Enhancing the Open-Air Auditory Experience

Optimizing Acoustic Uniformity in Open-Air Theaters using Computationally Designed Crowd-Integrated Reflectors



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Optimizing Acoustic Uniformity in Open-Air Theaters using Computationally Designed Crowd-Integrated Reflectors

Master thesis

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Abstract

Open-air performance venues suffer from great acoustic inconsistency. Without enclosing boundaries, Sound Pressure Level (SPL) decays with distance from the stage, producing a listening experience that varies significantly across the audience area. Existing passive solutions focus almost exclusively on acoustic shells surrounding the sound source, which can increase average energy but cannot resolve the front-to-back decay gradient. This thesis addresses that gap by shifting the optimization target from the source side to the audience zone itself.

A performance-based computational workflow was developed in Grasshopper, combining Aeolus ray-tracing simulation with a multi-objective optimization using Octopus. The workflow optimizes the geometry of a crowd-integrated reflector structure consisting of architectural tree-column elements in within the audience area, to minimize SPL standard deviation across a receiver grid. Sightline preservation, panel collision avoidance and spatial constraints derived from the venue's geometry were build into the optimization, making sure that every evaluated design remained valid.

The Amsterdamse Bostheater served as the design case. On-site acoustic measurements were conducted to establish a baseline and to validate the CATT-Acoustic simulation model, which showed agreement with measured values within ±1.5 dB for the large majority of receiver positions. The optimized reflector geometry was validated in CATT, independent of the Aeolus optimization environment. Results show a reduction in SPL standard deviation of 0.648 dB for the central source position and 0.477 dB for the off-axis position, with local improvements of up to 3 dB concentrated at the back and lateral audience zones where the acoustic decay was greatest. These improvements are consistent across both source positions and are maintained when a full audience absorption model is applied. Secondary parameters like C80 and G show corresponding reductions in standard deviation and increases in average value. Lateral Fraction (LF) increases substantially, which results in a gain in spatial impression that is new for to the crowd-integrated reflectors and absent in conventional acoustic shell research.

The results demonstrate that a crowd-integrated, computationally optimized passive structure can improve acoustic uniformity in an open-air theater. The sequential multi-objective workflow is shown to be computationally feasible in its parametric structure, providing a foundation for performance-based acoustic design in outdoor performance venues.

Foreword

This thesis is the conclusion of my Master's in Building Technology: Architecture, Urbanism and Building Sciences at Delft University of Technology. Looking back, the direction this thesis took is one I never could have predicted when I first sat down to think about a thesis on outdoor acoustics.

The subject grew from a curiosity: why do we accept such poor sound quality in open-air venues? Rather than asking how an acoustic shell on the stage could be improved, the question became something different: how can the reflector extrend outward, beyond the source, and into the audience itself.

What began as a design question slowly became a technical one, and in the end a research project that sits somewhere in between the two. Which, looking back, feels like the right place for it to land.

I would like to thank my supervisors, **prof. dr. ir. M.J. Tenpierik** and **dr. G. Mirra,** for their guidance throughout this process. Their feedback sharpened both the research and my thinking, and their enthousiasm to engage with a topic that sits at the edge of acoustics and architectural design made this thesis possible in the way it is.

I am also thankful to the team of the Amsterdamse Bostheater for giving me access to the venue for on-site measurements. The ability to get a baseline for this research in real field data was essential, and the support I received from them made that possible.

Finally, thank you to my family, friends and partner for their support throughout this thesis. Having people around who were always there to talk things through made the harder stretches a lot more manageable, even when the conversation turned to acoustic simulations and optimization runs.

This project has taught me more than I expected and has strenghtened my interest in the field of acoustics. I hope to continue working at the intersection of acoustics and design in the years ahead of this thesis.

Delft, June 2026
Timo Meester

Table of Contents

Abstract 3
Foreword 4
Table of Contents 5
1. Introduction 7
  1.1 Problem statement 7
  1.2 Research objective 9
  1.3 Boundary conditions 10
  1.3 Research questions 11
  1.4 Relevance 12
  1.5 Scope 13
2. Research Approach 14
  2.1 Research methodology 14
    2.1.1 Literature review 14
    2.1.2 Design of the computational workflow 14
    2.1.3 Validation and optimalisation of the computational workflow 14
    2.1.4 Discussion and conclusion 14
  2.2 Theoretical framework 17
    2.2.1 Architectural Acoustics 17
    2.2.2 Performance Acoustics 21
    2.2.2 Natural Acoustics 26
    2.2.3 Acoustic Modelling 32
3. The design case: Amsterdamse Bostheater 35
  3.1 On-site measurements 36
    3.1.1 Methodology 36
    3.1.2 Measured results 37
    3.1.2 Line measurements 38
4. Design of the computational workflow 40
  4.1 The Octopus optimiser 42
    4.1.1 Sequential optimization strategy 42
    4.1.2 Population settings and iteration 43
    4.1.3 Visualization of the optimization process 43
  4.2 Integration of constraints. 44
5. Design of the reflector 45
  5.1 Conceptual framework 45
  5.2 Rubric of requirements 46
  5.3 Acoustic indoor environment to the outside 48
  5.4 Parameterizing the design 50

5.5 Evolution of the design of the acoustic structure 52
5.5.1 Iteration 1: engineered approach. 52
5.5.2 Iteration 2: architectural approach 59
5.5.3 Iteration 3: final design 66
5.5.4 Final design visualisation 78
6. CATT Simulation 81
6.1 Model Setup 81
6.1.1 Geometry 81
6.1.2 Material absorption 81
6.1.4 Source and Receiver Configuration 83
6.2 Validation against field measurements 84
6.3 Simulation results 84
6.3.1 Baseline condition: no reflectors, no audience 84
6.3.2 Effect of the reflectors: with reflectors, no audience 85
6.3.3 Effect of the audience: with audience 87
6.3.4 Effect of other acoustic parameters 89
6.3.5 Time-trace video 93
7. Discussion 94
7.1 The effectiveness of the computational workflow 94
7.2 The contribution of the computational workflow 95
7.3 The Aeolus–CATT difference 96
7.4 The effect of the audience 96
7.5 The secondary acoustic parameters 97
7.6 Limitations 97
7.7 Societal impact 98
8. Conclusion 99
8.1 Main research question 99
8.2 Acoustic parameters 99
8.3 Constraints 100
8.4 The reflector design 100
8.5 The limits of Geometrical Acoustics 101
8.6 Recommendations for future research 101
In response to the design philosophy 102
9. Reflection 103
10. References 105
11. Appendix 109

1. Introduction

This project explores achieving acoustic uniformity in large outdoor performance venues. This chapter begins with the problem statement, which describes the need to move further than acoustic shells towards crowd-integrated passive structures. Following the problem statement, the chapter outlines the research objective and the specific research questions required to achieve this objective. The last part of this chapter describes the relevance of this project, highlighting its impact on social and scientific values and describes the scope of the computational analysis.

1.1 Problem statement

The control of acoustics is one of the most complex challenges in the design of architectural spaces which are intended for performance. The acoustics do not only influence the intelligibility of lyrics or the clarity of music but are a direct reflection of the listener's emotional and perceptual experience. The quality of the auditory experience is very important to the success of any performance, due to it forming a strong link between the artist and the audience. Within acoustic design, achieving consistent sound quality parameters across the whole audience is recognised as an indicator of excellence and audience uniformity (Barron, 2009).

However, this need of consistency struggles in the context of large outdoor performance venues, for which the demand has grown exponentially with the expansion of live-music festivals and permanent open-air theatres (Naveed et al., 2017). Unlike enclosed spaces where reflective boundaries can be manipulated to control the sound field, outdoor acoustics are exposed and unpredictable. Key acoustic parameters, such as Sound Pressure Level (SPL), Clarity (C80) and Binaural Quality Index (BQI) are inconsistent due to a lack of reflective boundaries and atmospheric effects like wind or temperature changes (Attenborough, 2014). This consistent lack of uniformity compromises the listener experience and forms the starting point for this thesis.

In response to this acoustic inconsistency, current large outdoor venues and festivals rely almost only on electronic line-array speaker systems to regulate the sound and maintain the Sound Pressure Level across the audience. The reliance on active electronic systems leads to an acoustic compromise that impacts the listener due to an uneven sound distribution, which creates acoustically better and lesser zones within the audience. This failure to improve the uniformity of the sound field compromises the subjective listening experience, which can be measured in psychoacoustic criteria such as Envelopment and Spatial Impression. This results in a lower sense of spatial depth and in an unnatural or flat sound (Beranek, 2003).

Current research into passive systems in open-air venues mostly focuses on the acoustic shell surrounding the sound source. These studies show that the shell's geometry can positively influence sound distribution across the audience area (Bradley, 1995). In 2018, Mirra researched such a shell where a computational model was used where the best shell geometry is determined based on a specified source position. The most important optimization objective variable in these models is the total Sound Strength (G) or the total Sound Pressure Level (SPL) value over the audience area. (Mirra et al., 2018)

This focus on maximizing total sound energy is aimed at solving the audience problem of not enough loudness due to sound decay. This improves the average strength, but it does not succeed to consistency. For example, in figure 1, where the sound distribution of an optimized acoustic shell is shown, the SPL shows a decay as distance from the source is increased. This means audience members in the front hear the music louder than audience members further back in the crowd. This decay problem is always present due to sound propagation outdoors, the acoustic shell can only partially correct this issue near the stage.

To address the decay and uniformity problem, this thesis shifts the focus to a new optimization objective. While existing solutions primarily use a reflector shell behind the performer, this research will focus on creating a workflow which will optimize reflective surfaces integrated within or around the crowd area. By moving beyond source-side reflectors, this computationally designed, crowd-integrated structure aims to mitigate decay through targeted reflection and scattering at strategic points within the audience zone itself.

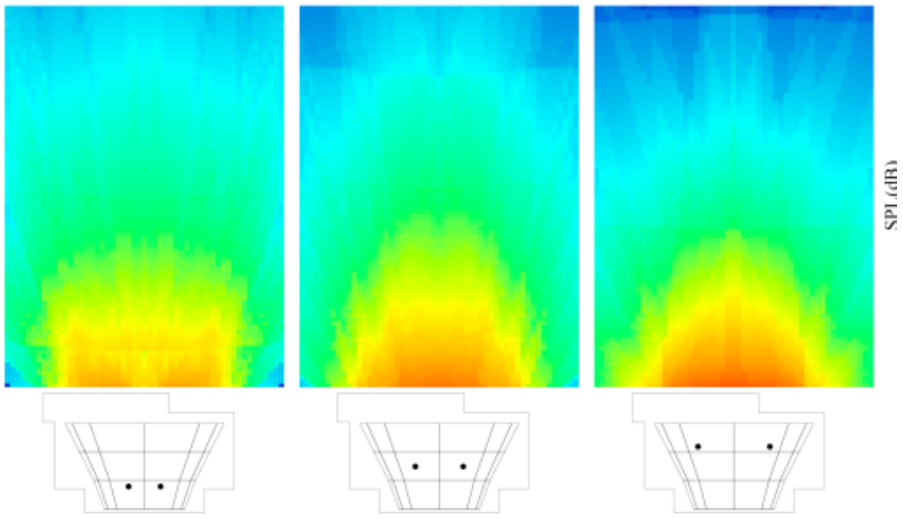


Figure 1: Sound Pressure Level (Mirra et. Al, 2018)

1.2 Research objective

The main objective of this thesis is to develop a performance-based computational workflow which is able to optimize the design of a crowd-integrated acoustic structure. This workflow will systematically optimize the structure's geometry to minimize sound decay and maximize acoustic uniformity across the audience zone of large outdoor performance venues.

The research will start by establishing a computational workflow. This involves creating a performance-based design framework using raytracing software.
The research will resume with a design and integration phase. This step involves designing and parameterizing the geometry of the crowd-integrated structure. The design must be optimized not only for acoustic performance but must adhere to architectural and functional constraints. These parameters and constraints will be researched in a literature review.

The third part is the acoustic validation of the computational workflow. The research will conduct field measurements at an existing open-air theater to accurately map its current acoustic parameters. This measured data will be used to create and validate the baseline computational workflow, which makes sure the simulation accurately reflects the real-world applications.

The effectiveness of the optimized structure will be proven through acoustic simulations, which must demonstrate a measurable reduction in sound decay and a significant increase in acoustic uniformity across the audience area, when compared against the current baseline condition of the measured open-air venue.

1.3 Boundary conditions

To make sure the research remains rigorous and focused, several boundary conditions are established. These parameters act as the constraints within which the computational workflow and how the design optimization must operate.

The primary boundary conditions relate to the environmental and spatial environment of the Amsterdamse Bostheater. The acoustic properties of the ground and surrounding vegetation are treated as constant absorption coefficients, established during the field measurement phase. This prevents environmental variables from fluctuating and allows the research to isolate the geometric influence of the reflectors on sound propagation.

From an architectural standpoint, the most important boundary condition is the preservation of sightlines and audience circulation. The proposed crowd-integrated structure must comply with a visual clearance sightline, making sure that no reflector geometry obstructs the view of the stage from any seat in the audience area. The integration of these structures must also respect the existing safety pathways of the venue. These spatial constraints are coded into the Grasshopper model, forcing the algorithm to find solutions only within the valid constrains.

Finally, the computational analysis is bounded by the technical limitations of Geometrical Acoustics (GA). The simulation assumes that the wavelength of the sound is significantly smaller than the dimensions of the reflective surfaces. Therefore, the model operates under the boundary that frequencies below the Schroeder frequency, where wave-based behaviour like diffraction is apparent, will be acknowledged but not prioritized for optimization. The sound source itself is constrained to multiple fixed omnidirectional point on the stage, representing a natural performer, to maintain a baseline for all analysis.

1.4 Research questions

Main research question:

Which performance-based computational design workflow can optimize a passive, crowd-integrated acoustic structure for maximizing acoustic uniformity in large outdoor performance venues?

Sub-question 1:

What are the most usable acoustic uniformity metrics for quantifying the non-uniform listening experience in large outdoor performance venues?

Sub-question 2:

Which geometric parameters are most important for the performance of crowd-integrated reflectors to ensure acoustic uniformity across a large audience area?

Sub-question 3:
What sequential steps are required in the computational workflow to optimize a crowd-integrated acoustic structure?

Sub-question 4:
What are important architectural constraints that must be integrated into the computational workflow as boundary conditions to ensure the designed structure is realistically usable?

Sub-question 5:

What is the degree of acoustic uniformity in a representative, existing open-air venue before the structural intervention is implemented?

Sub-question 6:

What is the improvement in acoustic uniformity and the mitigation of sound decay achieved by the optimized crowd-integrated structure compared to the baseline scenario?

Sub-question 7:

What are the optimal geometrical features of the resulting structure and what are the trade-offs between achieving uniformity and satisfying the architectural constraints?

1.5 Relevance

Scientific Relevance

The scientific relevance is in addressing the current research gap. Existing literature focuses on acoustic improvement at the source or in enclosed spaces. This research is new by shifting the focus to acoustic improvement in the audience volume itself. The key contribution is moving away from shell-reflector studies to see the potential of crowd-integrated, passive diffusion and scattering to tackle uniformity correction in large performance environments.

Next to this, this thesis introduces methodological innovation through computational design. It uses an application of a performance-based design methodology applied to outdoor acoustic structures. By using optimization algorithms like Octopus with Geometric Acoustic simulation software, the research will deliver a computational workflow for designing complex acoustic geometries under constraints. This workflow will result in an adaptable tool for future acoustic challenges in outside environments where traditional modelling is not ideal.

Finally, the work contributes to the advancement of outdoor acoustics parameters. The research defines and uses acoustic uniformity metrics in outdoor context. This contribution enhances the understanding of how complex metrics, which are normally used for indoor acoustics, can be used and improved upon when designing passive elements in outdoor sound fields.

Societal Relevance

The most direct societal impact is achieved by researching the audience experience and uniformity. Acoustic uniformity results into a more enjoyable audience experience. Currently, variations in sound quality create acoustically dead zones and areas with too much acoustic energy, which negatively influence the experienced value of an outdoor event. The proposed crowd-integrated structure aims to eliminate these acoustic inconsistencies, making sure that all attendees receive a high-quality auditory experience.

In addition, the thesis delivers a practical and sustainable solution for events. The design is passive, whichs offers a sustainable solution to expensive active sound reinforcement systems. For event organizers, this presents a durable method for permanent venues to improve sound quality without increasing power consumption or relying on system calibration.

Finally, the research offers a good societal impact for venue design. The resulting structure design and the performance-based design method provide insights for architects, acousticians and urban planners involved in the design or renovation of amphitheaters,

outdoor theaters and festival grounds. The research delivers a demonstrable proof-of-concept, actively encouraging the industry to adopt acoustic integration into the architectural design of outdoor venues, rather than treating acoustics as a post-design add-on.
The scope of this research is defined by the development and validation of a performance-based computational workflow made for passive acoustic interventions in outdoor environments. To optimise the computational workflow, the study focuses on the Amsterdamse Bostheater as its primary case. While the workflow is designed to be adaptable to other open-air venues, the specific geometric optimizations and field-calibrated results are unique to the spatial configuration of this open-air theatre.

1.6 Scope

The investigation is done using Geometric Acoustics (GA) software. The analysis uses raytracing algorithms to simulate and optimize sound distribution, focusing on performance metrics like Sound Pressure Level (SPL), Sound Strength (G), Clarity (C80) and the Binaural Quality Index (BQI). By using genetic algorithms, like Galapagos within Grasshopper, the aim of the research is to identify the optimal geometric design of crowd-integrated reflectors to maximize acoustic uniformity across a receiver grid.

To maintain a focus on architectural geometry and acoustic performance, technical dimensions are excluded from this study. Because the research relies on raytracing rather than wave-based modeling, complex low-frequency phenomena are not addressed in this study. Furthermore, the study treats the sound source as a natural, unamplified point source. Therefore, the optimization of active electronic sound reinforcement systems or line-array processing remains outside the research boundaries.
While the proposed structures must function within a real-world context, the scope does not extend to detailed structural engineering or vibro-acoustic analysis. Issues regarding load-bearing capacity, wind-load resistance andthe resonant frequencies of building materials are acknowledged as important for realisation but are not part of the acoustic optimization phase done in this thesis.

Similarly, the simulation assumes a static atmospheric state, which means the effects of changing wind speeds or temperature changes are not modelled, which allows for a controlled evaluation of how geometry alone influences the simulated sound field.

2. Research approach

2.1 Research methodology

This thesis uses a multi-stage, performance-based design approach that combines a literature review, real-world acoustic measurement, computational modelling and acoustic validation. The methodology is structured around the following phases:

2.1.1 Literature Review

This phase establishes the theoretical context for the research project. The literature review is divided into four different parts. Research was done by searching for books and research papers using Scopus and Google Scholar. The given search terms were combined using AND OR to search for research papers when using these engines.

1. Architectural acoustics

In this part, general acoustics are studied to dive deeper into the theory of acoustics, which include Sound Pressure Level, reflection, absorption and diffuse sound fields. Search strings used were: “SPL AND reflection”, “diffuse sound field AND acoustics”, “sound impulse response AND acoustics”, acoustic theory AND frequency AND reflectors AND diffusers”.

2. Music acoustics

This section dives into the acoustic theory of music, measured in performance spaces. It describes subjects like reverberation time, strength factor, genre-specific acoustics, acoustics of crowds. Search strings used were: “reverberation time AND performance space”, “clarity OR strength factor OR Binaural Index Quality AND concert hall”, “binaural measurements AND music acoustics”, “outdoor sound decay AND audience”.

3. Passive/Outdoor acoustics

To give an insight into outdoor performance spaces, this part dives into the acoustics of outdoor performance spaces and combines this with natural acoustics. A small case study was also done into existing acoustic reflectors. Search strings used were: “outdoor acoustics AND performance space”, “passive acoustics OR acoustic reflector AND outdoor”, “acoustics AND opera house OR amphitheater”, “acoustic reflector AND uniformity .

4. Acoustic modelling

To dive into the computational part of this thesis, this part dives into the modelling of acoustic software. It compares different methods and goes into the performance based design combined with acoustic software. Search strings used were: “ray-tracing AND acoustic software”, “geometrical acoustics OR wave acoustics AND model”, “performance-based design AND acoustics”, “grasshopper AND acoustics AND parametric”.

To conclude, a summary of the theory is done at the end of this chapter.

2.1.2 Design of the computational workflow

Following the literature review, the gathered knowledge will be integrated into the design phase of the crowd-integrated structure. Key parameters identified during the research will be implemented into the model. Through sketching and iterative design cycles, a final concept will be developed. A very important aspect of this process will be the definition of optimizable parameters and their constraints.

Once the structure has been designed, it can be introduced into the Grasshopper environment. The structure will be fully parameterized, allowing for automated adjustments to its geometry, orientation and positioning within the theater. Next to this, the design process uses architectural constraints as constrains, making sure that the structure enhances the acoustic environment without compromising the functional requirements or sightlines of the open-air theater.

2.1.3 Optimisation of the computational workflow

To establish a baseline for the validation of computational workflow, field measurements are conducted using an omnidirectional source in an open-air theater which host non-amplified performances. For this study, the Amsterdamse Bostheater is selected as the case.

The measurement protocol will use an omnidirectional sound source emitting white noise. Data will be collected via several linear measurement arrays to map the acoustic field, allowing for calibration of the baseline digital model. A detailed breakdown of the measurement plan and spatial configuration at the Amsterdamse Bostheater is provided in chapter 3.

Beyond model calibration, these on-site measurements serve to characterize the specific acoustic challenges which are apparent to outdoor performance environments, such as large sound decay and minimized early reflections.

The data obtained from field measurements is used to validate a computational simulation of the open-air theater environment. For this study, the theater's geometry will be modelled in Rhinoceros, while a Grasshopper script will be developed to perform the acoustic analysis using the Aeolus or Pachyderm plugin. This workflow enables a direct comparison between the simulated outputs and the physical field measurements.
The optimization phase is done using Octopus, a genetic algorithm solver within Grasshopper. This process iteratively explores the design space by modulating the structure's parameters to achieve more optimal acoustics. Octopus will aim to minimize the variance of SPL across the entire audience area, which results in a uniform distribution of decibels. The resulting structure will be modelled in CATT-Acoustics and will be tested on other parameters like C80 and G.

2.1.4 Discussion and conclusion

The final stage of the research process involves a transition from data analysis to a discussion and conclusion. In the discussion section, a reflective stance is adopted to evaluate the study's findings. Rather than taking results at face value, this phase involves questioning the research by questioning the methodology, acknowledging limitations and exploring how the research design may have shaped the outcomes. This important evaluation makes sure of a transparent interpretation. Following this, the conclusion serves as the definitive synthesis of the project. Its function is to provide direct, evidence-based answers to the

2.2 Theorethical framework

To establish a foundation for developing a workflow to computationally improve acoustic uniformity at performance venues, a literature review was conducted. This involved studying sources related to general acoustics, performance acoustics, natural acoustics, performance based and the current state of acoustic shells.

2.2.1 Architectural acoustics

To develop a computational solution for acoustic uniformity, it is essential to define the fundamental physical mechanisms which control sound propagation and perception. This chapter also dives further into how acoustic uniformity should be achieved.

Sound

Acoustics is the branch of physics concerned with mechanical waves in gasses, liquids and solids, focusing on the properties of sound. Physically, sound is a disturbance that moves through a medium as a longitudinal wave, characterized by alternating regions of high pressure and low pressure, which result in sound waves. These waves in the medium can be perceived by the human auditory system. The compression zones of the wave travel at a constant speed, which is the speed of sound (343 m/s at 20° Celsius) (Vorländer, 2008).

