycling valuable old resources due to the lack of data on their internal stability, this methodology elevates non-standard waste into high-value, predictable, and structurally certified building components. This proves that the future of circular design relies on treating salvaged materials as data-rich assets.

In framing the prospective evolution of this methodology, a clear operational distinction must be established between the work executed in this thesis and its application within the field of urban mining. This thesis executed an inter-material study, testing fundamentally different materials to map out a broad, relational landscape of acoustic and geometric boundaries. However, as a future theoretical application within urban mining, the purpose of the tools would turn towards an intra-material study, testing different pieces of the same material category.

In this speculative framework, the tool's behaviour would shift from finding relationships between distinct material families to detecting anomalies and structural integrity variations within a group of the same materials. A structurally sound reclaimed element would produce a stable, balanced Spectral Triangle, clustered tightly within its expected machine learning neighbourhood. On the other hand, a piece suffering from internal cracks, decay, or moisture retention would cause the triangle, or line, to be visibly different, exposing it as an anomaly. Ultimately, this positions the methodology as an elastic framework: built here as an aesthetic tool to map different material relations, but structurally ready to act as a forensic verification engine for circular architecture.

To adapt this methodology from individual, hand-sized material blocks to the structural scale of an entire building, the interface and capture protocols would need to undergo a scalar and systemic shift. At a building scale, relying on isolated, manual pendulum strikes becomes impractical. Instead, this method would need to be adjusted to a bigger scale, and perhaps automated.

Further developing the workflow could also mean incorporating sensors to each piece, to record the physical vibrations, that can complement the sonic waves. Although the focus was to test different materials, this methodology could also be applied to test different pieces from the same material. The results would be closer to each other and more difficult to analyse but could be a way to test integrity.

The integration of custom-designed visual interfaces within this material investigation serves a dual purpose: it is both an analytical necessity and a definitive stance on the importance of aesthetics in scientific and architectural research. Data collection, particularly when dealing with complex, variable acoustic signals, inherently generates a vast volume of information that can easily devolve into overwhelming, unreadable noise. Within this framework, aesthetics is not implemented as decorative post-process. Instead, it functions as a tool—a cognitive filter designed to bring structural clarity and legible form to hidden physical phenomena.

Just as sonification maps abstract numerical data onto audible frequencies to make complex changes perceivable through our sensory system, the graphic translations developed in this thesis map acoustic vibrations onto intuitive spatial forms.

By converting raw statistics into a distinct visual language, these interfaces democratize dense, engineering data. This structural translation makes the performance profiles of materials easily comprehensive for users. Whether the collaborator is an architect, a craftsman, or an artist, the curated aesthetic language bridges the interdisciplinary gap, transforming abstract signal into shared, intuitive design intelligence.

Ultimately, by testing these fragments, the thesis treats reused elements as dynamic, resonant bodies. The acoustic forensic protocol overcomes the visual biases that often lead to the downcycling or disposal of non-standard components. Through the lens of Xenakis's structural mathematics and Leitner's spatial aesthetics, the evaluation of reclaimed materials transitions from a speculative risk into a predictable, data-rich creative act.

While sound has always been an inherent component of architecture, the discipline has historically restricted it to the realm of room acoustics; this thesis intentionally departs from that tradition to focus on the inner, hidden sound of the individual material component. The investigation shifts away from the acoustic qualities experienced within a built space or the sonic consequences of a finished form, focusing instead on the acoustic signatures existing inside the very fragments that create the built architecture.

Working on this project has revealed an entirely new world to discover, unlocking the curiosity to pay far closer attention to the acoustic properties of the environment and to find poetic, non-standard ways to relate the materials. Ultimately, if a short period of time of focused work uncovered such a profound, hidden layer of connection between sound and architecture, it leaves open the question of what could be achieved through long-term dedicated research.

demos



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Figure 1_ undulating glass panes for the Convent of Sainte-Marie de la Tourette. **(a)** Xenakis's drawing demonstrating the mathematical distribution and density variations of the windows. *From Archives*, by Les Amis d'Iannis Xenakis, n.d. (<https://www.iannis-xenakis.org/en/undulating-glass-panes/>). Original work from the Collection Famille Iannis Xenakis; **(b)** exterior view of the concrete facade. *From AD Classics: Convent of La Tourette / Le Corbusier*, by ArchDaily, 2010 (<https://www.archdaily.com/96824/ad-classics-convent-of-la-tourette-le-corbuise>).

Figure 2_ draft from *Metastasis* (1953-54) composition. *Metastasis*, partition graphique sur papier calque, OM 1/4p.28. *From Archives*, by Les Amis d'Iannis Xenakis, n.d. (<https://www.iannis-xenakis.org/en/archives/>). Original work from the Collection Famille Iannis Xenakis.

Figure 3_ drawings by Iannis Xenakis showing mathematical logic in music composition. **(a)** *Eonta*, partition graphique sur papier millimétré, OM S/14 p.S4. **(b)** *Pithoprakta*, partition graphique sur papier millimétré, OM 1/13 p.1. *From Archives*, by Les Amis d'Iannis Xenakis, n.d. (<https://www.iannis-xenakis.org/en/archives/>). Original works from the Collection Famille Iannis Xenakis.

Figure 4_ AGORAPHON (1992), urban installation for the MEDIALE exhibition in Hamburg. *From Works*, by Bernhard Leitner, n.d. (<https://www.bernhardleitner.at/works>). Copyright by Bernhard Leitner.

Figure 5_ Sound Gate (1971)- Sound and Space study. *From Works*, by B. Leitner, n.d. (<https://www.bernhardleitner.at/works>). Copyright by Bernhard Leitner.

Figure 6_ Cylinder Space (1974). **(a)** Initial study representing sound paths. *From Works*, by B. Leitner, n.d. (<https://www.bernhardleitner.at/works>). Copyright by Bernhard Leitner.

Figure 7_ final architectural structure at Parc de la Villette. *From Works*, by B. Leitner, n.d. (<https://www.bernhardleitner.at/works>). Copyright by Bernhard Leitner.

Figure 8_ sound diagrams for Cylinder Sound. **(a)** drawings representing different sound patterns. **(b)** diagram relating sound with structure. *From AD Classics: Le Cylindre Sonore / Bernhard Leitner*, by ArchDaily, 2011 (<https://www.archdaily.com/1c8152/ad-classics-le-cylindre-sonore-bernhard-leitner/>). Original drawings by Bernhard Leitner, 1987.

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Figure 13_ outdoor Air Temperature Sensor 2' screenshot representation using Touch Designer, from the DATASONICA project. *From Datasonica, by T. Alocci, n.d. (<https://www.tizianaalocci.com/home/datasonica>).*

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Figure 41_ 3d translation of *soundRays* using the sample materials, with different test sketches underneath.

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