In addition to speed, these waves are defined by their frequency and wavelength. Frequency refers to the number of pressure cycles that occur per second, measured in Hertz (Hz) and is perceived by the human ear as pitch. Wavelength is the physical distance between two pressure peaks in the medium. These two properties are inversely related: a higher frequency results in a shorter wavelength, while a lower frequency results in a longer wavelength (Vorländer, 2008).

The magnitude of the pressure fluctuation in a sound wave is measured as the amplitude. The larger the amplitude of this wave, the louder the sound will be perceived. This loudness is measured as the Sound Pressure Level (SPL) in decibel (dB), which is a logarithmic unit. This is because the human ear responds in approximately a logarithmic scale to

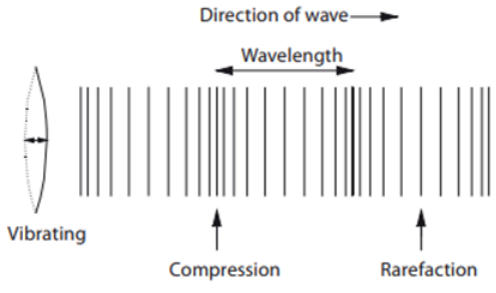


Figure 2: Sound wave (Vorländer, 2008)

Event	Level in dB
Hearing threshold in midfrequencies	0
Anechoic chamber	0–15
Bedroom	25–30
Living room	40–55
Conversation	60
Office	70
Typical noise limit for factories	85
Pneumatic hammer	100
Rock concert, disco or walkman maximum	110
Jet engine, 25 m away	120
Rocket at start	>190

Figure 3: Sound Pressure Level of typical sound events (Vorländer, 2008)

different sound pressure levels. This scale operates from 0 dB to 130 dB and in theory, each decibel has noticeable difference. In figure 3, some decibel levels are shown of typical sound events (Vorländer, 2008).

A soundwave can be plotted over time and is known as the envelope, which can be divided into four different sections. The first part of the envelope where the sound rises to its peak, is called Attack. From the peak, the sound lowers, which is called Decay. The sound then is lowered more and remains relatively the same which is called Sustain. When the sound completely fades away, it is called Release. An overview of this is seen in figure 3 (Hartmann, 2013).

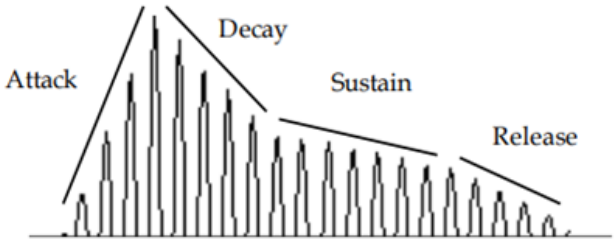


Figure 4: Visual representation of a sound envelope (Hartmann, 2013)

SPL is a unit which is distance dependent and will decrease when moving away from the sound source. This fall-off in Sound Pressure Level is generally described by the inverse square law. When a sound wave spreads and the distance between the source and the receiver is doubled, the SPL is lowered by 6 dB. This is due to the fact that as the travel distance of the sound gets further, the sound sphere around the source has to cover a larger surface area (Vorländer, 2008).

The sound does not only decay because of the inverse square law, but also because of atmospheric absorption. As a sound wave travels through the air, its energy is gradually converted into thermal energy. This process is caused by thermal conduction, where the exchange of heat during compression cycles result in a loss of energy.

Furthermore, a phenomenon known as molecular relaxation contributes to this decay, as oxygen and nitrogen molecules in the air absorb energy into their internal vibrations. This energy loss is highly dependent on the frequency of the sound; because higher frequencies cause molecules to vibrate more rapidly, they experience more friction and energy loss per meter than lower frequencies. As the distance from a sound source increases, the sound not only becomes quieter due to geometric spreading but also loses its high-frequency clarity, resulting in a more muffled tone over long distances (Kuttruff, 2007).

Reflection

When a sound wave reaches an object in its medium, the sound wave interacts with this object, depending on its material. When the wave interacts with the material, its amplitude and direction can be changed. This change in direction can be named reflection.

There are two types of reflection, which depends on the regularity of the reflected wave. When a sound wave reflects on a smooth, mirror-like surface, a specular reflection (a) is created. In this type of reflection, the sound is consistently reflected with the same angle as the incoming angle. If the sound is reflected by a bumpy, non-smooth surface, it leads to a diffuse reflection (b). In this type of reflection, the angle of the reflected sound wave differs when it is reflected, compared to the angle of the incoming soundwave. The magnitude of this diffuseness depends on the roughness of the material in relation to the wavelength of the sound (Hartmann, 2013).

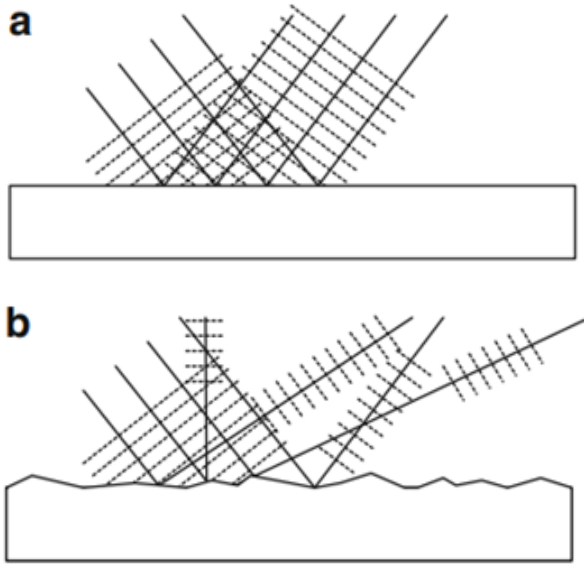


Figure 5: Reflection on smooth and rough surfaces (Hartmann, 2013)

Absorption

Materials can be designed to be less reflective, which results in sound waves returning with significantly less energy than the incoming sound waves. This process is known as absorption. When a sound wave strikes a surface, a portion of its energy is converted into thermal energy through friction as air molecules vibrate against the fibres or pores of the material. Highly porous materials are very effective absorbers because their structure allows for sound waves to penetrate deep into the material. In architectural acoustics, rooms often become cluttered by excessive reflections, which leads to long reverberation times. To improve the acoustic quality of these spaces, consultants strategically introduce absorbent materials to manage these reflections and enhance overall clarity (Ginn & Briiel & Kjaer, 1978).

Scattering

Scattering refers to the process where sound waves are reflected in many different directions after striking a complex or uneven surface. While a flat, hard surface produces a specular reflection similar to a mirror reflecting light, a scattering surface breaks the sound wave apart. This phenomenon is very important for creating a sense of acoustic envelopment and making sure that sound is distributed evenly throughout a room (Darmon et al., 2020).

The degree and quality of scattering are dictated by the geometry and density of the surface material. Rigid, non-porous materials with deep, irregular geometric patterns are most effective at scattering sound without losing energy to absorption (Cox & D'Antonio, 2016).

In sound perception, good scattering is characterized by spatial uniformity, where the listener feels immersed in the sound field. However, bad scattering can occur when material inconsistencies lead to acoustic coloration or comb filtering, which negatively impacts the quality of the listening experience (Barron, 2009).

Diffuse sound field

A sound field is considered diffuse when the sound pressure level is uniform throughout the room and the sound waves travel in all directions with equal probability. Unlike specular reflection which can create hot spots of concentrated sound a diffuse sound field makes sure that every listener experiences a consistent auditory environment regardless of their position. This is achieved by using scattering elements such as irregular wall geometries or specialized diffuser panels to break up sound waves. By preventing the sound from pooling or creating distinct echoes diffuse sound fields provide a sense of envelopment making the music feel as though it is surrounding the audience rather than originating from a single isolated source (Everest et al., 2009).

Summary

Sound is a longitudinal wave measured in decibels. It decays through distance and atmospheric absorption. When interacting with surfaces, sound is reflected, absorbed, or scattered based on material properties. Mastering these interactions creates diffuse sound fields, making sure of uniform pressure and balanced, immersive auditory environments.

Key takeaways

In this thesis, parametrically designed reflectors are used to manipulate sound through reflection and scattering, making these acoustic parameters very important. Using the sound envelope to define auditory characteristics, the objective is to optimize the outdoor space to be as diffuse as possible for a balanced acoustic environment.

2.2.2 Performance acoustics

Understanding how we hear sound in a performance space is a complex challenge. It involves two parts: the way sound waves move through a space and the way people actually experience that sound. These personal experiences are shaped by many things, including factors that have nothing to do with sound at all. Because of this, the study of room acoustics acts as a bridge, connecting our personal feelings to data we can actually measure.

The most noticeable thing we hear in a room is reverberation, or how the sound reverberates. This makes reverberation time the most important way to describe a room's sound. However, there are other important factors that change how a room feels to a listener. Unlike reverberation, which is often similar throughout a space, these other factors change depending on exactly where a person is sitting.

Reverberation is created by sound waves bouncing off the room's surfaces many times. Because of this, a listener hears the original direct sound followed by a series of delayed reflections. To understand how a room behaves, experts look at how it responds to a single, sharp sound called an impulse. The most common way to visualize this is through a room impulse response, which shows exactly how sound energy reaches the listener over time (Vorländer, 2008).

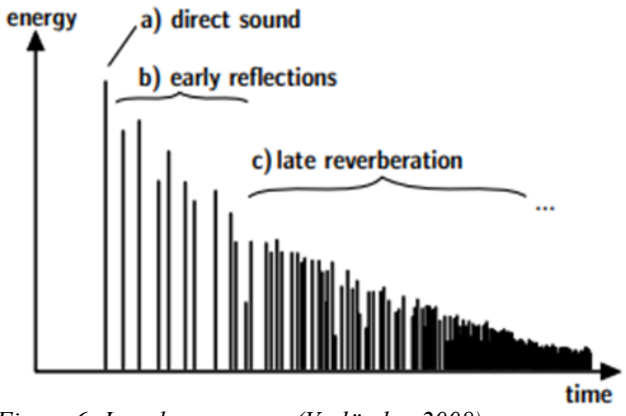


Figure 6: Impulse response (Vorländer, 2008)

Our modern understanding of room acoustics has grown because we realized that early arriving reflections are very important. For a long time, people relied almost entirely on reverberation time to judge a room, but we now know that this only tells one part of the story. Even though the official standards still focus on reverberation, they now include extra sections that define newer and more helpful ways to measure acoustical quality. The following sections will give further insight into those parameters.

Clarity

While the significance of early reflections was recognized as early as the 1850s, these ideas were overlooked for years after the introduction of the reverberation time equation by Sabine. Once the focus eventually shifted back to early reflections, a new measurement called Deutlichkeit, was created to describe Clarity. This is a ratio that compares the energy from the reflections in the first 50 milliseconds to the total energy of the sound (Bradley, 2011).

Later research suggested using C80 as a way to measure clarity for music. Today, we also use a similar version called C50 to measure how clear speech sounds. Deutlichkeit and Clarity are related by the following formula:

$$C_{50} = 10 \times \log\left(\frac{D}{1-D}\right)\ dB$$

Both C50 and C80 compare the early sound energy to the late sound energy and express the result in decibels (Bradley, 2011).

Strength factor

In performance spaces, the Strength factor (G), is a measure used to describe how much a room amplifies the sound from a source compared to how it would sound in an open field at 10-meter distance from the same source. While Clarity and Reverberation focus on the timing and decay of sound, the Strength factor tells us about the subjective loudness and the acoustic support which the surrounding provides to the performers. It is calculated by comparing the SPL of a source at a specific point in the room to the SPL of that same source measured at a distance of 10 meters in a free field (Beranek, 2011).

This measurement is expressed in decibels and is important for making sure that an orchestra or a speaker can be heard throughout a large hall without the need for electronic help. A high G indicates that the room surfaces are reflecting sound energy efficiently back to the audience area, while a lower value might suggest that the room is too large or too absorbent, which causes the sound to feel thin or distant. A too high G is also not ideal because with a full orchestra, this may lead to the audience leaving the performance with headaches. In modern architectural design, achieving a balanced G is very important for creating an intimate connection between the stage and the listeners, as it provides the necessary volume and power for the music to feel impactful (Beranek, 2011).

Psychoacoustics

If an audience is asked what they particularly enjoy about a concert or theater hall, the concept of 'intimacy' or 'proximity' are often mentioned (Beranek, 2003). The audience feels the need to be connected to the performer by the perception of acoustical quality that the concert hall is small and 'intimate'. Researchers from the Aalto University in Finland found in 2015 that concert halls with a great perceptual distance compression were more appreciated than the ones with a low perceptual distance compression. In the best concert hall, the distance of 26 meters was estimated around 15 meters. The correlation between the acoustic parameters of the different halls were also compared to the perceptual distance compression. It was found that the increasing difference between the direct and reverberant energy was related to lowering the perceptual distance. The results of the study are shown in figure 7 (Kuusinen & Lokki, 2015).

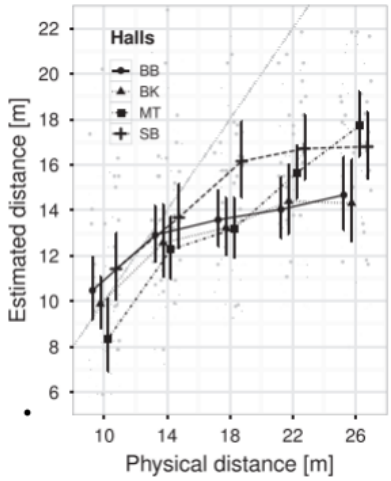


Figure 7: Comparison estimated vs physical distance (Kuusinen & Lokki, 2015)

Binaural measurements

In music acoustics, Inter-Aural Cross-Correlation (IACC) and the Binaural Quality Index (BQI) are metrics for evaluating how a listener perceives the spatial size and immersion of a performance. IACC measures the similarity between the sound signals arriving at the left and right ears. A low IACC value indicates that the ears are receiving different information. BQI is a specific index derived from this, calculated as:

BQI = 1 - IACC

These parameters quantify two very important subjective experiences: Apparent Source Width (ASW), which describes how broad and grand the music sounds and Listener Envelopment (LEV), which describes the feeling of being surrounded by the music rather than just watching it from a distance (Okano et al., 1998).

Genre/instrument specifics

Many instruments depend on resonance to create sound. The length and diameter of a flute, the volume of a drum and the body volume of an acoustic guitar are examples of resonators and ways to achieve a particular resonance frequency. The lowest note produced by such instrument is called the fundamental frequency and the overtones are referred to as the harmonics of the instrument. Different instruments are tuned to different frequency spectra. In figure 8, these different scales of frequencies are shown per instrument/vocal. The A above middle C on a piano is often tuned to 440 Hz and the lowest E string on an acoustic or electric bass is about 41 Hz (Adelman-Larsen, 2014).

The overtones that create the spectrum of the instrument and thereby its characteristic sound together with the sound created where the hand, stick or another tool touches the instrument, in many cases extend to the highest sound possible for the human ear to hear above 15–20 kHz (Adelman-Larsen, 2014).

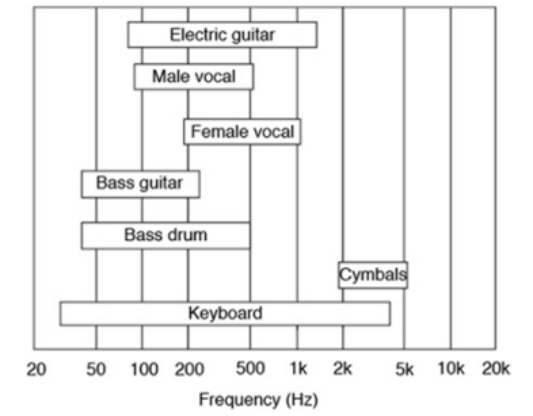


Figure 8: Frequency spectra of different instruments (Adelman-Larsen, 2014)

Unlike a theoretical point source that radiates sound equally in all directions, musical instruments exhibit their own directivity patterns. Directivity refers to how the sound energy is distributed in the space surrounding the performer. Generally, low frequencies are omnidirectional, meaning they wrap around the instrument and fill the room evenly. When frequency increases, the sound becomes more directional (Meyer, 2009). For example, a trumpet projects high-frequency energy in a narrow beam directly out of the instrument, while a violin sends different frequencies from different parts of its body. This makes the orientation of the performer on stage an important factor in how the audience perceives the sound.

The spectral priority of music shifts a lot across different genres, which dictates the necessary acoustic response of a performance space. Pop and rock music are really on the low-frequency energy found between 40 Hz and 100 Hz, which characterizes the kick drum and the bass guitar. The venues designed for these genres must manage high sound pressure levels in the bass region without allowing for resonant booming that obscures the rhythm (Adelman-Larsen, 2014).

Jazz performances prioritize mid-range and high-frequency detail to make sure the nuances of acoustic instruments and the cymbals remain audible. Classical music needs a more uniform frequency response across the audible range to preserve the harmonic structures of strings and woodwinds, which often extend into the highest registers of human hearing (Adelman-Larsen, 2014).

Summary

Room acoustics bridges physical measurements with subjective experience. While reverberation time remains a foundational metric, modern analysis utilizes Room Impulse Responses to evaluate Clarity, Strength factor and the Binaural Index Quality.
By balancing these parameters, designers enhance acoustic intimacy and Envelopment, making sure that a space supports the specific frequency spectra of different instruments and performers.

Key takeaways

For this thesis, it is important to consider which parameters are important for parameterizing the acoustic structures. Clarity, Strength factor and BQI are all important to take into account, because in a performance space, these will greatly impact the listener experience. When simulating, it is good to consider which instruments are playing in the space, because different instruments have different frequency spectra.

2.2.3 Natural acoustics

Natural acoustics are most effectively used in performance venues designed for unamplified performance, where the building is an active participant in the sound production.

The geometry of the space serves as the engine for this amplification. In opera houses and theaters, the horseshoe or U-shape are the most effective configuration for natural acoustic control (Kang & Haan, 2023). This design uses the side boxes and balconies to scatter sound, which prevents the development of late reflections while providing the lateral reflections which are necessary for spatial envelopment of the listener (Mazarella, 2018). The arch and the ceiling are often built with specific curvatures to act as a megaphone, making sure that the sound of a soloist can overcome the ambient noise of a large audience without electronic help. This architectural shaping directly influences the room's Sound Strength (G) and Clarity (C80), two parameters that are harder to balance in non-electronic environments (D'Orazio et al., 2019).

In situations where the stage is too deep for orchestral music, an acoustic shell is used. A shell design involves creating a continuous enclosure that seals the performer from the absorbent stage wings. While these shells are important for improving the G-value of the performance, Stage Support (ST1), which allows musicians to hear one another and play in sync, can be difficult to manage. Shtrepi's 2023 study of outdoor acoustics demonstrated that late reflections are not a very important factor for stage support when using an acoustic shell, emphasizing the importance of early energy in these environments (Shtrepi et al., 2023).

The design of the individual reflectors within these halls or acoustic shells follows strict geometric and physical laws. A good reflector is characterized by its density and its surface profile. Flat reflectors reflect the sound specularly, which can be used to direct sound waves to a specific direction. Convex reflectors are preferred for their ability to diffuse sound waves, which can divide the sound through the performance space. Concave geometries are typically avoided as they focus sound into a single point, which creates an uneven energy distribution across the audience area (Cox et al., 2005).

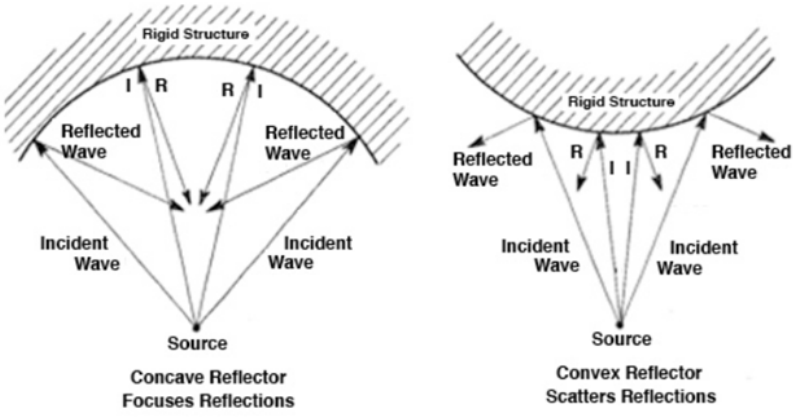


Figure 9: Concave vs Convex reflectors (Cox et al., 2005).

These reflectors are designed with ray-tracing techniques to make sure that the Initial Time Delay Gap (ITDG), the interval between the direct sound and the first reflection, is very small to create intimacy (Long, 2014). Barron (2009) describes, if reflectors are positioned too high or at improper angles, the delay goes over the threshold of perception, which causes the audience to experience an echo instead of reinforcement. By integrating these reflecting surfaces into the architecture of the ceiling and walls, designers can precisely manipulate the Lateral Fraction (LF). This results in sound energy arriving from the sides of the listener's head, which is perfect for the BQI of the performance space.

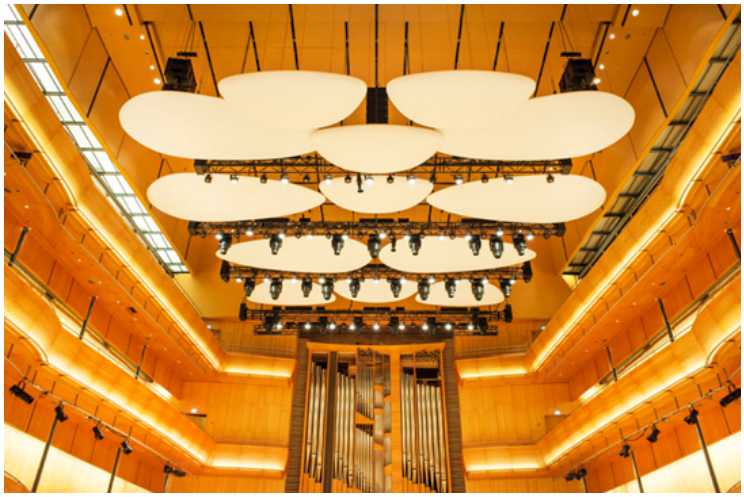


Figure 10: Stavanger concert hall

Reflective umbrellas

In his 2018 research paper, Integrating Form, Structure and Acoustics, Alberto Pugnale dives into Frei Otto's tensile structures, moving away from their original purpose as rain cover to acoustic reflectors. Pugnale mentions that while these shapes were born from structural necessity, their curved shape makes them very effective at scattering and reflecting sound. By applying parametric modelling and algorithms, the paper investigates whether these umbrella-like designs can be refined to serve as passive acoustic devices.

Through computational optimization, Pugnale demonstrates that by adjusting the height and position of the umbrellas, the structure's ability to project sound to a distant audience can be significantly improved. A multi-objective optimization process was used to determine the ideal spatial and height configuration for an optimal audience experience.

The results showed that shifting certain umbrellas to the rear of the seating area created a more uniform sound pressure level, instead of collectively placing them in front of the podium (Pugnale, 2018).

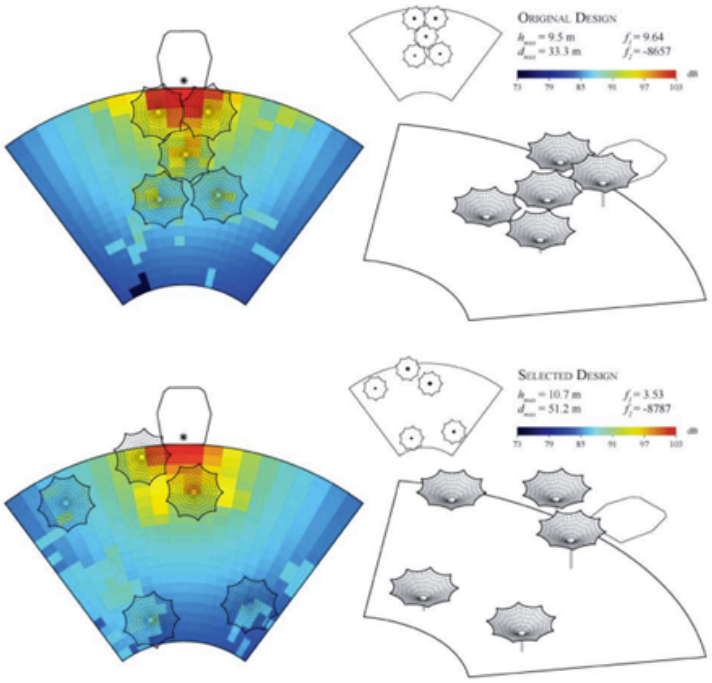




Figure 11: Spatial distribution of sound reflectiors (Pugnale, 2018). *Figure 12: Visualisation (Pugnale, 2018).*

Researchers Willem Boning and Alban Bassuet describe the design of the “Tiara”, an outdoor acoustic shell at the Tippet Rise Art Center. Unlike traditional sheds or shells that separate the performer from the landscape, the structure was conceived as a room without walls to maintain 360-degree views while providing the acoustic intimacy of a small chamber hall. To achieve this, Arup Acoustics utilized genetic algorithms and image-source method analysis to optimize the geometry of the structure’s corners (Boning & Bassuet, 2023).

By precisely angling these surfaces, the researchers made sure that sound energy would be reflected back to the performers and audience from multiple directions, strongly mimicking the immersive qualities of historic indoor venues. Validation through on-site impulse response measurements confirmed that the structure successfully enlarged the source image and provided a balanced, enveloping sound environment that felt unified with the surrounding (Boning & Bassuet, 2023).



Figure 13: Tiara in the Tippet Rise Art Center (Boning & Bassuet, 2023)

Outdoor acoustics

In traditional indoor performance spaces, acoustics are typically characterized by reverberation time due to the presence of reflections within the space. This environment differs from outdoor performance settings, where echo problems are more common because the reflection density is much lower than in a room. Because parameters like Early Decay Time (EDT) and Direct-to-Reverberant Ratio (DRR) rely on a reverberant field that is absent in open-air settings, they are considered unsuitable for these environments. Instead, the focus shifts to Sound Strength (G) and Clarity (C80) as the primary metrics for evaluation. Sound Strength is very important outdoors to determine how effectively the stage house and surrounding surfaces amplify the sound for distant listeners, while Clarity remains the essential measure for making sure that the temporal details of the music or speech are not lost in a space that lacks a traditional decay curve (Rindel, 2025).

To compensate for the lack of natural boundaries, designers can introduce large-scale architectural elements to mimic the supportive acoustics of an indoor hall. This is achieved by installing specific reflectors that act as the functional equivalents of the walls and ceiling of an indoor space. These surfaces, typically known as acoustic shells or stage canopies, are positioned to intercept sound energy that would otherwise escape vertically and redirect it toward the audience and the performers on stage. By recreating these early reflections, designers can provide the acoustic support that is otherwise lost to the open sky, helping the performers hear one another and making sure the sound reaches the back of the audience.

To improve outdoor acoustics, modern engineering employs a combination of passive and active solutions. Passive improvements often include tiered seating, similar to the ancient Greek design where sound energy is lost as it passes over the audience. Additionally, Active Acoustic Systems (AAS) are frequently used to electronically simulate the missing reverberant field through a network of microphones and loudspeakers, artificially extending the decay of sound to suit the genre of music being performed. Strategic landscaping and the use of natural barriers, such as berms or hillsides, are also utilized to provide a high signal-to-noise ratio by shielding the venue from environmental noise. (Mo & Wang, 2013) Furthermore, standard reverberation parameters like T20 have been found to be unusable in these outdoor performance spaces. This is due to the fact that the start of the decay curve for late impulse responses was measured at 15 to 20 dB lower than the source power level. Since audience members focus most of their attention on the beginning portion of the decay curve during a performance, this late reverberation often drops below the threshold of audibility (Rindel, 2023).

However, while the introduction of artificial reflections is necessary for sound strength, designers must be cautious not to compromise Clarity (C80) or the Binaural Quality Index (BQI). If the added reflections arrive too late or with excessive intensity, they can blur the timing of musical notes, leading to poor clarity and a muddy sound. Furthermore, the spatial

orientation of the reflectors is very important; to maintain a high BQI, reflections should arrive from lateral directions rather than just from the front or overhead. This ensures that the sound does not feel flat or two-dimensional but instead provides the listener with a sense of spatial envelopment and source broadening (Farnetani et al., 2008).



Figure 14: Sidney Myer Music Bowl (Sidney Myer Music Bowl, 2002)

The Sidney Myer Music Bowl is an outdoor performance located in Melbourne, Australia. It is one of the first large open-air podiums built in Australia and holds place for 2000 seats. It was built in 1959 and pioneered in shell structures in outdoor podia. The need for such a shell was due to the noise coming from the city. The shell is made from aluminium-faced plywood panels, connected through a framework of steel ropes (Sidney Myer Music Bowl, 2002).

The site's 10-meter deep excavation is an important acoustic feature, providing a line of sight for the audience while naturally shielding the bowl from the noise of the surrounding city. Scientifically, the venue is noted for its advanced sound reinforcement system and documented performance in areas like reverberation time and pulse response, making sure that high-quality sound reaches the overflow crowds situated beyond the stage's direct view (Muncey & Nickson, 1959).

Acoustics of crowds

Based on the research of Beranek in 1960, the presence of an audience in a performance space acts as a primary component of sound absorption. Traditional methods, such as the Sabine method, calculated audience absorption on a per person basis, leading to inaccuracies where predicted reverberation times were often 0.3 to 0.5 seconds higher than the measured results (Beranek, 1960).

Beranek proposes a shift in this, suggesting that the absorbing power of a seated audience, chorus, or orchestra increases in proportion to the floor area they occupy, rather than the number of individuals present. This unit area approach accounts for the diffraction of sound around the edges of the audience and remains nearly constant regardless of whether the seating density varies between 1.5 and 3 square meter per person. By treating the audience as a large, absorbent surface area, acousticians can more accurately calculate reverberation times, making sure that the acoustic environment remains optimum for both the performers and the listeners. The absorption coefficient of an audience plane is 0.88 (Beranek, 1960).

Summary

Passive acoustics uses architectural geometry, such as acoustic shells and curved reflectors, to amplify and distribute sound without electronics. By optimizing surface density and profiles, which favours convex shapes for diffusion while avoiding concave focal points, designers manipulate early reflections to improve Strength and Clarity. In outdoor settings, where natural reverberation is not apparent, reflectors can be strategically placed minimize the Initial Time Delay Gap to create indoor-like intimacy and envelopment.

Key takeaways

Since this research focuses primarily on passive acoustics, understanding the geometric requirements for reflectors is important for optimizing sound in open-air environments. By analysing case studies like the Tiara and reflective umbrellas, this thesis identifies how parametric surface profiles and precise placement can minimize the acoustic parameters. These precedents provide very important insight into how the final design can successfully mimic indoor intimacy while maintaining a balanced, enveloping outdoor sound field.

2.2.4 Acoustic modelling

Computer modelling of room acoustics was first proposed during the 1960s and was quickly put into practice by early researchers in the field. Although using physical scale models is still a powerful method today, digital simulations are increasingly replacing them in the consulting world. Modern commercial software has become much more user friendly and accurate while remaining significantly cheaper than building physical models. Once an architectural plan is converted into a digital file and the wall data, sound sources and receiver locations are set, sound propagation can be simulated rapidly. This allows for various design modifications to be tested without a large amount of physical effort.

The algorithms used in these programs are generally based on geometrical acoustics (GA). In this approach, the description of the sound field is simplified to focus on energy, transition time and the direction of sound rays. This method is considered accurate as long as the dimensions of the room are large compared to the sound wavelengths and if broadband signals are being studied. These approximations work with sufficient accuracy in large rooms as long as the sound remains above the cutoff frequency, which is also known as the Schroeder frequency (Vorländer, 2003).

In a GA model, the process begins with the creation of a three-dimensional CAD model to represent the dimensions of the space. The user then assigns specific absorption coefficients to each surface based on the building materials. Once these parameters are set, the software uses raytracing to simulate the movement of sound rays as they travel through the room. During this simulation, the model calculates the specific energy loss that occurs each time a ray strikes a surface, allowing the consultant to predict how the sound will decay and interact with the architecture (Vorländer, 2013).

Performance based design in acoustics

In the evolution of modern architectural practice, performance-based design has transitioned from a verification tool used at the end of a project to a generative tool integrated into the early stages of the design process (Canuto, 2025). This shift is primarily driven by the upcoming of parametric and scripting tools that allow architects to move beyond singular performance criteria, such as simple reverberation time, to explore conditions where multiple acoustic parameters interact (Peters, 2010). By treating acoustic performance as a driver of form, designers can produce auralizations and visualizations that create the geometry and material choices of a building before it is constructed.

A breakthrough in this field was the concept of acoustic sculpting, where the form of a structure, in proscenium-type auditoriums, is generated directly from programmatic and acoustical parameters through algorithmic processes (Mahalingam, 1992). This computational approach allows for the sculpting of space based on the physics of sound. For instance, evolutionary algorithms can be used to evolve a spatial volume by using the

Sabine equation as a performance benchmark, creating an architectural creation which is optimized for its sonic environment (Foged et al., 2012). These methods often rely on ray-tracing techniques, though the accuracy of such simulations depends heavily on the mathematical models used to detect sound rays and define receiver sizes within the digital environment (Xiangyang et al., 2003).

For performance-based design in performance acoustics, the use of Rhinoceros and its programming plugin, Grasshopper, are generally used. Within this system, geometry is no longer treated as a static entity but is instead defined by parametric relationships. This allows designers to move beyond the simple design then test workflow, instead using acoustic targets, such as Reverberation Time (RT) or Clarity (C80) values, as the generative criteria that shape the architectural form (Badino et al., 2020).

The power of Grasshopper in this context is best illustrated through projects where the architectural form is too complex to be managed manually. For example, in the design of the Fuzhou Strait Culture and Art Centre, architects utilized a Grasshopper workflow to manage a continuous "skin" that integrated walls, balconies and the ceiling into a unified surface. Because any change to the curvature of a balcony would impact the sound reflections across the opera hall, the parametric model allowed the team to subdivide the skin into patches and iteratively adjust their orientation. This made sure a homogenous coverage of lateral reflections and prevented acoustic defects like sound focusing, which would have been nearly impossible to resolve using traditional methods (Badino et al., 2020).

Similarly, the Smithsonian Institution Courtyard Enclosure used these tools to coordinate a massive grid of steel tubes and sound-absorbing materials, proving that aesthetically unique roof structures could be tuned to meet reverberation requirements through data exchange between the design model and acoustic simulations (Peters, 2010).

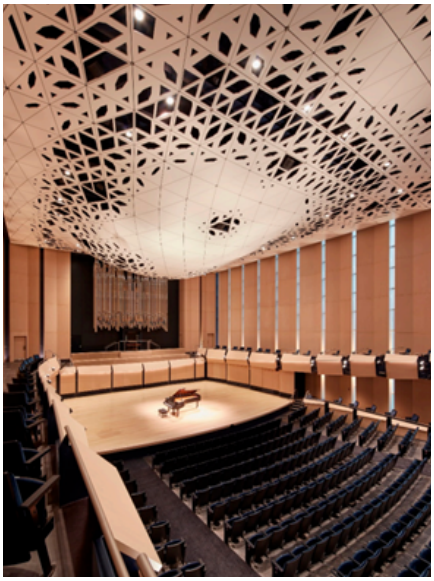


Figure 15: Fuzhou Strait Culture and Art Centre (Badino et al., 2020)

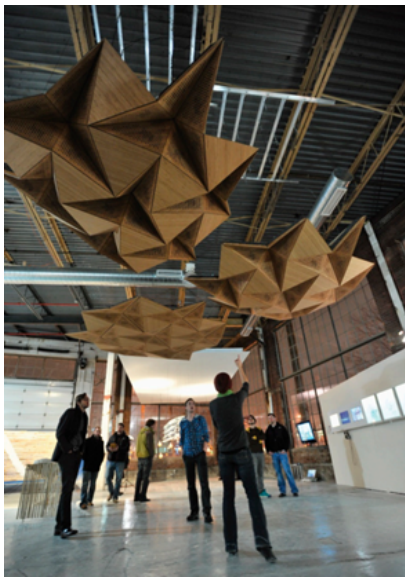


Figure 16: Smithsonian Institution Courtyard Enclosure (Peters, 2010)

By using evolutionary solvers such as Octopus to sculpt these spaces, the architect moves beyond aesthetic styling and becomes a performance manager, making sure that the final architectural output is optimized for its specific environment (Foged et al., 2012; Mahalingam, 1992). In a review from Badino et al. (2020), researchers made an overview of acoustic performance-based design, which shows which program was used for what type of project. In Figure 17, this overview is shown.

		NAME	PRIMARY FUNCTION	FEATURES TO WHICH APBD WAS APPLIED	AUTOMATED/ MANUAL	DIGITAL TOOLS EMPLOYED
MUSIC VENUES	concert halls	PHILHARMONIE DE PARIS	music performance	geometry of nuages, fronts and walls of balconies	with automated processes	Rhinoceros, Grasshopper, Maya, Odeon
		ELBPHILHARMONIE	music performance	surface pattern of the diffusing surfaces	with automated processes	Rhinoceros, parametric modeling software, custom acoustic simulation tool, optimization program
		ANNELIESE BROST MUSIKFORUM RUHR	music performance	overall geometry of the canopy, balcony front and undersides	manual processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Odeon*
		CONCERT HALL OF URESHINO CULTURAL CENTER	music performance	overall geometry and folding pattern of roof	with automated processes	parametric origami generator, custom acoustic simulation tool, optimization program
		UNIVERSITY OF IOWA CONCERT HALL	music performance	overall geometry and surface pattern of the ceiling system	manual processes	Rhinoceros, Grasshopper, custom acoustic simulation tool
		FUZHOU SYMPHONY HALL	music performance	geometry and surface pattern of the "petals"	manual processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Odeon
	opera hall	FUZHOU OPERA HALL	music performance	geometry of the continuous skin	manual processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Odeon
	dance club	CONGA ROOM	music performance	panel configuration of the ceiling system	manual processes	CATIA, Rhinoceros, Ecotect*
	outdoor acoustic shells	STAGE BY THE SEA	music performance	overall shape of the acoustic shell	with automated processes	Rhinoceros, Grasshopper, Dynamo for Revit, custom acoustic simulation tool, Galapagos*
		RESONANT STRING SHELL (ReS) 6.0	music performance	overall shape of the acoustic shell, components	with automated processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Octopus, CATT-Acoustic
		SOUNDFORMS	music performance	overall shape of the acoustic shell and reflectors	with automated processes	Rhinoceros, Grasshopper, Dynamo for Revit, custom acoustic simulation tool, Galapagos, Odeon*
		TIARA ACOUSTI SHELL	music performance	overall shape of the acoustic shell	with automated processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Galapagos
	pavilions	AALBORG ACOUSTIC PAVILION 2011	music performance	overall geometry of the pavilion and surface pattern	with automated processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Galapagos
		AALBORG ACOUSTIC PAVILION 2012	speech / music performance	overall geometry of the pavilion and surface pattern	with automated processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Galapagos
	indoor inst.	RESONANT CHAMBER	various performances (including music)	overall shape and configurations of the responsive system	manual processes	Rhinoceros, Grasshopper, custom acoustic simulation tool, Kangaroo
	enclosure	ENCLOSURE OF SMITHSONIAN INSTITUTION	various performances (including music)	overall shape of the courtyard enclosure	with automated processes	custom generative script, acoustic simulation tool

Figure 17: An overview of digital tools employed for acoustic performance-based design.

Summary

Modern room acoustics has transitioned from physical scale models to digital simulations based on geometrical acoustics. By integrating parametric tools like Grasshopper, acoustic performance no longer serves as a final check but as a generative design driver. Using algorithms and raytracing, complex architecture, from opera halls to micro-geometries, is sculpted and optimized, creating a scientifically grounded balance between aesthetics and superior auditory experience.

Key takeaways

Since this research uses a performance-based design (PBD) approach, integrating acoustic simulation early in the generative process is important for sculpting the final architectural form. By making use of geometrical acoustics (GA) and parametric tools like Grasshopper, this thesis moves beyond traditional static drafting toward an algorithmic workflow where acoustic target directly drive geometric evolution. These computational methodologies provide a framework for managing complex, non-standard surfaces, making sure that the resulting crowd-integrated reflectors are both aesthetically unique and physically optimized to provide a uniform outdoor sound field.

3. The design case: Amsterdamse Bostheater

The Amsterdamse Bostheater is an open-air theater located in the Amsterdamse Bos, which is an urban forest on the southwest edge of Amsterdam. The theater was opened in 1954 and was originally intended for large performances, folk dances, theater and lectures, as well as activities for the youth. Since then, it has been used as one of the most unique cultural venues in the Netherlands.

Today, the Bostheater is considered one of the largest theater stages in the Netherlands. The venue can hold up to 1,500 visitors in its audience. It is used for theater productions, concerts, film screenings and children's performances throughout the summer season.
From an acoustic standpoint, the theater presents a challenging and interesting design case. As an open-air venue, it lacks the enclosing boundaries that allow indoor theaters to distribute sound energy through reflections. Sound radiates freely in all directions, resulting in fast energy decay with distance and an uneven distribution of sound pressure across the seating area.

It is for these reasons that the Amsterdamse Bostheater serves as the design case for the workflow developed in this thesis. The theater's geometry, audience layout and stage geometry give the framework in which the reflector optimization methodology is used and evaluated.
To better understand the acoustic challenges in the Amsterdamse Bostheater, on-site measurements were done and will be presented in the next sections of this chapter.



Figure 18: Amsterdamse bostheater, audience view.



Figure 19: Amsterdamse bostheater, podium view.

3.1 On-site measurements

3.1.1 Methodology

To map the acoustic conditions of the Amsterdamse Bostheater, a series of sound pressure level measurements were carried out on site. An omnidirectional speaker was used as a sound source, positioned on the stage at a fixed output level of 90 dB(A) at 1 meter distance. Three measurement lines were used across the audience area, each running along the central axis of a row. Measurement points were taken at regular intervals in the middle of each row, capturing the SPL distribution in the audience area. In addition to these line measurements, some extra points were recorded at the end of each row. This allows the lateral variation in sound pressure level to be measured, providing a more complete measurement of the spatial distribution across the seating area. In figure 21, a plan overview is shown of the measurement points.



Figure 20: Omnidirectional source.

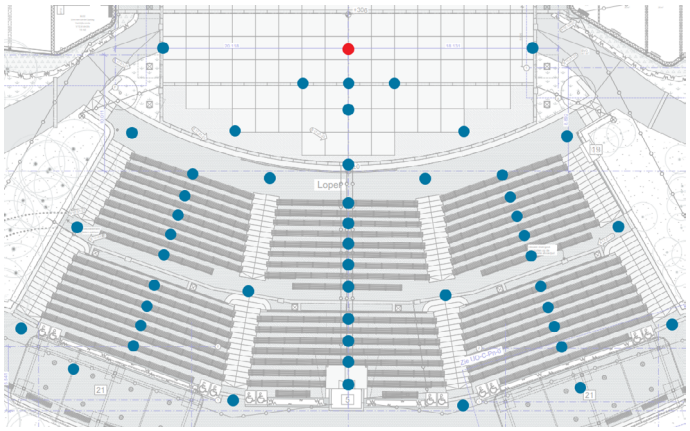


Figure 21: Overview measurement points

In total, 51 measurement points were recorded. The measurements were conducted using an SPL meter and data was processed in Excel. All measurements were taken under calm weather conditions to minimize the influence of wind and background noise on the recorded values. The measurement was done on the 14th of January, 2026. On this day there was some snow on the podium.

The resulting dataset serves as the base for validating the simulation model.

3.1.2 Measured results

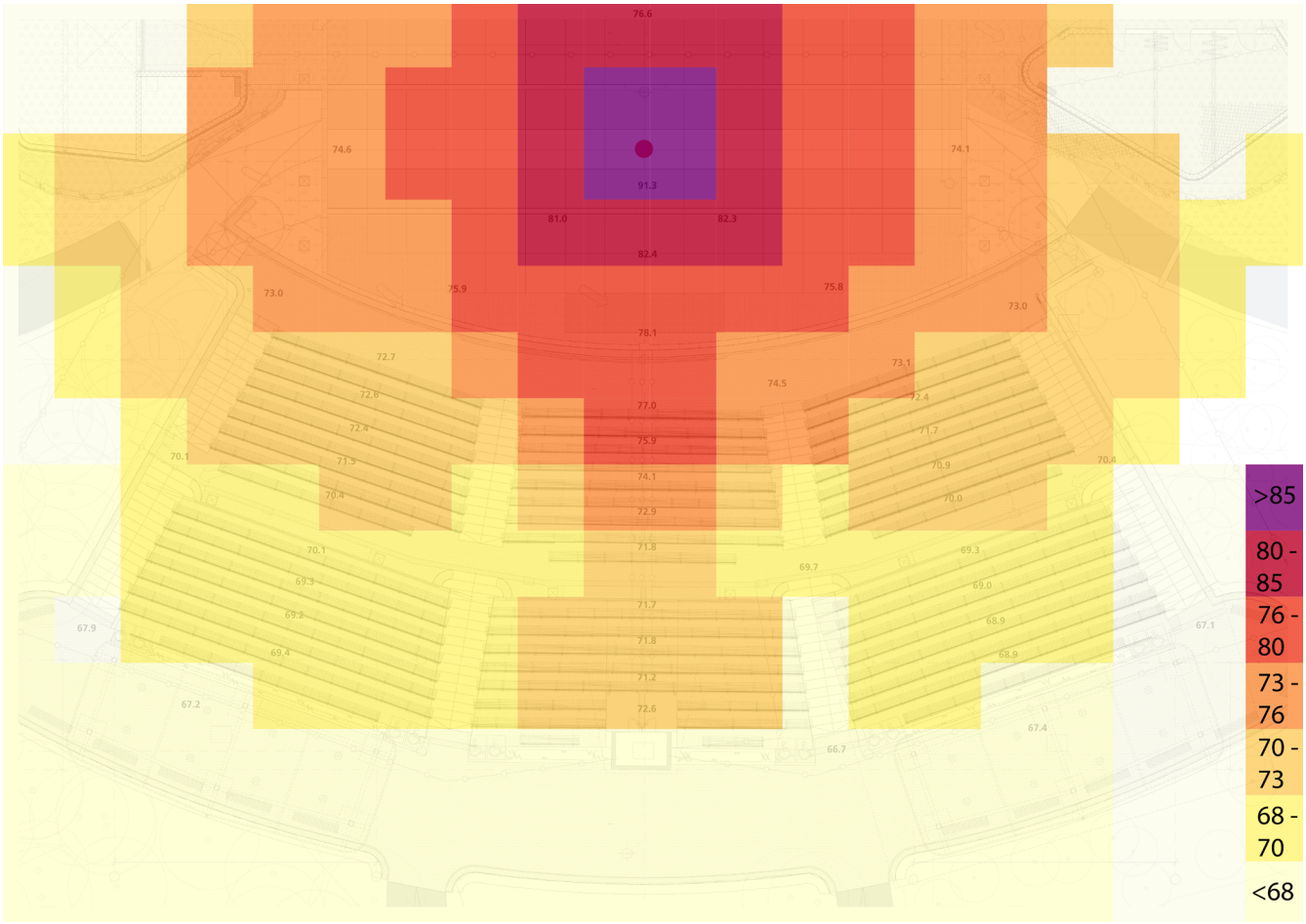


Figure 22: SPL results in dB(A)

The measurement results are presented in figure 22, which shows the recorded SPL values at each measurement point plotted onto the theater plan.

The results reveal a spatial gradient in sound pressure level across the audience area. Sound levels are highest directly in front of the stage, where values exceed 85 dB(A) in the area next to the source. Further away from the stage, SPL drops, reaching around 77 - 78 dB(A) at the front rows of the central seating area and goes down further to around 71 - 73 dB(A) in the middle rows. At the back of the seating area, SPL goes down to 67 - 68 dB(A), representing a total difference of over 10 dB between the front and back of the audience area.

The heatmap also reveals a degree of lateral variation. The central seating block records higher levels than the side sections at the same distances from the stage. The side seating areas receive the least acoustic energy, with values going below 68 dB(A).

The results confirm the acoustic challenge overview of an open-air performance space. This consists of an SPL decay and bad uniformity across the seating area. These conditions define the baseline against which the performance of the reflector designs will be evaluated.

3.1.3 Line measurements

To further analyse the decay behaviour of sound across the seating area, three line measurements were done along the central and lateral axes of the theater. Each graph plots the measured SPL values against the distance from the source on a logarithmic scale, with trend line. The DL2 value, spatial decay, is used as an indicator of how closely the sound field follows free-field behaviour.

Line measurement 1, taken along the middle row of the central seating block, has a DL2 value of 4.4 dB(A). Line measurement 2, taken along the right side of the seating area, shows a higher deviation of 5.3 dB(A). Line measurement 3, on the left side, has a DL2 of 4.7 dB(A). Across all three measurements, the decay follows a consistent downward trend with distance, almost in line with the expected free-field decay rate of 6 dB per doubling of distance, though with some scatter around the regression line at bigger distance from the source.

The DL2 values across the three lines are relatively similar, suggesting that the lateral sections of the theater do not deviate dramatically from the central axis in terms of decay. The consistent deviation from the theoretical decay curve across all lines indicates that the sound field is not purely free field. This is likely due to partial reflections from the stage surroundings and ground surface. These results reinforce the picture made by the spatial measurements. This means the Bostheater is a venue with significant SPL decay and limited natural acoustic support for the rear and lateral seating areas.

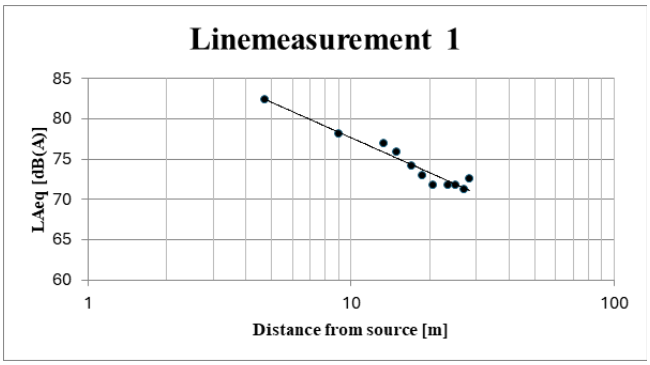


Figure 23: Linemeasurement 1

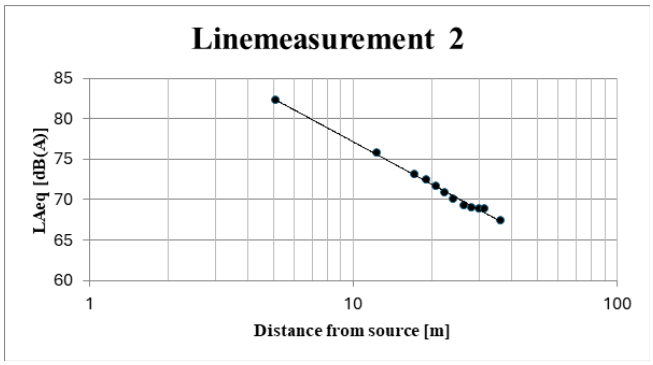


Figure 24: Linemeasurement 2

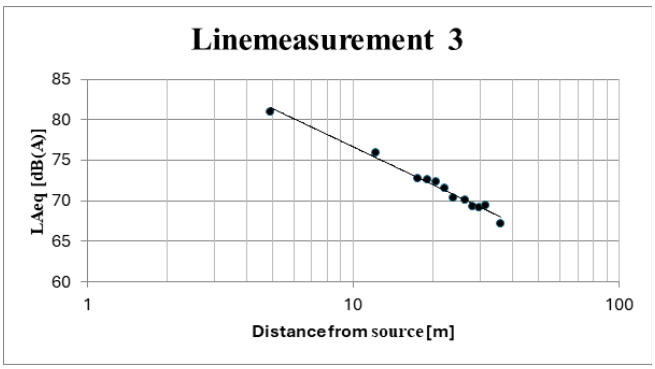


Figure 25: Linemeasurement 3

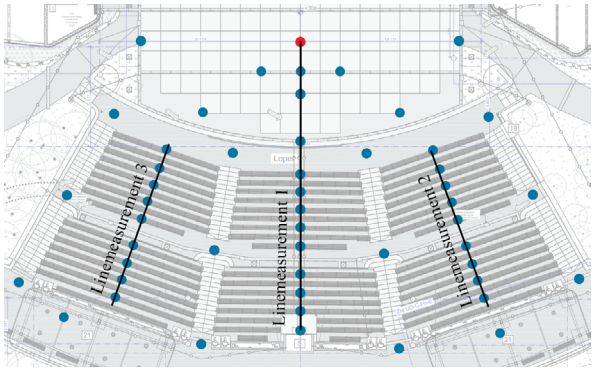


Figure 26: Overview linemeasurements

4. Design of the computational workflow

The acoustic simulation environment is built around a geometric model of the Amsterdamse Bostheater, which was made in Rhino. The model is based on the architectural drawings of the theater and captures the surfaces which are relevant to the acoustic behaviour of the venue: the stage platform, the seating tribunes and the ground plane. At this stage of the workflow the model serves a single purpose, it provides the spatial framework from which source and receiver points are defined and used in the simulation. The surface geometry itself does not contribute absorption or reflection in the Aeolus simulation. Those effects are introduced later when the model is imported into CATT-Acoustic for the validation phase described in chapter 6.

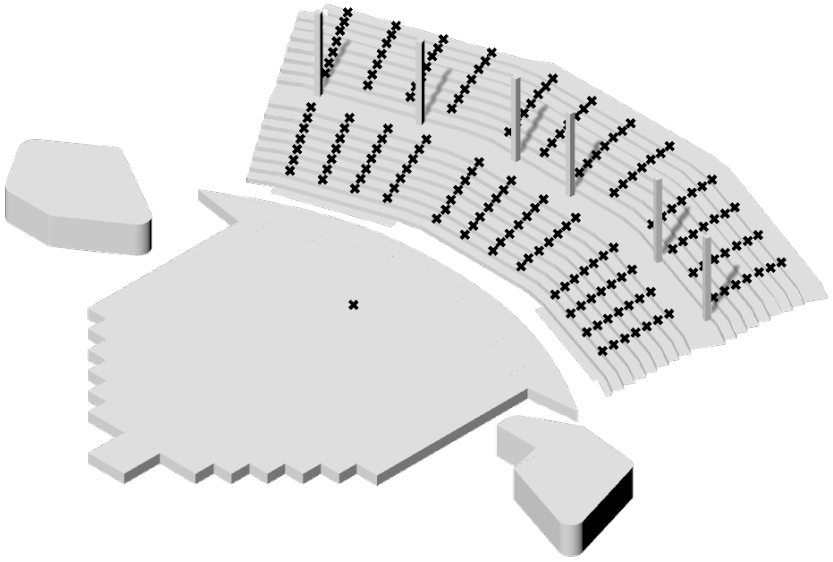


Figure 27: 3D Rhino Model

The acoustic simulations which the optimization uses are made using Aeolus, a ray-tracing plugin for Grasshopper developed for use in early-stage architectural acoustic design. Aeolus sends sound rays from a source point through the model geometry and records the arriving sound energy at each receiver position, from which it calculates the SPL across the audience area. Because Aeolus operates within the Grasshopper environment, its inputs and outputs can be directly connected to the parametric model of the reflector geometry. This allows each design to be evaluated automatically as part of the optimization loop without manual intervention.

The Grasshopper script fully organises the workflow from geometry generation to acoustic evaluation. The reflector geometry is defined parametrically and fed into the Aeolus simulation component with the receiver points from the Bostheater model. For each solution, Aeolus calculates the SPL at all receiver points, from which the standard deviation across the audience area is calculated as the performance metric. The results are passed to the optimization component as objective values to be minimized or maximized. A visualization of this workflow is shown in figure 28.

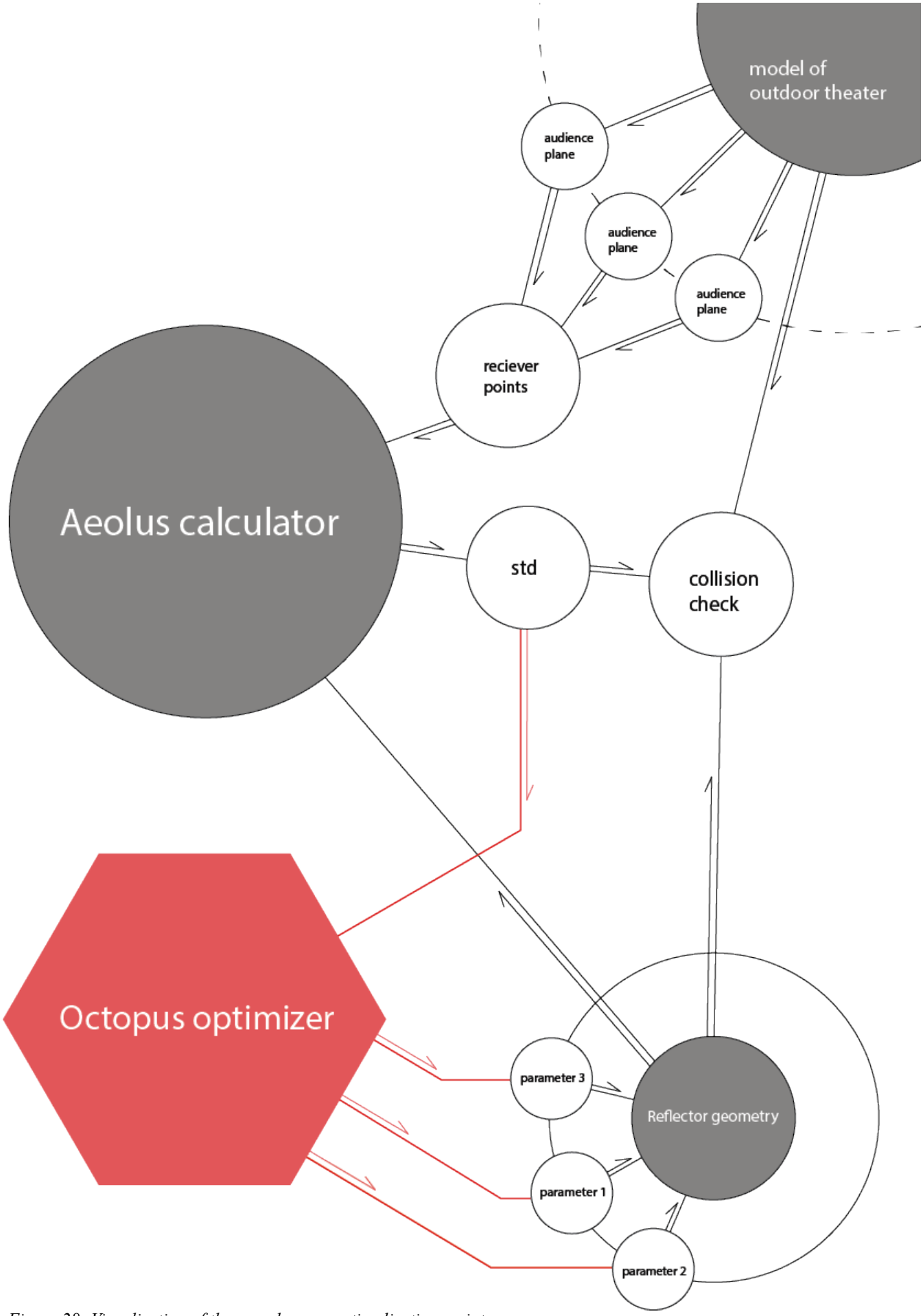


Figure 28: Visualisation of the grasshopper optimalisation script.

4.1 The Octopus optimiser

The optimization is carried out using Octopus, which is a multi-objective optimization plugin for Grasshopper which uses evolutionary algorithms. SPEA-2 is used for multi-objective workflows and a genetic algorithm variant for single-objective problems. The main objective of the optimization of this thesis is to maximize SPL uniformity across the audience area of the outdoor theater. This is calculated as the standard deviation of SPL across the receiver grid, which the algorithm wants to minimize. When multiple source positions are included together, this becomes a multi-objective problem, with the standard deviation for each source treated as a separate objective.

4.1.1 Sequential optimization strategy

At each stage of the workflow, the inputs, simulation outputs are defined. The inputs are the active geometric parameters of the reflector together with the fixed theater geometry, the source positions and the receiver grid. Aeolus uses these inputs to calculate the SPL at each receiver point in the audience area. From this distribution, the standard deviation of SPL across the receiver grid is calculated as the primary performance metric. This single value is passed to Octopus as the objective to be minimized. When multiple source positions are active simultaneously, each source contributes one standard deviation value, producing a multi-objective problem. The output of each optimization stage is a Pareto front of candidate geometries, from which one solution is selected and its parameter values recorded. These values form the input to the next stage. The final output of the complete workflow is a fully defined reflector geometry whose parameter values have been determined by the optimizer across all stages.

Because of the large number of variables in a full parametric reflector model, an optimization of all parameters at once would result in a very large search space. The optimization is therefore structured as a sequential, step-by-step process in which subsets of variables are optimized in different stages. Each stage takes the output of the previous as its starting condition. This means that it is progressively going towards a solution while keeping individual stages manageable. The stages are ordered by their influence on the objective function: the parameter sets with the greatest impact on uniformity are done first, which results in a stable acoustic foundation before extra variables are introduced.

Parameter	Value used	Function
Population size	250	Controls diversity of candidate solutions
Max. generations	30	Defines stopping criterion
Mutation probability	0.20	Introduces variation to avoid local optima
Crossover rate	0.80	Controls recombination of parent solutions
Elitism	0.30	Preserves best solutions across generations

Table 1: Parameter values used in the Octopus solver

4.1.3 Visualization of the optimization process

The optimization process is visualized within the Grasshopper environment. When Octopus runs, the progress of the objective through generations can be seen and the current Pareto front graph is updated live. This allows the designer to monitor the progress and stop if the algorithm is converging on an undesirable region of the solution space. The Pareto front is used at the end of each optimization stage to select a solution that best balances acoustic performance with architectural feasibility, which is then carried forward as the starting geometry for the next stage. In figure 29, this visualization is shown.

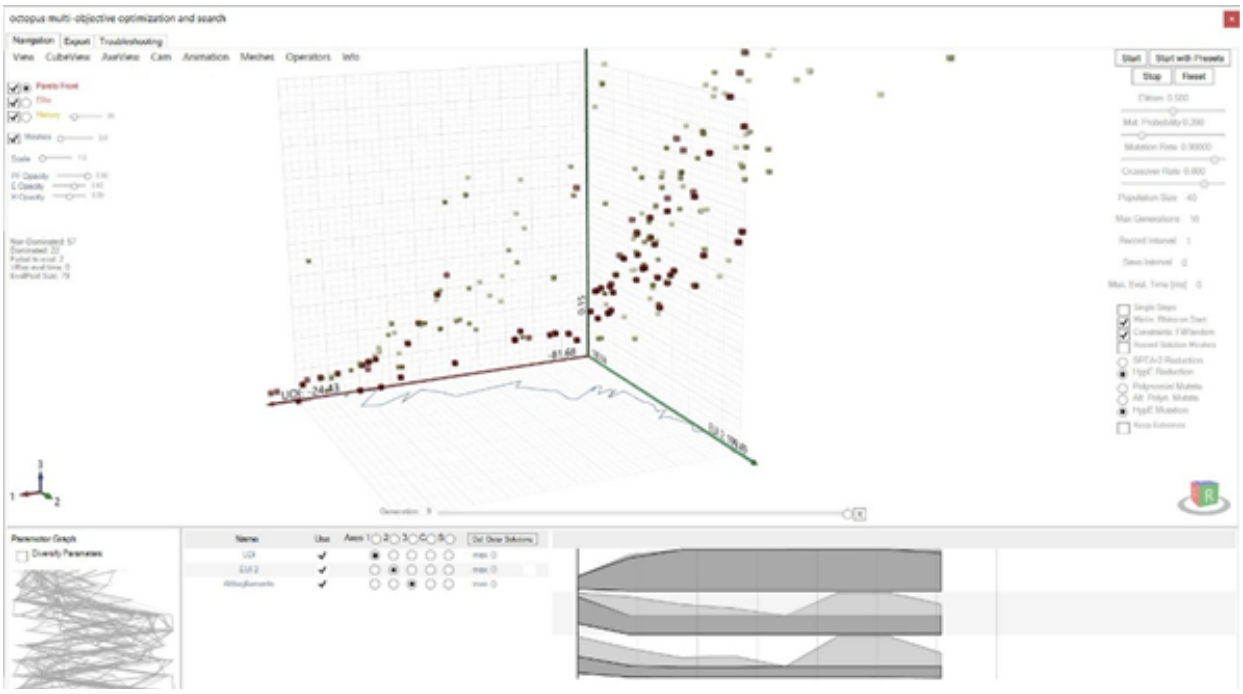


Figure 29: Octopus optimizer.

4.2 Integration of constraints

The computational workflow uses two categories of constraints. Geometric boundary conditions, which are built directly into the parametric model as slider limits and collision checks, built within Grasshopper that penalize invalid configurations during optimization. The first constraint type is the slider range. Every optimization variable in the model is assigned a minimum and maximum value. These ranges are obtained from the spatial constraints of the theater. This controls the physical boundaries in which each parameter can move without going past the structural or architectural vision of the design. By setting these limits to the sliders, the optimizer is prevented from generating a geometry that exceeds the parameter space.

The second constraint type addresses sightlines. The spatial requirement for a crowd-integrated structure is that no reflective surface obstructs the view of the stage from any seat in the audience. In Grasshopper, this is built in through a bounding volume that defines the maximum spatial area in the seating area that any part of the structure is allowed to occupy. The bounding volume is derived from the sightline geometry of the Bostheater. Using the seat positions and the stage edge as reference points, a volume is calculated that all valid geometry must stay within. During the optimization, each solution is collision-checked with this volume and designs that place reflective surface outside the zone are penalized.

Where a design is made of multiple reflective surfaces close to each other, an additional collision-check is used between panels. Because the optimizer treats each panel as an independent variable, it can in principle generate solutions where surfaces from different parts of the structure overlap. The collision check flags any design in which two or more surfaces overlap and adds a penalty to the objective.

5. Design of the reflector

5.1 Design philosophy

The design philosophy of the crowd-integrated reflector system is based on the principle of acoustic uniformity. By making sure that every seat in an open-air venue receives an equal quality of sound. As established in the literature review, existing passive design focussed on an acoustic shell, which can only partially compensate for the decay of sound pressure. This thesis proposes additional reflectors, which are placed in the audience zone.

However, the goal is not to recreate an indoor acoustic environment outdoors. The open-air theater offers an experiential quality that is valued in its own right. The connection to the surrounding landscape, the natural ambient sound environment and the sense of openness which defines the outdoor performance experience. A solution that attempts to fully enclose the audience zone would destroy what makes these venues special. This thesis therefore draws a clear distinction between improving acoustic uniformity and replicating indoor acoustics. The goal is not to introduce reverberation or long decay of a concert hall. It is only to address what is missing outdoors: the early reflections that provide loudness support and spatial width.

In indoor spaces, walls and ceilings return sound energy to the listener. Outdoors, this energy is lost to the open sky and environment. The crowd-integrated reflectors proposed in this thesis target the sound that otherwise would be lost to the surrounding or sky. By intercepting sound that would otherwise escape and redirecting it back into the audience area, the system adds acoustic support without adding artificial reverberation or changing the fundamental open character of the space. The audience should still feel that they are outside, but the only change is that the space will change acoustically.

This principle is a big part of the design philosophy and will shape the geometric and material choices of the reflector system. A second principle shaping the design is contextual integration. The reflectors must function in the spatial and social logic of an existing outdoor theater.

The third principle is parametric adaptability. Rather than designing a fixed object for a single venue, the workflow will produce a system whose geometric properties are all exposed as adjustable parameters. This allows the same computational framework to be applied to different open-air venues by recalibrating these parameters to suit a new spatial configuration. The Amsterdamse Bostheater serves as the case for validation, but the workflow is designed to be transferable.

5.2 Rubric of requirements

From the design philosophy, the goal of the designed reflector is:

Bringing the acoustic qualities of the indoors to the outdoors, without sacrificing the spatial qualities that make open-air performance irreplaceable.

To test the designs on its feasibility and if it suffices the goals of the project, a rubric is made to score every design iteration on meeting the needs of the design philosophy and the goal of the reflector:

Acoustic requirements				-
Criteria	**Insufficient (1)**	**Partial meets (2.5)**	**Meets requirements (4)**	**Score**
SPL uniformity	Standard deviation not meaningfully reduced relative to baseline. Rear and lateral zones remain strongly underserved. No clear improvement in SPL distribution visible in results plot.	Measurable reduction in std dev relative to baseline. Improvement visible in parts of the seating area but distribution remains uneven across all zones.	Clear reduction in std dev relative to baseline. Improvement is consistent across rear and lateral zones. Results plot shows a visibly more uniform SPL gradient across the full audience area.	-
Spatial requirements				-
Criteria	**Insufficient (1)**	**Partial meets (2)**	**Meets requirements (3)**	**Score**
Sightline integrity	Structure enters or blocks the sightlines of a significant portion of the audience. Audience members cannot see the stage unobstructed from one or more seating zones.	Structure marginally intrudes on sightlines for a small number of seats, or sits at the boundary of the sightline volume but does not cause full obstruction.	Structure clears all audience sightlines entirely. Every seat has an unobstructed view of the stage. Sightline bounding volume constraint is satisfied in the parametric model.	-
Preservation of openness	The structure encloses or strongly encloses the audience area. The sky is significantly obstructed. The sense of being in an open outdoor space is compromised.	Openness is partially maintained. Some zones feel enclosed or the sky view is noticeably reduced, but the space does not feel fully enclosed.	The audience area remains open. Sky is visible. The outdoor spatial character of the venue is preserved and the structure does not read as an enclosure.	-
Contextual integration	The structure reads as a purely technical apparatus with no visual connection to the forest context. Form and material are incompatible with the character of the venue.	Some formal or material connection to the setting. The structure is not entirely out of place but does not integrate naturally.	Form and material integrate with the setting. The structure is architecturally legible as part of the venue rather than a technical element. It does not compete with the stage for attention.	-

Technical requirements				-
Criteria	**Insufficient (1)**	**Partial meets (2)**	**Meets requirements (3)**	**Score**
Structural feasibility	The structural concept presents significant unresolved engineering challenges that are not addressed by the design.	The structural approach is plausible but includes one or more unresolved challenges. Engineering issues are identified but not fully resolved within the design.	The structural concept is sound and buildable. Column-mounted or otherwise self-supporting configuration. Wind load and installation challenges are addressed or do not present problems within the design logic.	-
Parametric compactness	The parametric model is poorly structured or not parametrised. Many redundant variables, or key geometric properties are fixed and cannot be adjusted by the optimizer.	The parametric setup is functional but not efficient. The design space is workable but larger than necessary, or some key parameters are missing or poorly defined.	All relevant geometric properties are exposed as a compact set of sliders. The optimizer has direct and meaningful control over the design with a minimum number of variables. The model can be recalibrated for other venues.	-
Principle of restraint	The design uses more material or structural complexity than the acoustic function requires. Elements are present that serve no acoustic or structural purpose.	Mostly restrained but includes some redundant elements, or material choices add visual weight without a clear acoustic or structural justification.	All material and geometric choices are minimal and purposeful. Nothing is present that does not serve acoustic or structural function. The intervention is as light as possible.	-
Total score				

Table 2: Rubric of requirements

After each design iteration, the rubric is completed and a score is assigned for each sub-criteria. The category score is the average of its sub-criteria scores, and the three category scores are added to a total out of 10. This total indicates the overall extent to which the design meets the requirements of the crowd-integrated reflector system.

5.3 Acoustic indoor environment to the outside

When analysing the behaviour of early reflections in an indoor environment, it is clear that the acoustic benefits of an indoor space can be replicated in an open-air theater without constructing a full box. By using only strategically chosen elements of a wall into an outdoor theater design, the first reflections of this box can be recreated.

The designed reflectors will build on this specific principle. The main objective of these surfaces is to optimize the uniformity of the SPL across the entire audience area. In outdoor settings, the natural decay of sound over distance creates a lack of consistency. As seen in the results of the real-life measurements, audience members in the back or side experience a large drop in SPL compared to the audience in the front.

To counteract this, the reflectors will be angled to redirect first-order reflections toward those specific areas of the audience. This intervention will result in a much more uniform listening experience, allowing every audience member to perceive the performance with the same level of detail and presence.

In indoor performance spaces, both the ceiling and the side walls function as reflective boundaries. The side walls return laterally travelling sound energy back into the audience zone, contributing to spatial envelopment. The ceiling intercepts upward-travelling sound energy and redirects it downward across the full seating area, directly contributing to Sound Strength (G) and Clarity (C80). Both surfaces are important to the indoor acoustic environment, but they serve different parts of the audience in different ways.

The ceiling is the more universally effective reference for a crowd-integrated reflector system. A side wall only covers the lateral edges of the audience area. Its influence is strongest for listeners seated near that boundary and diminishes toward the centre. A ceiling spans the full width of the audience zone. It is therefore capable of returning sound energy to every listener. This makes the overhead reflector the primary instrument for improving overall SPL uniformity across the audience area, while lateral reflectors serve as a targeted complement, addressing the edge zones that the overhead surface alone cannot fully reach.

This distinction directly controls the two-part structure of the crowd-integrated reflector system proposed in this thesis. This means a large overhead reflector positioned above the central audience zone and a series of lateral reflectors along the side aisles. Together, they replicate the essential acoustic functions of a ceiling and side walls, without enclosing the space.

In figure 30, a visualisation of the indoor to outdoor principle is shown.

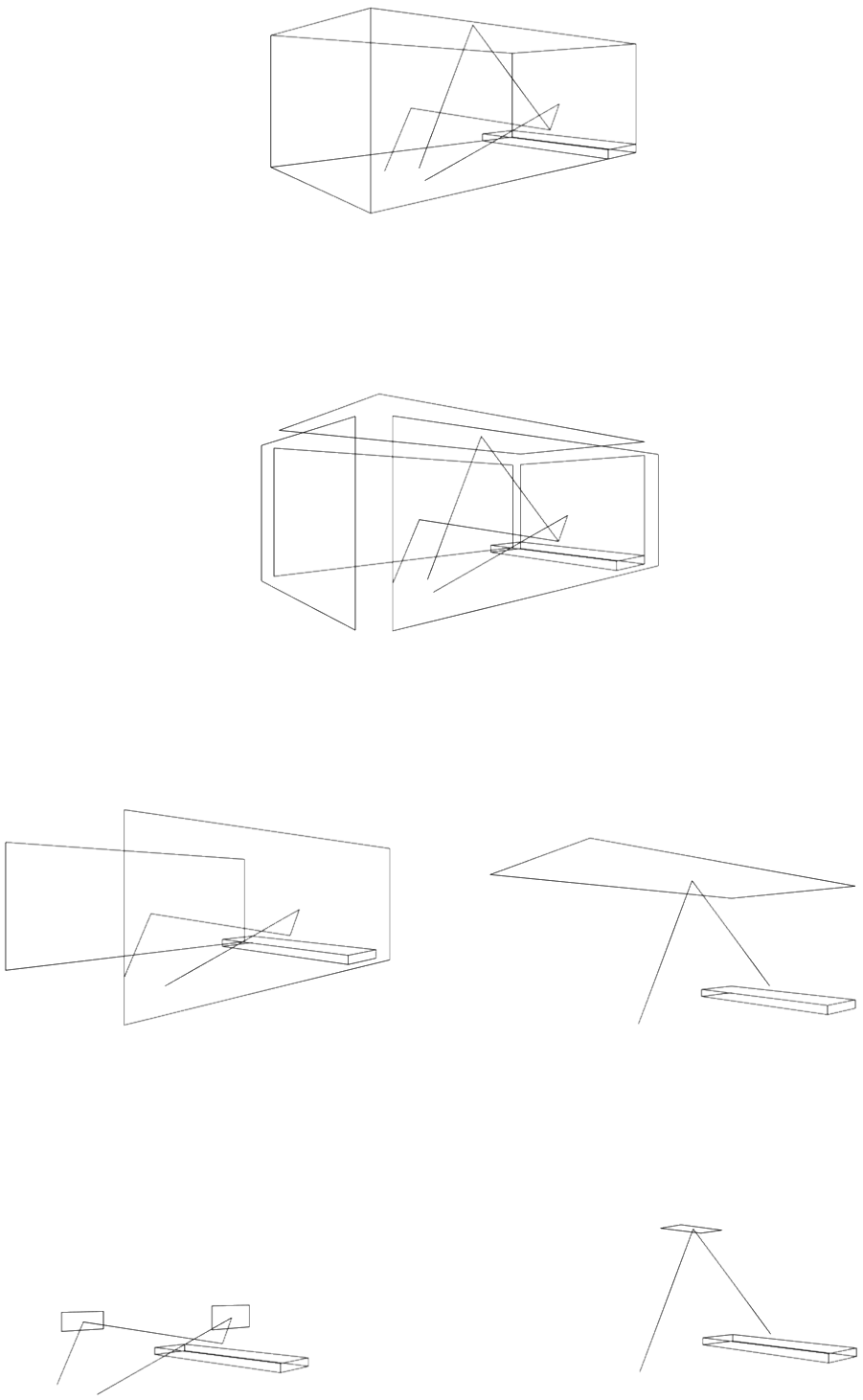


Figure 30: Bringing the indoor environment to the outside

5.4 Parameterizing the design

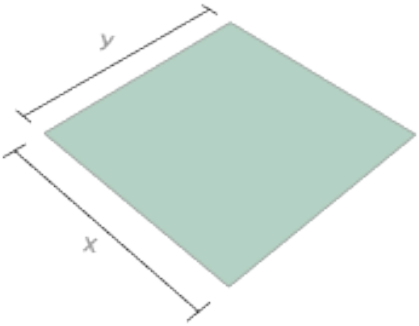
The effectiveness of a crowd-integrated reflector depends on several interacting geometric and material properties, each of which influences a different aspect of the sound field.
Size and surface area determine the frequency range over which the reflector is effective. For a surface to reflect rather than diffract sound, its dimensions must be significantly larger than the wavelength of the target frequency.

Surface curvature determines how reflected sound is distributed spatially. As established in the literature review, convex surfaces are preferred for crowd-integrated reflectors because they scatter sound broadly across the audience area. Concave surfaces, by contrast, focus energy into a single point and create uneven hotspots. Flat surfaces produce specular reflections and can be used for targeted redirection but offer less uniform distribution.
Tilt angle and orientation control where reflected sound is directed. A reflector that is tilted too steeply will redirect sound upward and away from the audience; one that is too shallow will reflect sound into the ground. The optimal tilt angle for each reflector depends on its position within the audience zone and its relationship to the sound source. This is perhaps the most sensitive parameter in the system, and it is the primary variable that the Octopus solver will modulate during optimization.

Positioning within the audience zone determines which part of the decay gradient the reflector addresses. Reflectors placed closer to the stage primarily serve the mid-field audience, while those placed further back address the far-field decay problem. As demonstrated in Pugnale's (2018) research on reflective umbrellas, positioning reflectors toward the rear of the seating area produced a more uniform SPL distribution than clustering them near the front.

Material properties determine the fraction of incident sound energy that is reflected versus absorbed. For maximum acoustic effectiveness, reflectors should be constructed from dense materials with a low absorption coefficient. Rigid materials such as aluminium composite panels, glass-reinforced concrete, or hard timber are all suitable candidates. The scattering coefficient of the surface also plays a role: a slightly textured surface will diffuse reflected energy more evenly than a perfectly smooth one, which can be beneficial for improving the BQI of the audience zone.

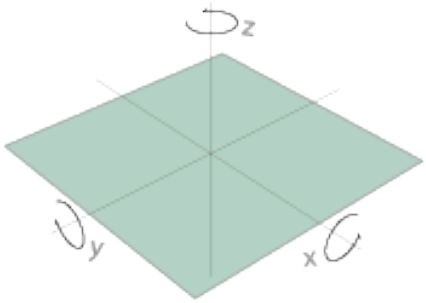
In figure 31, these different ways of parameterisation are visualised.



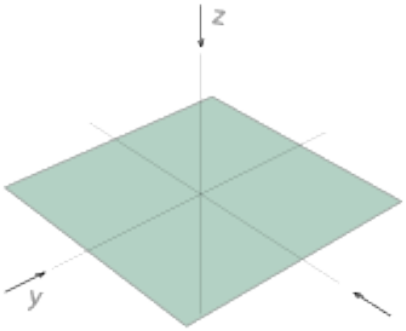
Size and surface area



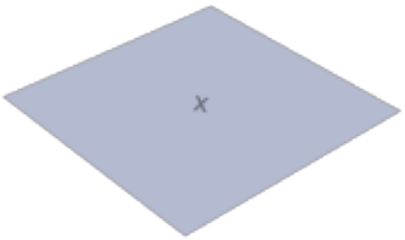
Shape curvature



Tilt angle and orientation



Positioning



Materiality

Figure 31: Parameterisation of a reflector

These parameters can be integrated into a design to change the way a reflector reflects acoustic energy. The reflector will be optimised in such a way that these parameters exist only in the grasshopper environment. This will make for a permanent structure, which is optimized for multiple source positions in a specific outdoor performance space.

5.5 Evolution of the design of the acoustic structure

From the design philosophy, a program of requirements was made to evaluate designs through a “research through design” process. This approach allows for continuous testing and reflection, making sure the concept is guided toward a final solution. The program of requirements is categorized into three core pillars: acoustic, spatial and technical requirements. For this first iteration, the design approach prioritized acoustic performance as the starting point for the design.

5.5.1 Iteration 1: engineered approach

The design phase began with the acoustic study mentioned in chapter 5.3, which identified the locations of first-order reflections within an indoor environment. These specific points were used as a start of the idea for the reflector. By targeting these locations, the design makes sure that the shortest possible path for reflected sound is chosen, thereby minimizing energy loss through decay.

5.5.1.1 Design and parameterization

Building on this logic, several sketches were developed to explore the parameterization of the panels. The objective was to combine individual flat panels into a single structure by rotating and joining them to function as a combined reflector.

The resulting sketches draw inspiration from existing indoor acoustic reflector systems, as seen in figures 32 to 36. This modular approach allows for a changeable geometry that tackles the changeable direction of the reflectors.



Figure 32: Existable indoor reflector system.

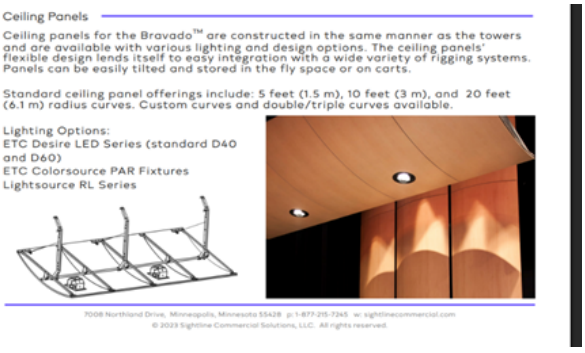


Figure 33: Existable indoor reflector system.

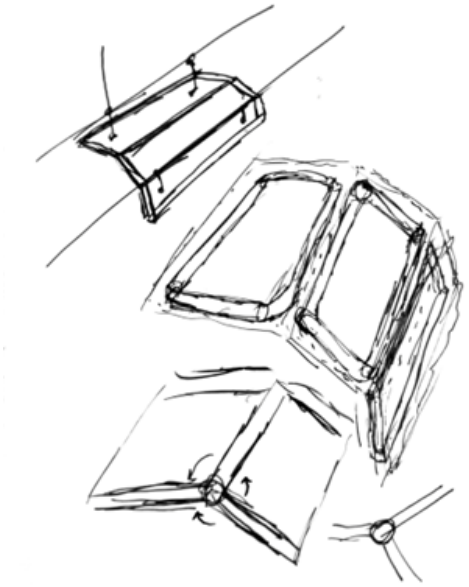


Figure 34: Sketch of the rotating frame

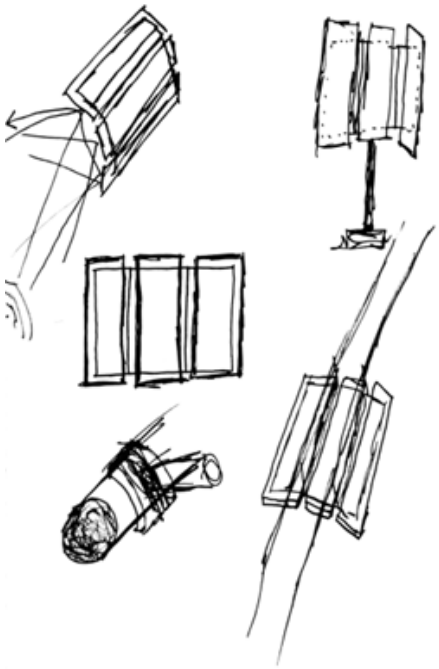


Figure 35: Sketch of iteration 1

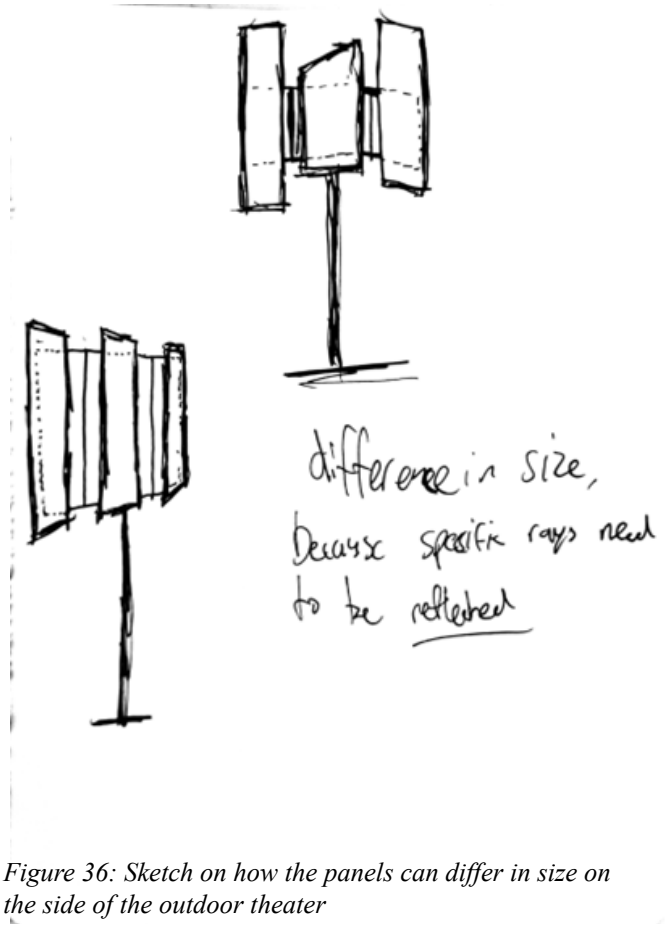


Figure 36: Sketch on how the panels can differ in size on the side of the outdoor theater

The first iteration took acoustic performance as its starting point. Building on the principles of first-order reflections in indoor acoustic concert halls, the design identified locations within the theater where reflected sound could travel the shortest possible path from source to surface to the receiver. By targeting these optimal positions, the reflectors were placed to minimize travel distance and energy loss because of distance decay and absorption. The intended acoustic effect of this was to increase the overall SPL reaching the audience and to improve its spatial uniformity across the seating area, making sure that listeners at different distances from the stage experience a more consistent acoustic environment.

A single structure was chosen over a distributed arrangement of smaller reflectors for several reasons. Practically, a combined structure is easier to install, reposition and store in the context of a temporary outdoor theater. Architecturally, it reads as a coherent design element rather than a collection of components, which matters in a setting where spatial quality is part of the experience.

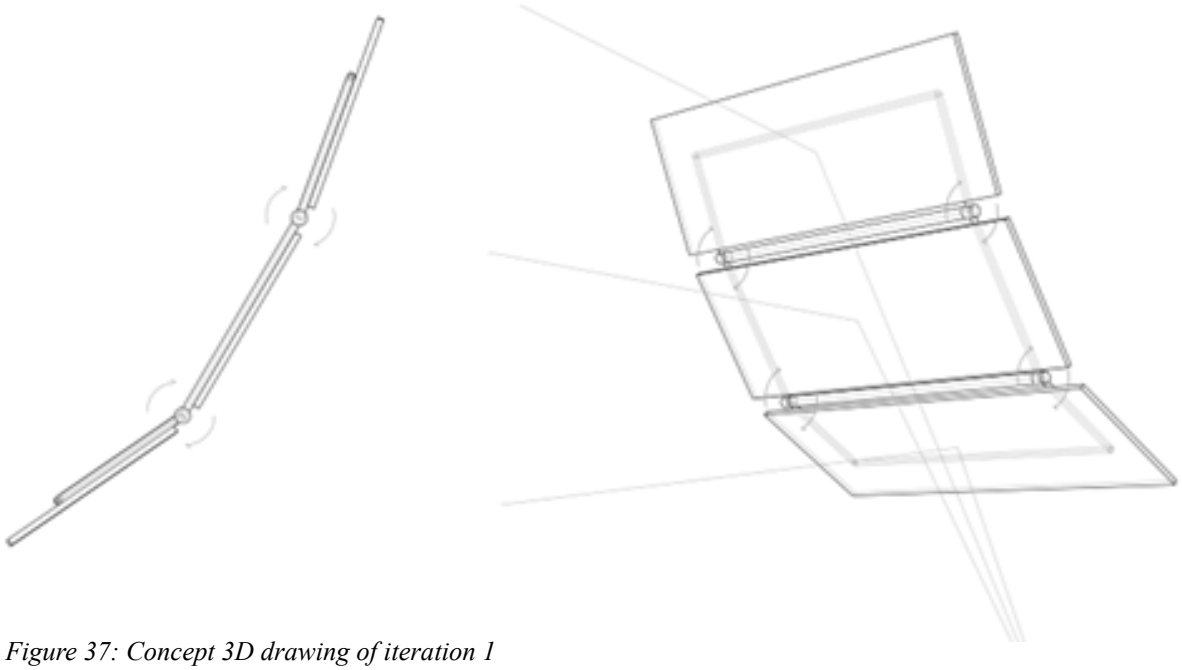


Figure 37: Concept 3D drawing of iteration 1

The resulting geometry was a series of flat, tilted panels positioned in close range to the stage, combined into this single structure. Each panel was oriented to intercept sound energy and redirect it toward the audience area, making that a greater portion of the acoustic energy reached listeners directly rather than disappearing into the open air. To allow for adaptability, the panels were connected with each other through a shared metal frame around which each panel could rotate. This mechanism allowed three distinct configurations to be embedded within a single system.

An overview of the design is shown in figures 37 and 38.

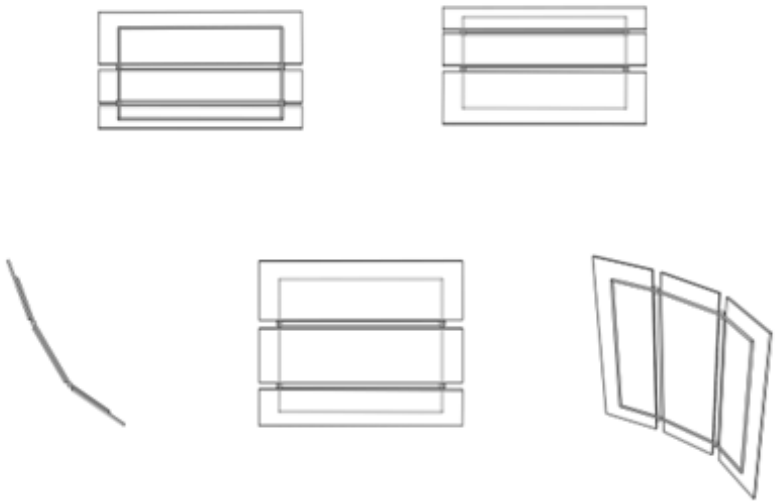


Figure 38: Top, sides and 3d view of iteration 1

In Grasshopper, the design was parameterised to allow optimization of its variables. Each panel was defined from a single reference point and rotated relative to the positions of the other panels. This approach meant that three sliders were good to control the rotation of each panel. This gives the optimizer direct influence over the configuration of the structure. The second geometric parameter was the position of the reflector assembly within the theater. Given the symmetry of the outdoor theater, this position could be expressed as a single value: a point which moves along a curve. This allowed a spatially complex concept, the three-dimensional placement of the structure, to be put into a single input, keeping the parameter space compact without sacrificing design flexibility.

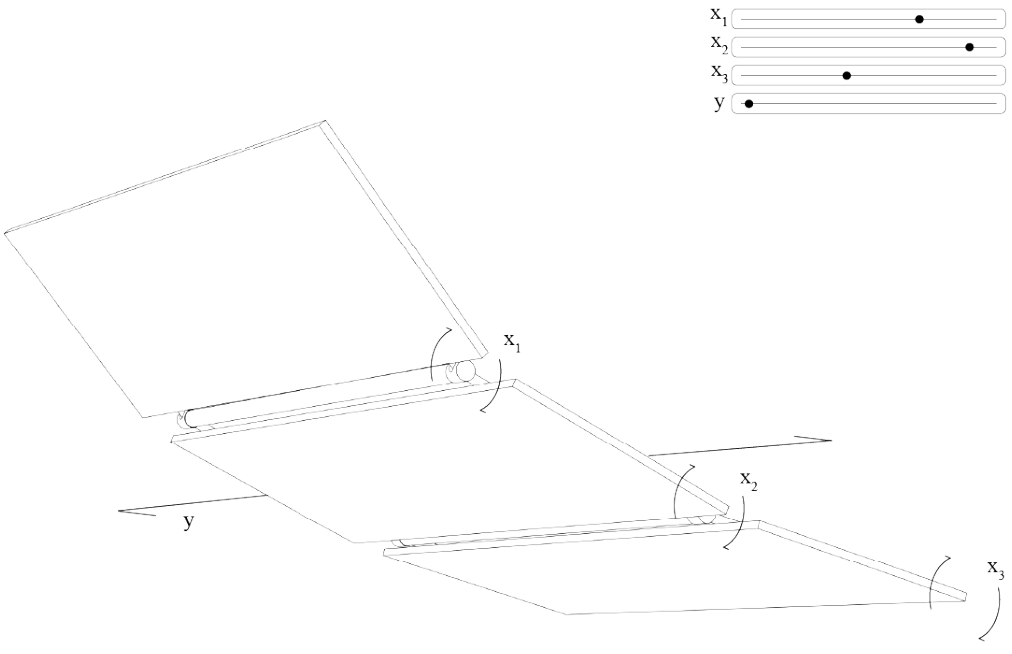


Figure 39: Visualisation of the parameterisation of iteration 1

5.5.1.2 Acoustic optimisation

The optimization of this iteration produced a standard deviation of SPL of 1.35 dB across the audience area, which indicates a good level of uniformity for a compact reflective surface. The algorithm successfully redirected large amounts of sound energy toward the audience, confirming that panels positioned close to the source and at low height are effective redirecting large amount of sound energy. In figure 40, the results of the optimisation are plotted.

A closer analysis of the SPL distribution revealed several weaknesses. The central zone of the audience area performed worse than the lateral zones and the corners of the seating area remained the most acoustically underserved positions throughout all optimization runs. This was partly a consequence of the algorithm's tendency to concentrate its optimization effort toward a single corner rather than improving the field as a whole. The size of the reflective surfaces emerged as the primary bottleneck: the panels were not large enough to influence the full audience area. Increasing coverage would require a large increase in surface area.

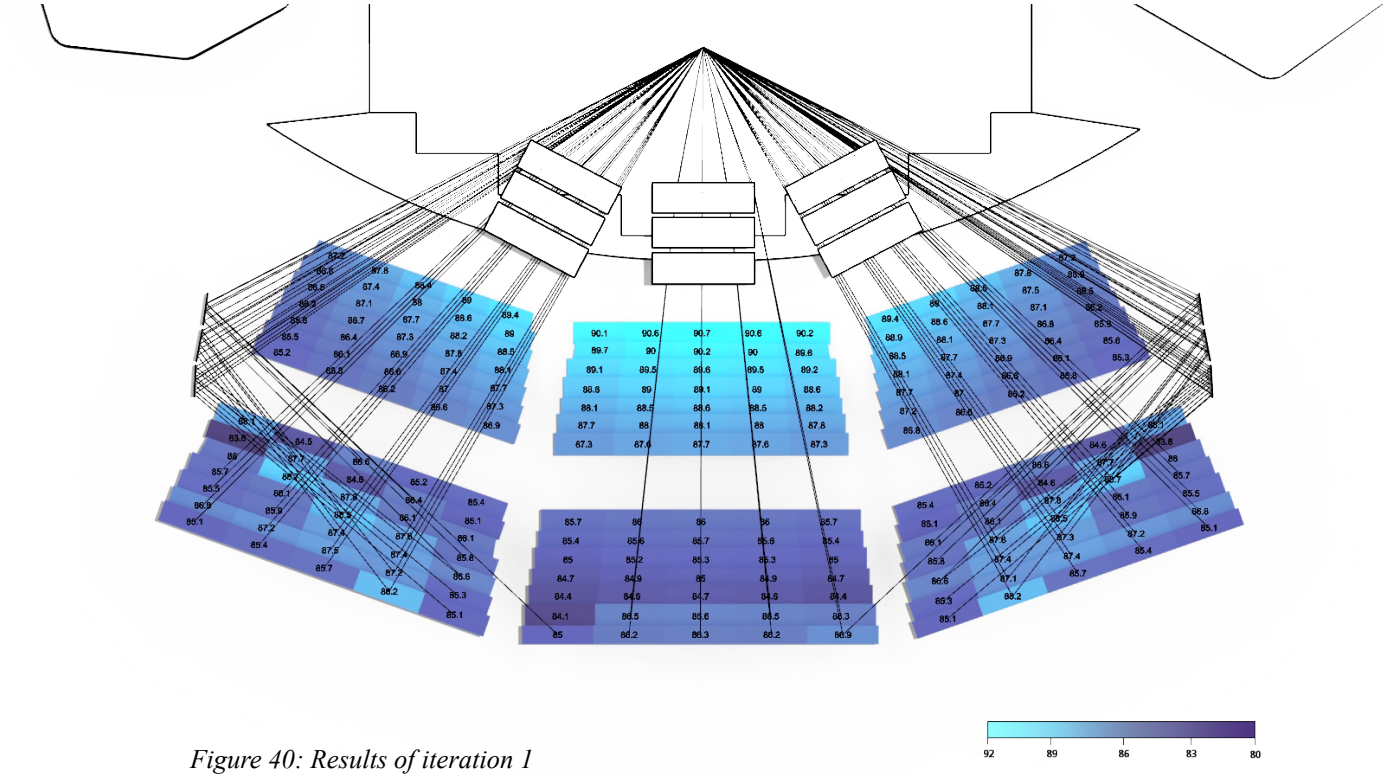


Figure 40: Results of iteration 1

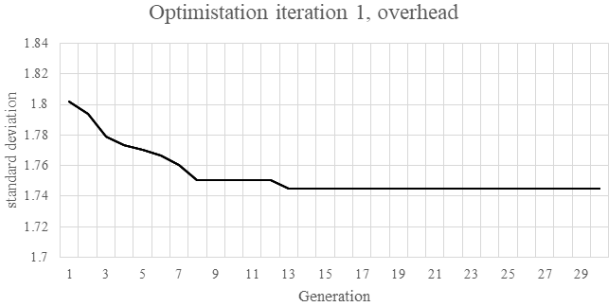


Figure 41: Optimization graph of iteration 1, overhead reflectors.

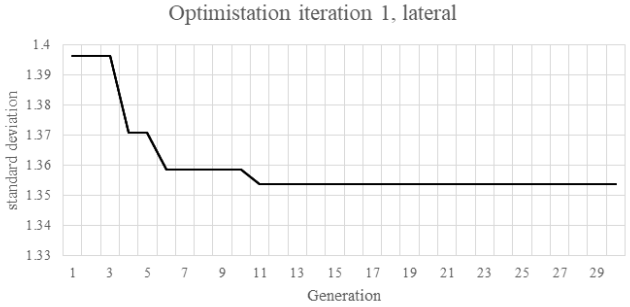


Figure 42: Optimization graph of iteration 1, lateral reflectors.

5.5.1.3 Evaluation

Acoustic requirements				2.5
Criteria	**Insufficient (1)**	**Partial meets (2.5)**	**Meets requirements (4)**	**Score**
SPL uniformity	Standard deviation not meaningfully reduced relative to baseline. Rear and lateral zones remain strongly underserved. No clear improvement in SPL distribution visible in results plot.	Measurable reduction in std dev relative to baseline. Improvement visible in parts of the seating area but distribution remains uneven across all zones.	Clear reduction in std dev relative to baseline. Improvement is consistent across rear and lateral zones. Results plot shows a visibly more uniform SPL gradient across the full audience area.	2.5
Spatial requirements				1.67
Criteria	**Insufficient (1)**	**Partial meets (2)**	**Meets requirements (3)**	**Score**
Sightline integrity	Structure enters or blocks the sightlines of a significant portion of the audience. Audience members cannot see the stage unobstructed from one or more seating zones.	Structure marginally intrudes on sightlines for a small number of seats, or sits at the boundary of the sightline volume but does not cause full obstruction.	Structure clears all audience sightlines entirely. Every seat has an unobstructed view of the stage. Sightline bounding volume constraint is satisfied in the parametric model.	2
Preservation of openness	The structure encloses or strongly encloses the audience area. The sky is significantly obstructed. The sense of being in an open outdoor space is compromised.	Openness is partially maintained. Some zones feel enclosed or the sky view is noticeably reduced, but the space does not feel fully enclosed.	The audience area remains open. Sky is visible. The outdoor spatial character of the venue is preserved and the structure does not read as an enclosure.	2
Contextual integration	The structure reads as a purely technical apparatus with no visual connection to the forest context. Form and material are incompatible with the character of the venue.	Some formal or material connection to the setting. The structure is not entirely out of place but does not integrate naturally.	Form and material integrate with the setting. The structure is architecturally legible as part of the venue rather than a technical element. It does not compete with the stage for attention.	1
Technical requirements				2
Criteria	**Insufficient (1)**	**Partial meets (2)**	**Meets requirements (3)**	**Score**
Structural feasibility	The structural concept presents significant unresolved engineering challenges that are not addressed by the design.	The structural approach is plausible but includes one or more unresolved challenges. Engineering issues are identified but not fully resolved within the design.	The structural concept is sound and buildable. Column-mounted or otherwise self-supporting configuration. Wind load and installation challenges are addressed or do not present problems within the design logic.	1

Parametric compactness	The parametric model is poorly structured or not parametrised. Many redundant variables, or key geometric properties are fixed and cannot be adjusted by the optimizer.	The parametric setup is functional but not efficient. The design space is workable but larger than necessary, or some key parameters are missing or poorly defined.	All relevant geometric properties are exposed as a compact set of sliders. The optimizer has direct and meaningful control over the design with a minimum number of variables. The model can be recalibrated for other venues.	3
Principle of restraint	The design uses more material or structural complexity than the acoustic function requires. Elements are present that serve no acoustic or structural purpose.	Mostly restrained but includes some redundant elements, or material choices add visual weight without a clear acoustic or structural justification.	All material and geometric choices are minimal and purposeful. Nothing is present that does not serve acoustic or structural function. The intervention is as light as possible.	2
Total score				**6.17**

Table 3: Rubric score of iteration 1

With a total score of 6.18 out of 10, the first iteration demonstrates a promising acoustic starting point but falls short of the overall design goals. The spatial score of 1.67 out of 3 reflects the fundamental conflict f this iteration: the acoustic logic demanded that panels be placed directly above and near the stage, which is precisely where they obstruct the sightlines of the audience and disrupt the open character of the venue. The contextual integration score of 1 out of 3 further underlines that the structure, while acoustically motivated, reads as a technical apparatus rather than an architectural element suited to the forested setting of the Bostheater. The technical score of 2 out of 3 is pulled down by the unresolved structural challenge of suspending a rigid overhead frame above the performance area, despite the parametric setup itself being efficient and well-structured. The iteration confirms that acoustic performance alone is an insufficient starting point for this design problem. A geometry that optimizes purely for SPL uniformity without spatial and contextual constraints will consistently produce solutions that are acoustically functional but architecturally and spatially incompatible with the venue. This finding directly motivates the shift in design priority for the second iteration.

5.5.2 Iteration 2: architectural approach

In response to the spatial and contextual shortcomings of the first iteration, the second iteration reversed the design priority. Rather than beginning from acoustic geometry, this iteration began from the spatial and contextual parts of the Amsterdamse Bostheater. The forested setting of the theater provided the primary conceptual reference. Through a series of sketches exploring canopy structures as a model for acoustic reflection, the design moved away from the panel geometry of the first iteration toward a form that could blend into its environment. In figure 43, these sketches are shown.

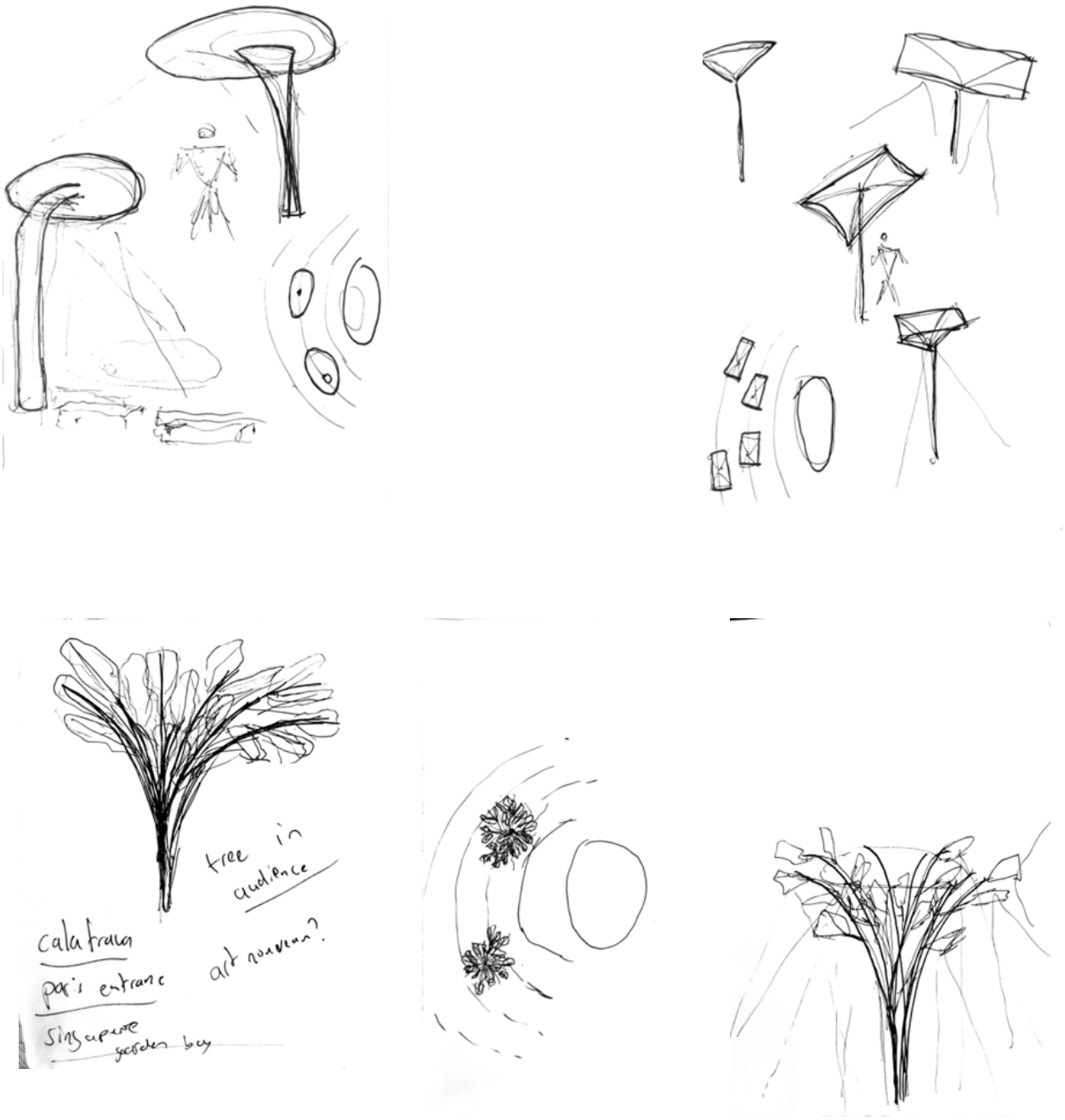


Figure 43: Sketches of iteration 2

5.5.2.1 Design and parameterisation

The design adopted a tree-like structure in which individual reflective panels were shaped as leaves, which were attached to branching elements coming from a central column. This allowed the overall structure to read as a natural intervention of its forest surroundings rather than a technical intervention imposed in it. The leaf panels were distributed across the branching structure at varying heights and angles, designed to clear all audience sightlines while remaining positioned within the audience zone. Spatial integration was prioritized, with the angular geometry of the panels treated as secondary to their contextual fit within the theater setting.

In Grasshopper, the design was parameterised using the same slider-based approach as the first iteration. Each leaf panel was defined from a reference point and given an orientation controlled by a rotation slider. This allows the algorithmic optimizer to influence the angle of each panel. The position of the structure was pre-defined and not translated into a slider.

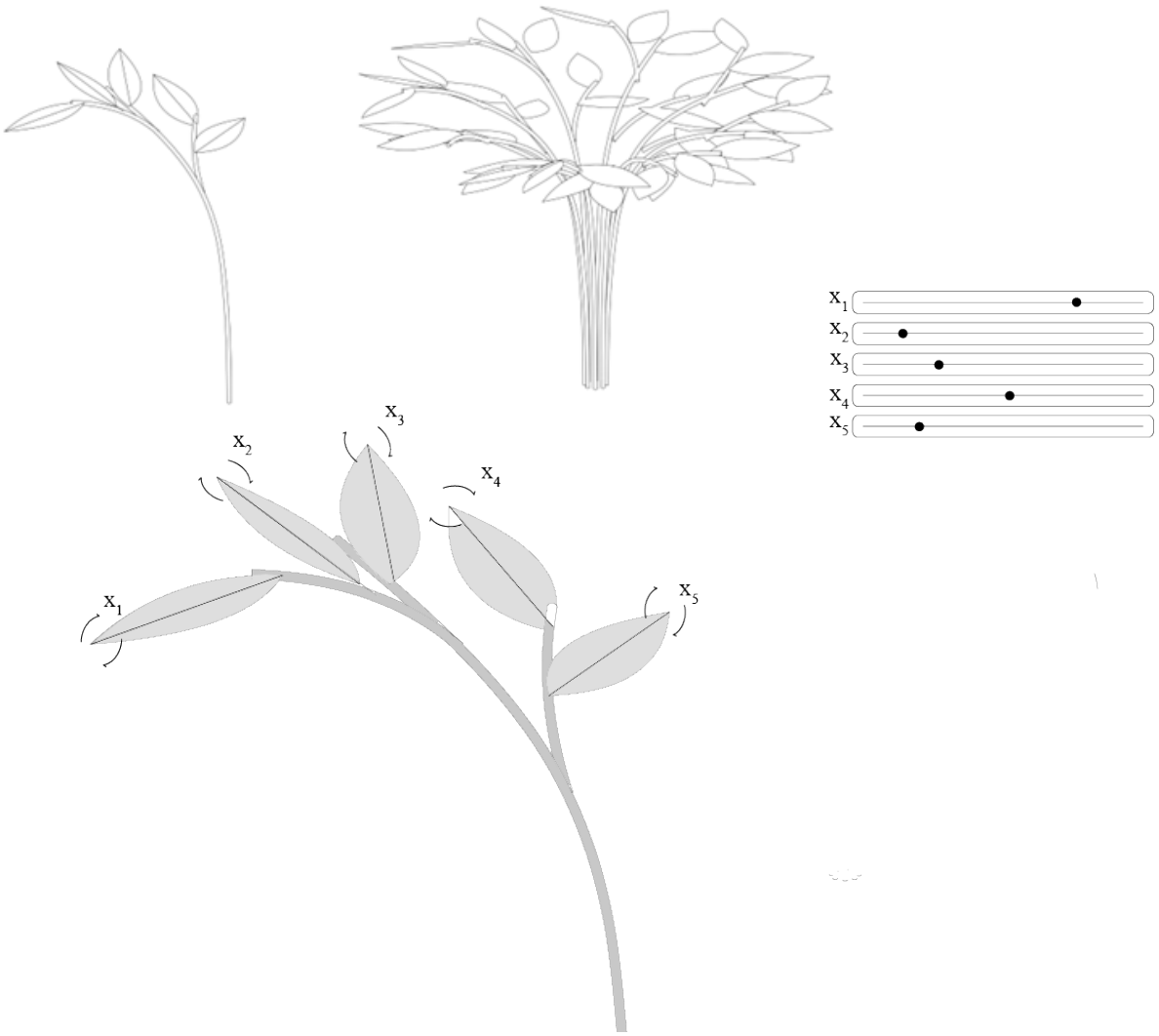


Figure 44: Grasshopper visualisation of iteration 2.

The parametric model of iteration 2 is built around a modular logic. The base geometry is a single branch, which is parameterised as an independent unit and then repeated to form the full tree structure. This is visible in figure 44, which shows the single branch on the left and the complete assembled tree on the right. The full tree, with its branches and leaf panels distributed across different heights and angles, emerges from the repetition and rotation of this one module.

The leaf panels are the acoustic elements of the design and the only parts of the geometry that are parameterised. As shown in figure 44, each branch carries five leaf panels, labelled x_1 through x_5, each of which can rotate around its own axis. The axis of each leaf is taken directly the geometry of the surface: the outer edge points of the panel are extracted and connected to form a curve. This curve becomes the axis around which the panel rotates. This means each leaf rotates around its own longitudinal axis rather than around defined axis, making sure that the rotation corresponds to a physically meaningful reorientation of the reflective surface.

Each of the five rotation axes is assigned a dedicated slider, shown in the parameter panel in the upper right of figure 44. These five sliders give the set of optimization variables for a single branch. Because the full tree is assembled from multiple identical branch modules, the total parameter counts scales with the number of branches, but each branch is always controlled by the same five-slider logic.

Figure 45 shows the resulting design placed within the theater in plan, section, and axonometric view. Two tree structures are positioned symmetrically within the front of the audience area.

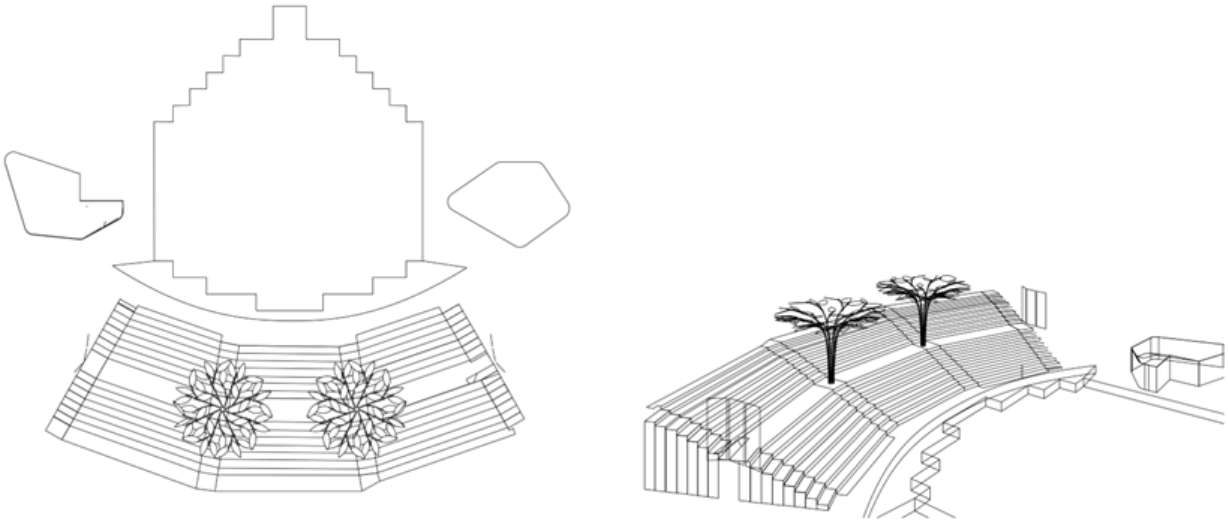


Figure 45: Top and 3D view of iteration 2

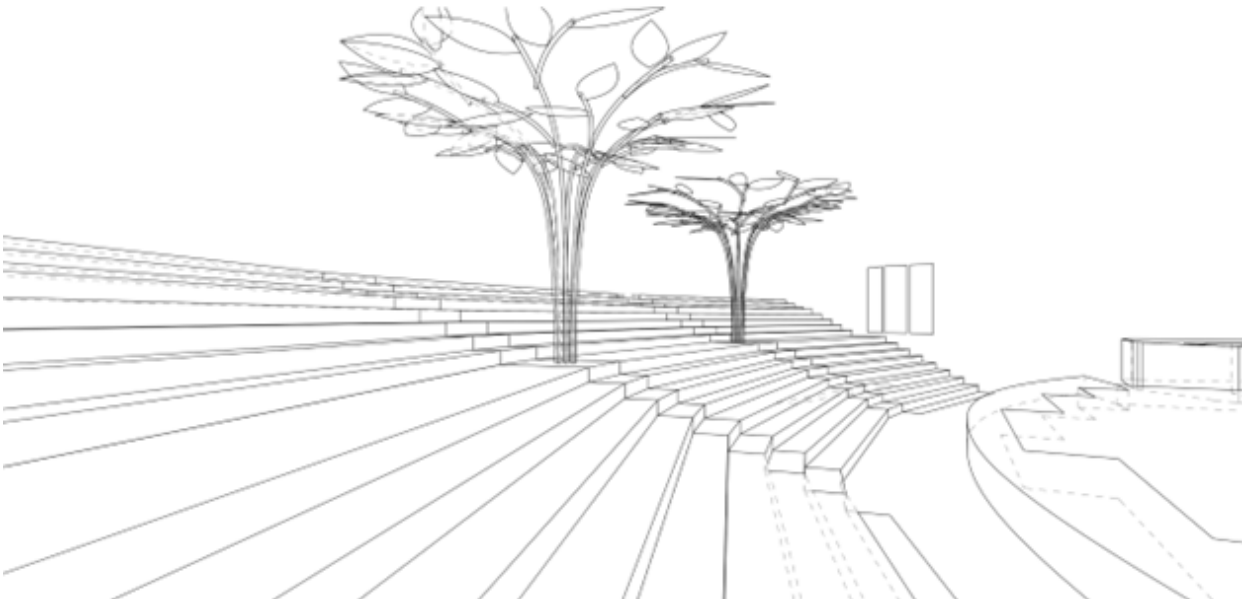


Figure 46: 3D view of iteration 2

5.5.2.2 Acoustic optimisation

The spatial performance of this iteration was very good. The structure sat entirely outside the sightlines of the audience, preserved the open character of the venue and integrated naturally with the forested context. The technical feasibility also improved: the tree-column structure offered a more architecturally refined approach to the challenge of suspending reflective surfaces above an audience area.

Acoustically, the iteration underperformed. The individual leaf panels were too small in surface area to redirect enough amounts of acoustic energy toward the audience. A reflective surface must exceed a minimum size relative to the target to function as an effective reflector. The leaf geometry, did not provide sufficient reflective area to produce a measurable improvement in SPL uniformity across the seating area. The plotted values of an optimisation is shown in figure 47.

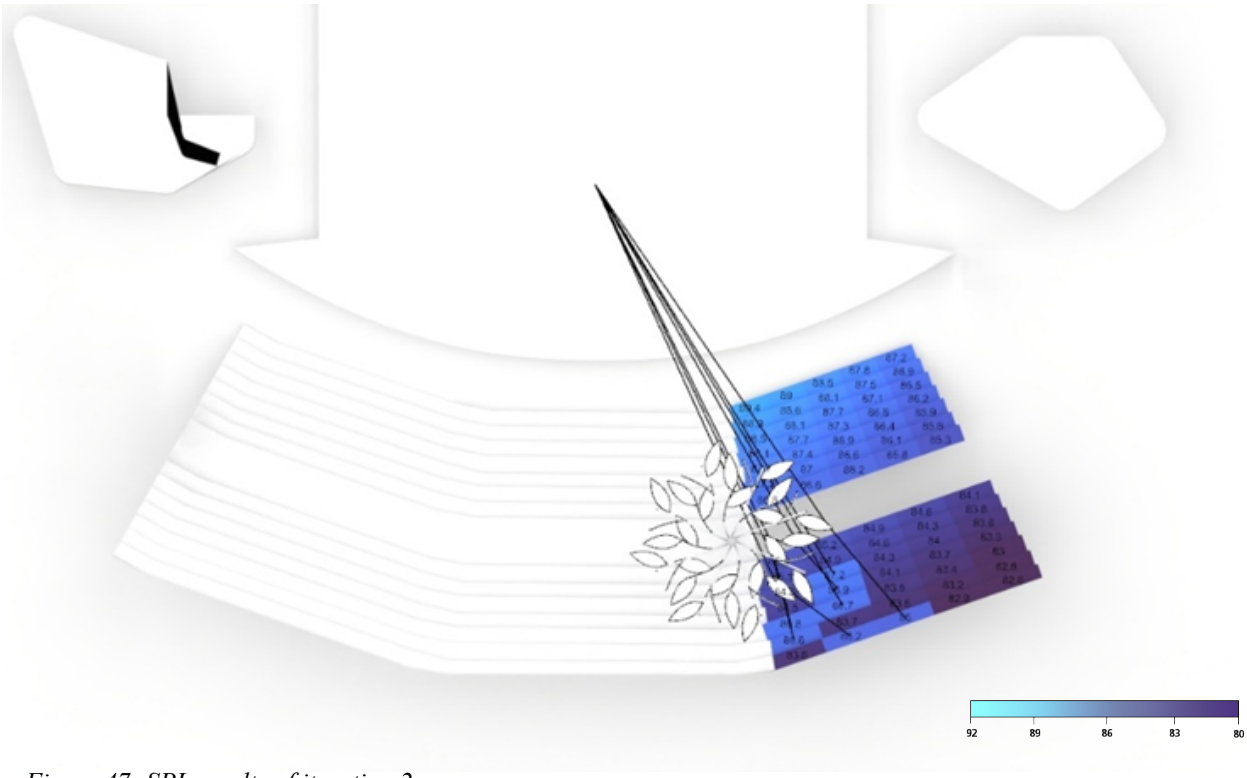


Figure 47: SPL results of iteration 2

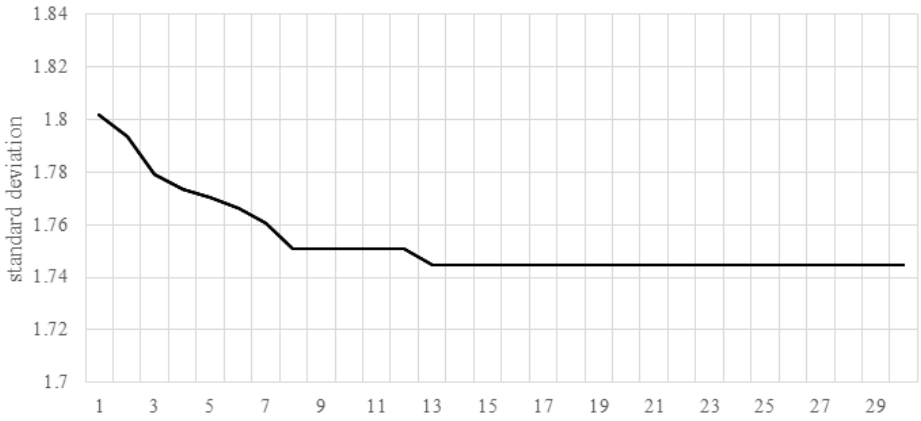


Figure 48: Optimisation graph of iteration 2.

5.5.2.3 Evaluation

Acoustic requirements				1
Criteria	**Insufficient (1)**	**Partial meets (2.5)**	**Meets requirements (4)**	**Score**
SPL uniformity	Standard deviation not meaningfully reduced relative to baseline. Rear and lateral zones remain strongly underserved. No clear improvement in SPL distribution visible in results plot.	Measurable reduction in std dev relative to baseline. Improvement visible in parts of the seating area but distribution remains uneven across all zones.	Clear reduction in std dev relative to baseline. Improvement is consistent across rear and lateral zones. Results plot shows a visibly more uniform SPL gradient across the full audience area.	1

Spatial requirements				3
Criteria	**Insufficient (1)**	**Partial meets (2)**	**Meets requirements (3)**	**Score**
Sightline integrity	Structure enters or blocks the sightlines of a significant portion of the audience. Audience members cannot see the stage unobstructed from one or more seating zones.	Structure marginally intrudes on sightlines for a small number of seats, or sits at the boundary of the sightline volume but does not cause full obstruction.	Structure clears all audience sightlines entirely. Every seat has an unobstructed view of the stage. Sightline bounding volume constraint is satisfied in the parametric model.	3
Preservation of openness	The structure encloses or strongly encloses the audience area. The sky is significantly obstructed. The sense of being in an open outdoor space is compromised.	Openness is partially maintained. Some zones feel enclosed or the sky view is noticeably reduced, but the space does not feel fully enclosed.	The audience area remains open. Sky is visible. The outdoor spatial character of the venue is preserved and the structure does not read as an enclosure.	3
Contextual integration	The structure reads as a purely technical apparatus with no visual connection to the forest context. Form and material are incompatible with the character of the venue.	Some formal or material connection to the setting. The structure is not entirely out of place but does not integrate naturally.	Form and material integrate with the setting. The structure is architecturally legible as part of the venue rather than a technical element. It does not compete with the stage for attention.	3
Technical requirements				2
Criteria	**Insufficient (1)**	**Partial meets (2)**	**Meets requirements (3)**	**Score**
Structural feasibility	The structural concept presents significant unresolved engineering challenges that are not addressed by the design.	The structural approach is plausible but includes one or more unresolved challenges. Engineering issues are identified but not fully resolved within the design.	The structural concept is sound and buildable. Column-mounted or otherwise self-supporting configuration. Wind load and installation challenges are addressed or do not present problems within the design logic.	3
Parametric compactness	The parametric model is poorly structured or not parametrised. Many redundant variables, or key geometric properties are fixed and cannot be adjusted by the optimizer.	The parametric setup is functional but not efficient. The design space is workable but larger than necessary, or some key parameters are missing or poorly defined.	All relevant geometric properties are exposed as a compact set of sliders. The optimizer has direct and meaningful control over the design with a minimum number of variables. The model can be recalibrated for other venues.	1

Principle of restraint	The design uses more material or structural complexity than the acoustic function requires. Elements are present that serve no acoustic or structural purpose.	Mostly restrained but includes some redundant elements, or material choices add visual weight without a clear acoustic or structural justification.	All material and geometric choices are minimal and purposeful. Nothing is present that does not serve acoustic or structural function. The intervention is as light as possible.	3
Total score				**6**

Table 4: Rubric score of iteration 2

With a total score of 6.0 out of 10, the second iteration matches the overall score of the first but represents an almost complete inversion of its strengths and weaknesses. Where iteration 1 failed spatially, iteration 2 achieves a perfect spatial score of 3 out of 3, confirming that the shift to a context-first design approach successfully resolved the sightline, openness and contextual integration problems that made the first iteration architecturally incompatible with the Bostheater. The tree-based formal language proved to be the right architectural direction for this venue and this design brief.

However, the acoustic score of 1 out of 4 reveals that spatial success came at the cost of acoustic performance. The individual leaf panels, while formally appropriate, were too small in surface area to redirect sufficient sound energy toward the audience. The optimization produced a standard deviation of 1.84 dB, identical to the unassisted baseline, meaning the reflectors contributed no measurable acoustic improvement at all. This is not a flaw in the concept but a consequence of a single parameter: panel size. The technical score of 2 out of 3 reflects the low parametric compactness of the design, with five sliders per branch and ten branches per tree, the optimizer had to navigate a parameter space of fifty variables, which is far larger than necessary for the acoustic task.

The clear lesson of this iteration is that the tree-based language is architecturally correct but acoustically undersized. Since the underperformance is attributable to a single fixable parameter rather than a conceptual flaw, the formal language can be carried forward. Scaling up the reflective surfaces within the same structural logic is the direct path toward a design that combines the spatial quality of iteration 2 with the acoustic effectiveness that iteration 1 approached but could not achieve within its spatial constraints. This is the starting point for the third and final iteration.

5.5.2 Iteration 3: final design

The third and final iteration combines the strengths of the first two designs. From the first iteration, it takes the acoustic logic: reflective surfaces must be large enough to capture and redirect large amounts of energy and low frequencies. Their position relative to the source is also very important for effectiveness. From the second iteration, it retains the spatial language: the tree structure, the leaf geometry and the contextual integration with the forest setting of the Bostheater.

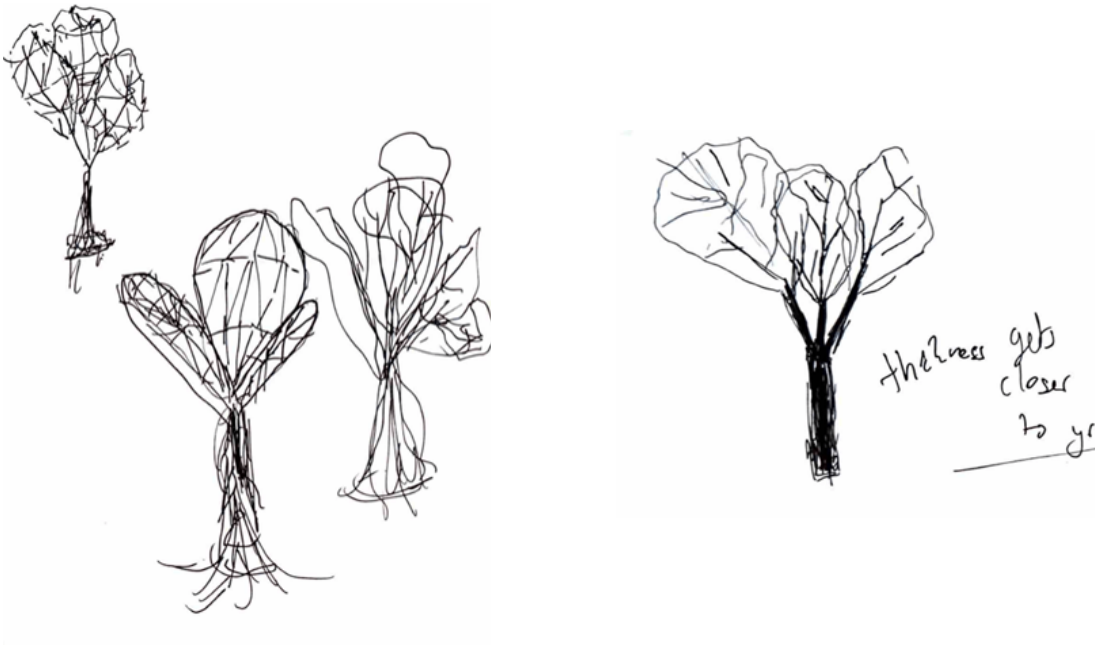
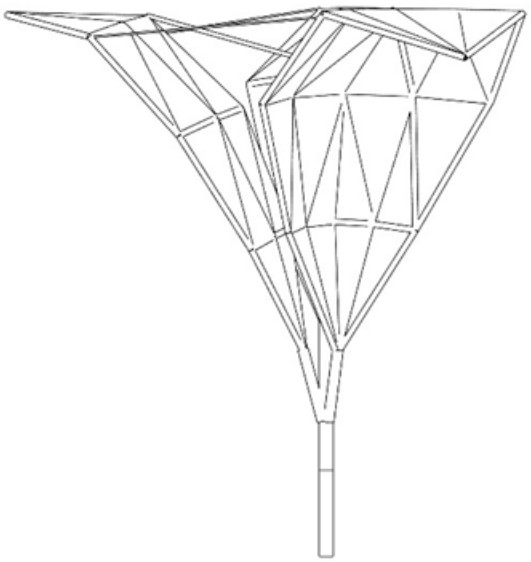


Figure 49: Concept sketches of iteration 3.

The central element of the design is a large overhead reflector structured as a tree, in which the “leaves” are scaled up relative to the second iteration. The enlarged panels provide the reflective surface area necessary for redirection of acoustic energy across the full audience area. The triangulated panels, visible in figure 51, allow the surface to be divided into individually adjustable surfaces. This divided approach allows the optimization algorithm to modulate the angle of each panel, giving the system a high degree of acoustic controllability within a single form.

The lateral reflectors consist of smaller tree structures positioned along the side aisles of the seating area, each carrying a single large leaf panel-oriented inward. These address the lateral decay problem identified in the first iteration: sound energy escaping sideways beyond the audience boundary is intercepted and redirected back into the lower-SPL edge zones. Together, the central rear tree and the lateral side trees recreate the acoustic function of a back wall and side walls without enclosing the space or compromising its open character.



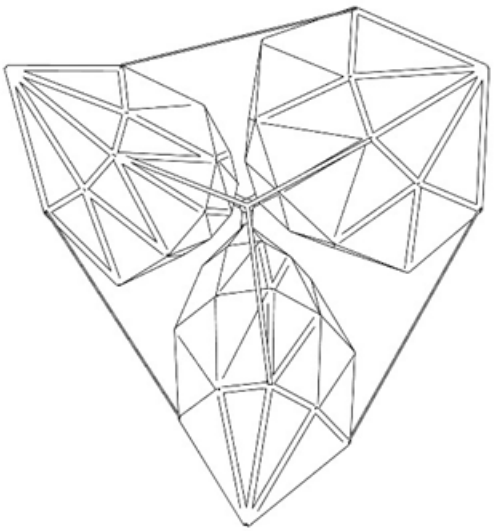


Figure 50: Top and side view of iteration 3.

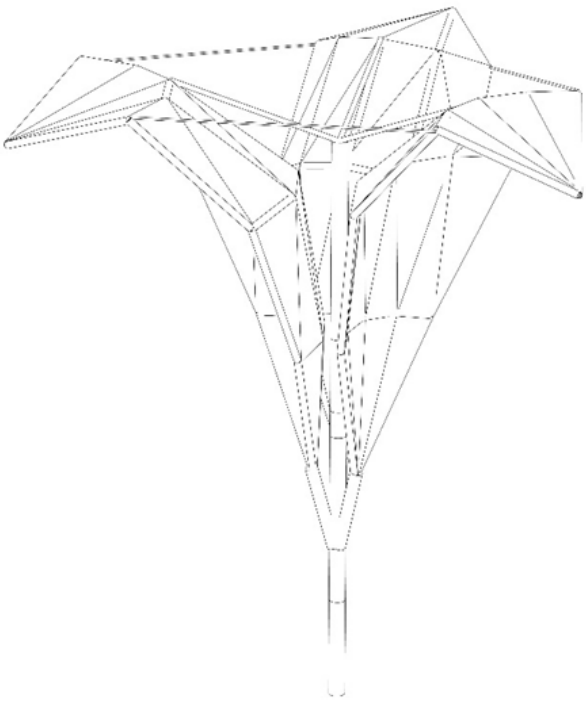
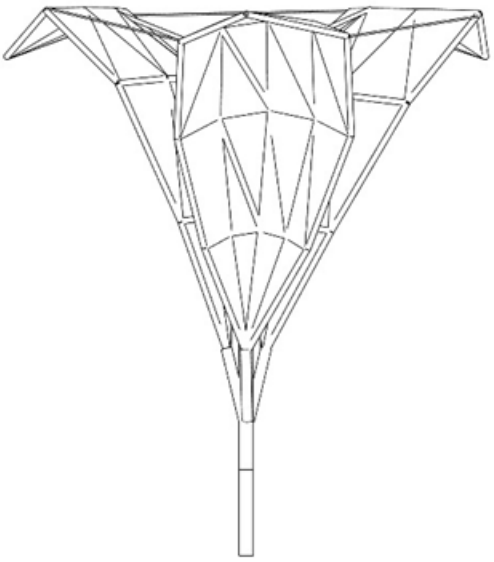


Figure 51: 3d view of iteration 3.



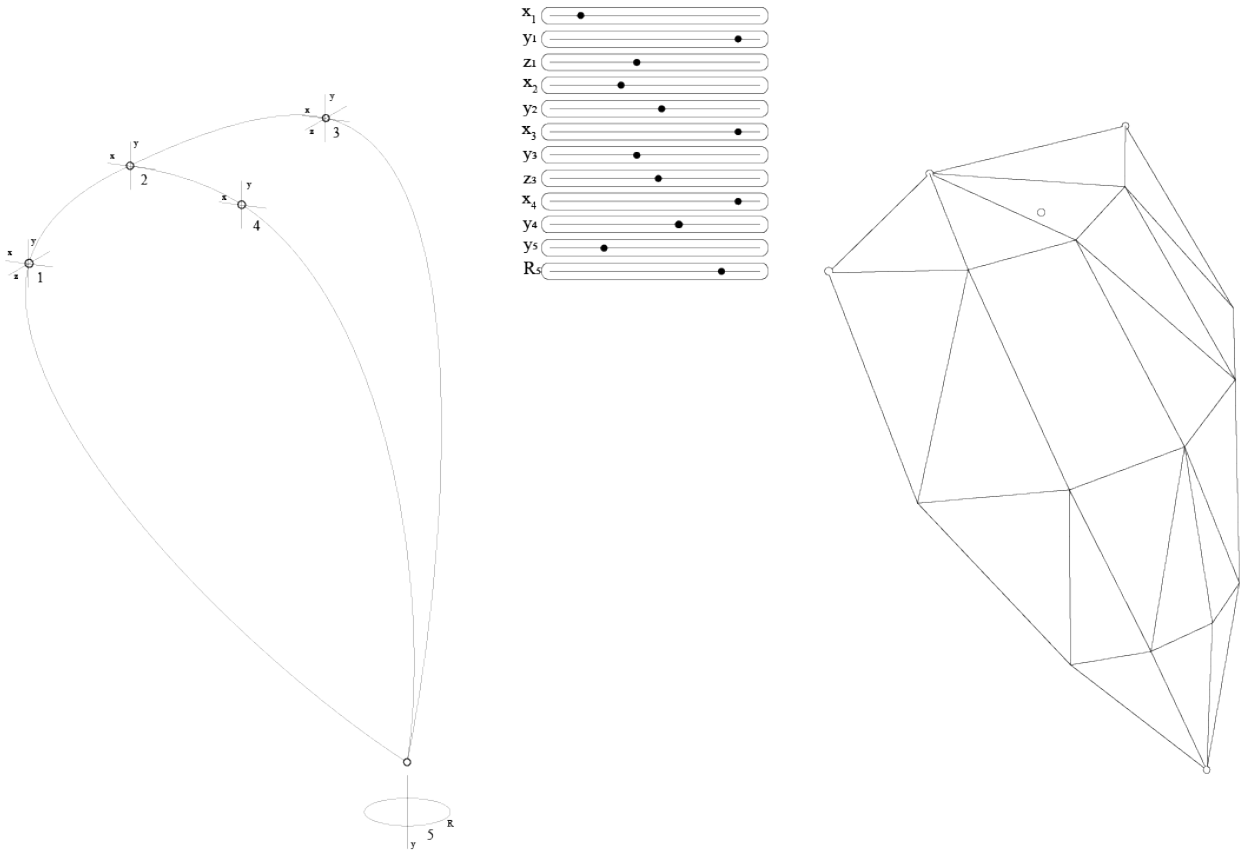


Figure 52: Grasshopper visualisation of iteration 3.

The parametric model shown in figure 52 is built around five numbered control points that define the profile curve of the reflective surface. Point 5, located at the base of the structure, is fixed in position and serves as the starting point from which the entire geometry is built. It is constrained to rotate only around the vertical axis (R), which allows the full canopy to be reoriented within the theater without altering its form. Points 2 and 4, which form the inner curve of the profile are each assigned x and y sliders, restricting their movement to the horizontal plane. This keeps the lower portion of the canopy at a controlled height while allowing the optimizer to adjust its curvature. Points 1, 2 and 3 at the outer part of the profile are each given full freedom in x, y and, giving the optimizer control over the outer reach of the total reflector, the region of the surface that has the greatest influence on the direction of reflected energy across the audience.

From the five control points, three profile curves are constructed and lofted into a surface. This surface is then converted into a planar triangulated mesh, visible on the right side of figure 52. The planarity of each mesh face is a technical requirement of the Aeolus acoustic simulation plugin. The triangulation allows each part of the leaf to function as an angled reflector.

5.5.3.1 Single source objective optimisation

Over the course of 33 generations, the optimisation converged from an initial SPL standard deviation of 1.84 dB to a final value of 1.25 dB. The final standard deviation of 1.25 dB represents a reduction of approximately 0.60 dB relative to the unassisted baseline condition. This is on par with the first iteration.

The single-source result establishes a validated baseline for the computational workflow and confirms that the parametric setup, simulation environment, and optimization algorithm are functioning as intended. However, the reliance on a single source position introduces a limitation: a geometry optimised purely for the central source may not perform optimally when the sound originates from off-axis positions, as is typical in theatrical practice where performers move across the full stage width. This motivated the extension of the optimisation to a multi-source objective, in which the central and lateral source positions are evaluated simultaneously and the optimizer is required to find a geometry that performs well across all three conditions at once.

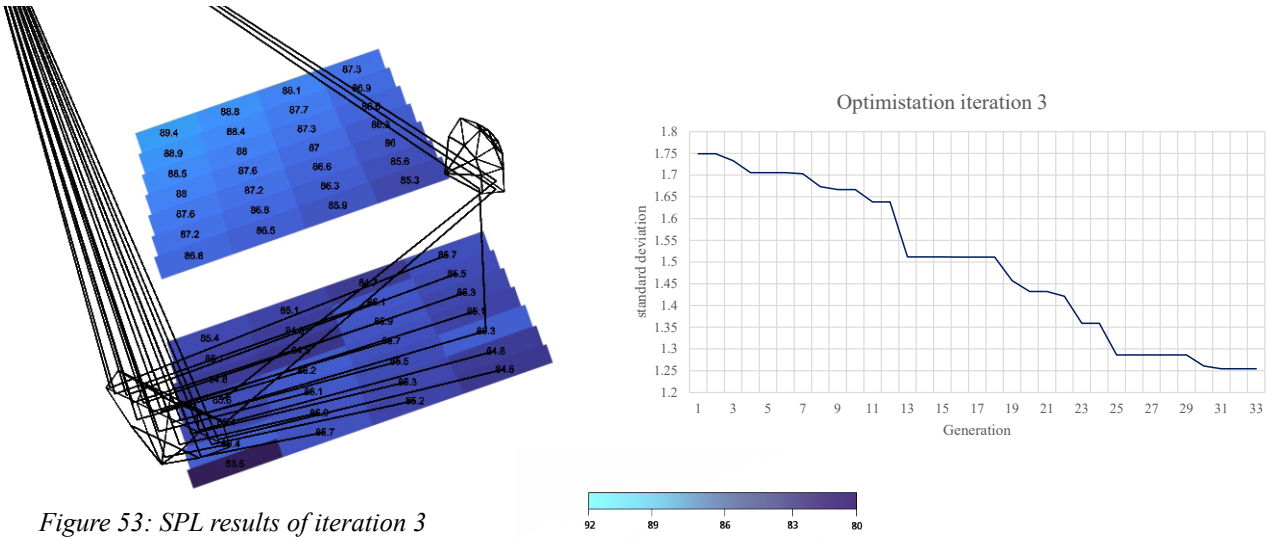


Figure 53: SPL results of iteration 3

5.5.3.2 Multi source objective optimisation

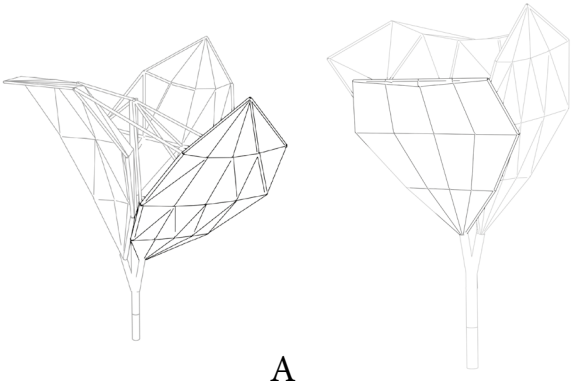
The lateral reflectors are optimized independently of the central overhead canopy, in a first stage of the sequential optimization process. This stage uses Octopus with three simultaneous fitness objectives: the standard deviation of SPL across the audience area for each of the three source positions used in the multi-source analysis. By minimizing all three simultaneously, the optimizer searches for a reflector geometry that produces consistent acoustic improvement regardless of where on the stage the sound source is located.

Before optimization, the baseline standard deviations for the three sources, measured without any reflectors, were 1.845 dB for the central source, 1.563 dB for the left source and 2.149 dB for the right source. These figures are visible in Figures 42 - 44, which show the SPL distribution across the audience grid for each source position. The gradient running from lighter values near the stage to progressively darker values toward the back and sides of the seating area shows the SPL decay problem that the reflectors are designed to correct energy is escaping outward beyond the audience boundary while the rear rows receive insufficient reflected energy.

The Octopus optimizer ran for 30 generations. The convergence graphs in Figure 42 show a consistent downward trend in standard deviation for all three sources, which shows that the algorithm found improvements in the full objective space without trading off one source position against another. The Pareto front plot at generation 30 shows three candidate solutions labelled A, B and C, each representing a different balance between the three objectives.

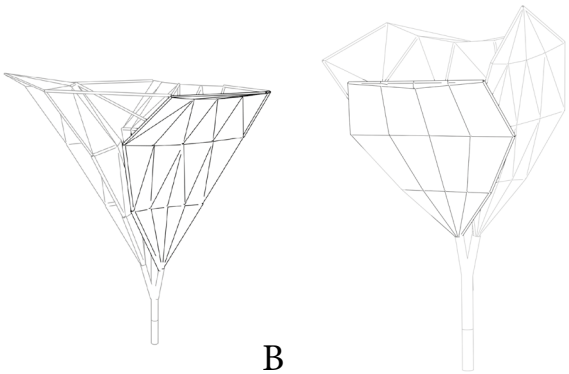
Option B was selected as the basis for the final design. While solution A produces slightly better overall uniformity for source 3, solution B achieves the best performance for the central source position, the primary performance scenario at the Bostheater and the largest absolute improvement for the left source. Solution C was rejected because despite its strong result for source 2, it underperforms for source 1 relative to both A and B, making it less robust across the full range of performance scenarios.

Figures 45 - 47 compare the SPL distribution of the baseline condition against the optimized configuration with solution B’s reflectors in place. The plots show an improvement in the uniformity of the colour gradient across the audience grid: the darker zones at the side edges and rear rows of the seating area are partially filled in, which indicate that reflected energy is being redirected into the low-SPL zones as intended. The reflector geometry itself is a single large panel mounted on a tree-column structure positioned along the side aisle, oriented inward toward the audience at an angle determined by the optimizer to maximize the energy redirection without compromising sightlines.



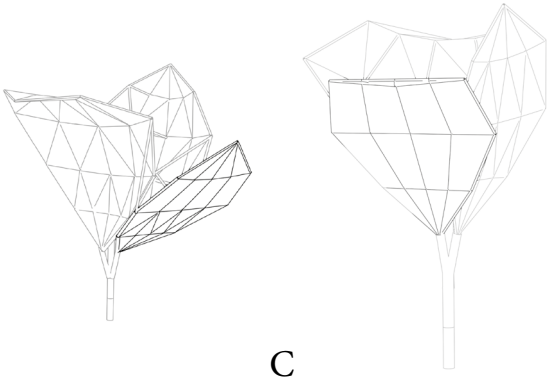
A

S1: 1.362043
S2: 1.343631
S3: 1.701595



B

S1: 1.300425
S2: 1.199824
S3: 1.856736



C

S1: 1.450088
S2: 1.169279
S3: 1.818424

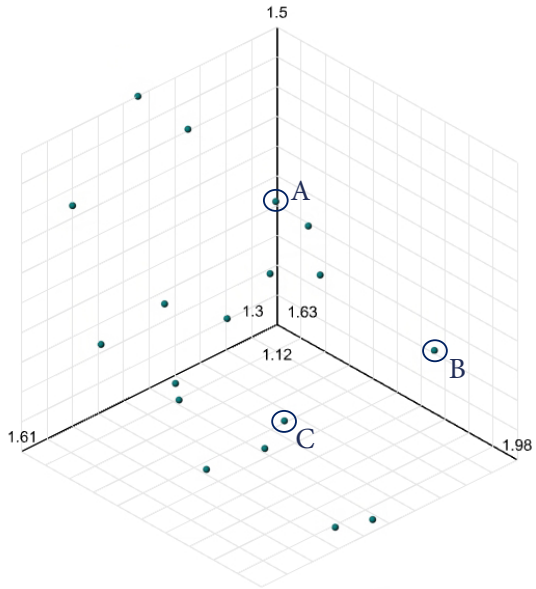


Figure 54: Pareto front graph of generation 30

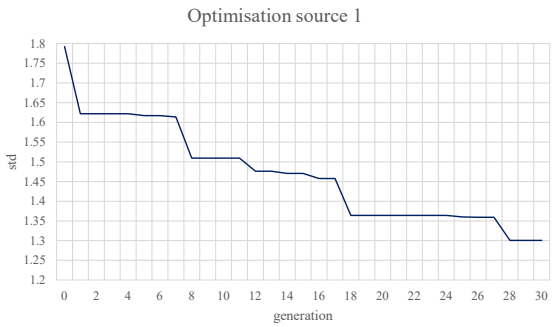


Figure 55: Algorithmic optimisation graph per generation for source 1

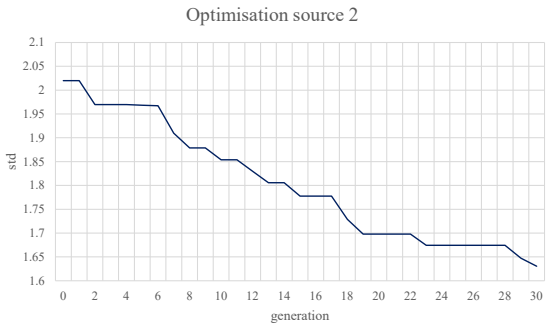


Figure 56: Algorithmic optimisation graph per generation for source 2

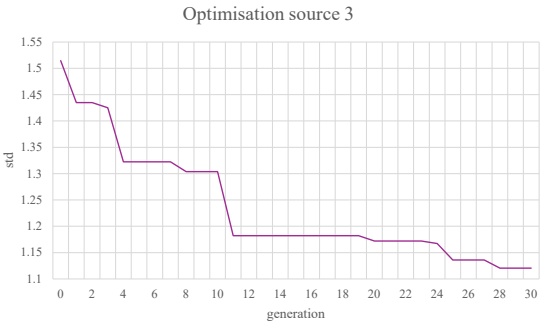


Figure 57: Algorithmic optimisation graph per generation for source 3

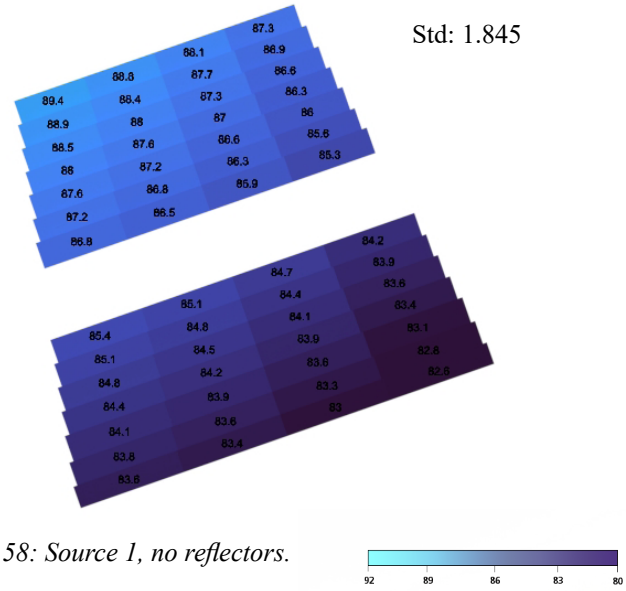


Figure 58: Source 1, no reflectors.

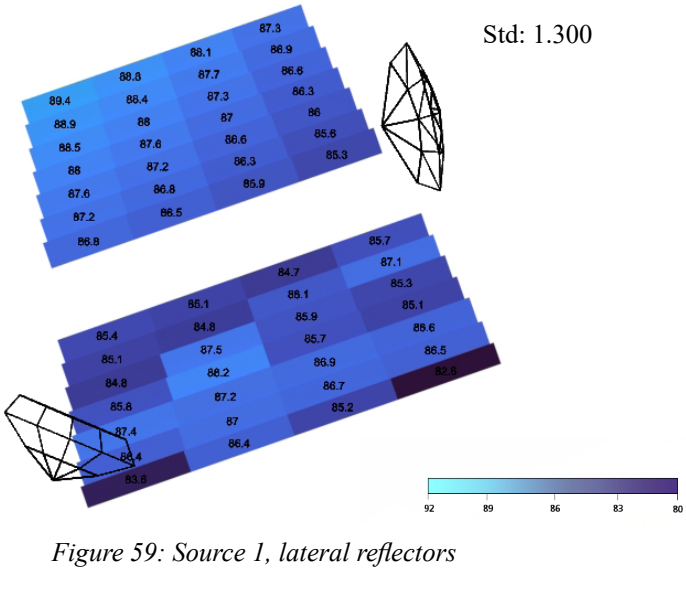


Figure 59: Source 1, lateral reflectors

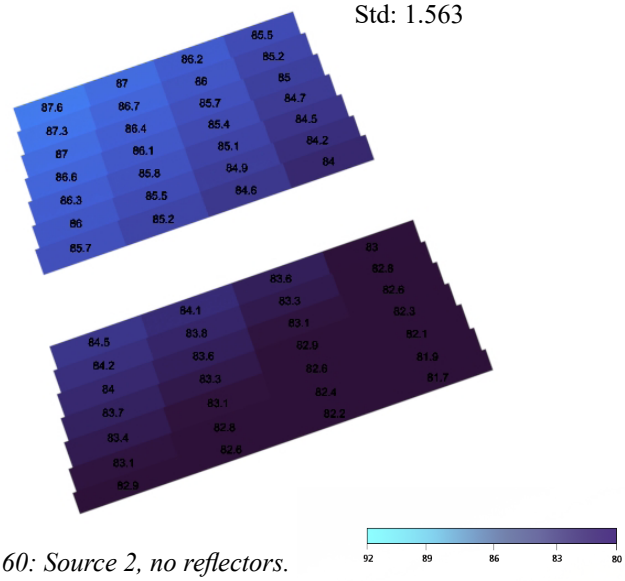


Figure 60: Source 2, no reflectors.

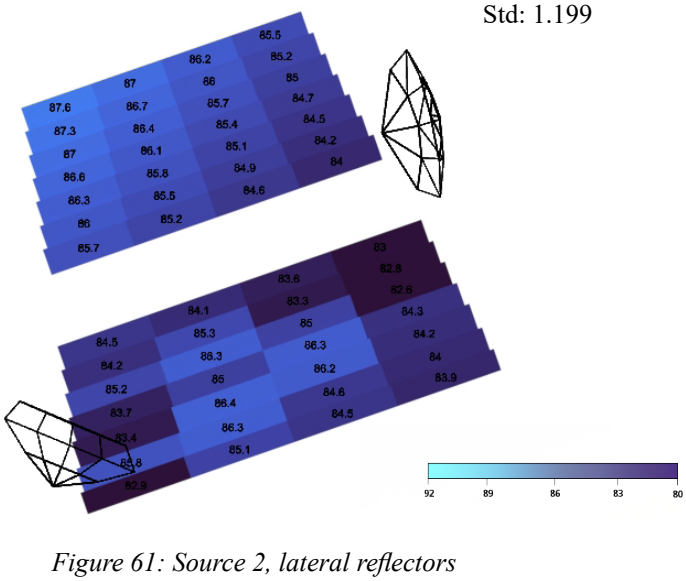


Figure 61: Source 2, lateral reflectors

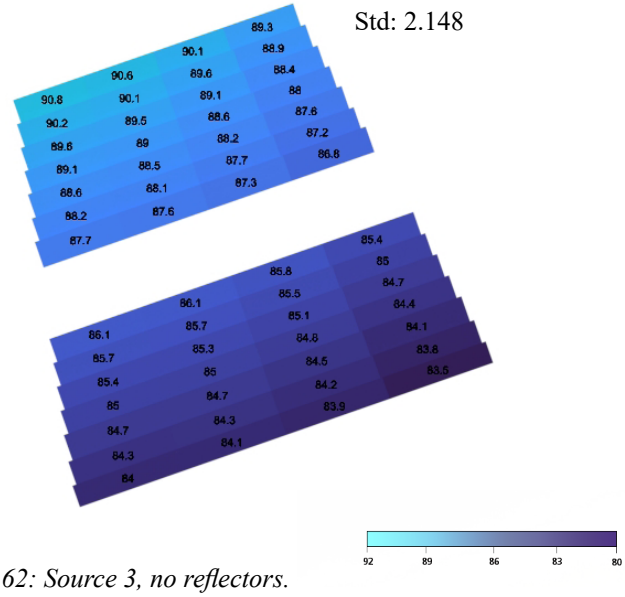


Figure 62: Source 3, no reflectors.

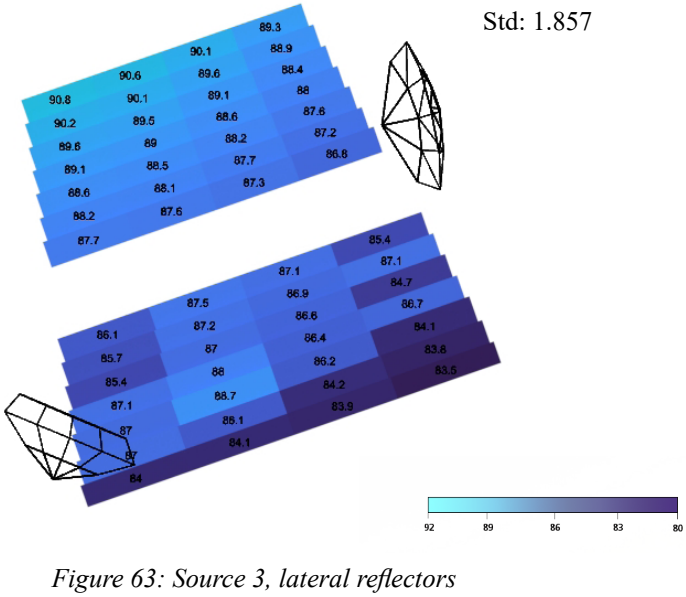


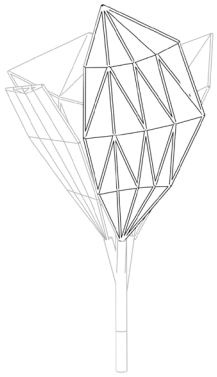
Figure 63: Source 3, lateral reflectors

With the lateral reflector geometry fixed from the first stage, the central canopy is optimized independently using only the central audience block as the evaluation zone. The baseline standard deviations for this stage, measured without any reflectors present, are 2.190 dB for the central source, 2.120 dB for the left source and 2.118 dB for the right source. These figures reflect the SPL non-uniformity across the central seating section alone, where the front-to-rear decay is most pronounced. The left and right source positions produce a slightly asymmetric distribution within the block, but the magnitude of the decay is consistent across all three.

The same three-objective Octopus setup is used as in the lateral stage, minimizing the SPL standard deviation of the central block simultaneously across all three source positions. Because the left and right sources produce a symmetrical response within the bilaterally symmetric theater, their standard deviations enter the optimization as almost similar objectives, though both are included independently since the reflector's interaction with one source can affect the reflected field of the other. The convergence graphs in figure 48 show a consistent reduction in standard deviation across all three sources over 30 generations, with the largest improvements occurring in the first ten generations as the algorithm moves away from the initial geometry.

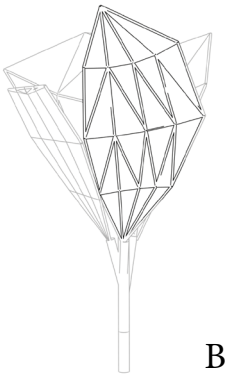
At generation 30, the Pareto front shows three candidate solutions labelled A, B and C. Option A was selected as the basis for the final design. Its result for source 1 is the best of the three options and its source 2 and source 3 results, while not the lowest individually, remain a meaningful improvement over the baseline. The figure indicates that options A, B and C produced geometries that look visually similar to one another. This is most likely due to the fact that this geometry is the best geometry for this situation, and with small change of parameters, the std of each source will change substantially.

Once the reflector geometry of option A is fixed, its acoustic effect is evaluated in combination with the optimized lateral reflectors from the first stage. Figures 49, 51 and 52 show the full theater SPL distribution for all three source positions with both the lateral and central reflectors used. The wireframe overlays confirm the combined configuration: the two lateral tree structures positioned at the side aisles and the middle reflector above the front of the audience area. The improvement relative to the no-reflector baseline is visible across the full seating layout: the side blocks, maintain their improved uniformity, while the central block shows a clear reduction in the front-to-rear gradient that was seen in the baseline condition. The back rows of the central section receive higher SPL values in the combined configuration, confirming that the middle reflector is successfully redirecting energy toward the area of greatest decay.



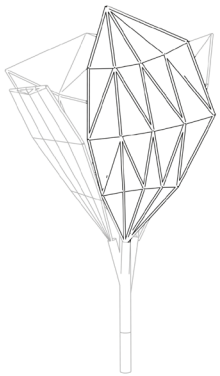
A

S1: 1.494526
S2: 1.798342
S3: 1.813652



B

S1: 1.703675
S2: 1.842443
S3: 1.821324



C

S1: 1.726626
S2: 1.724352
S3: 1.733453

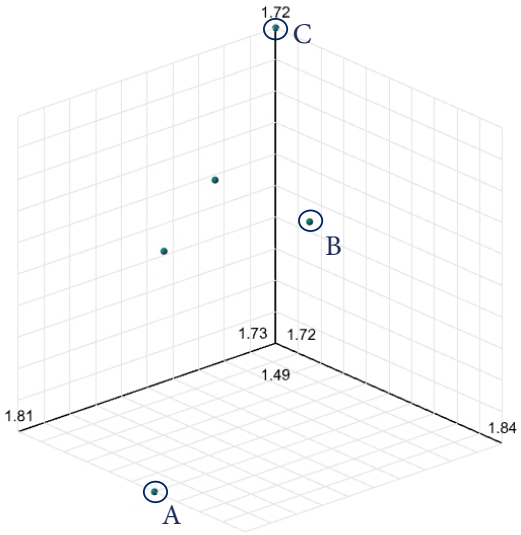


Figure 64: Pareto front graph of generation 30

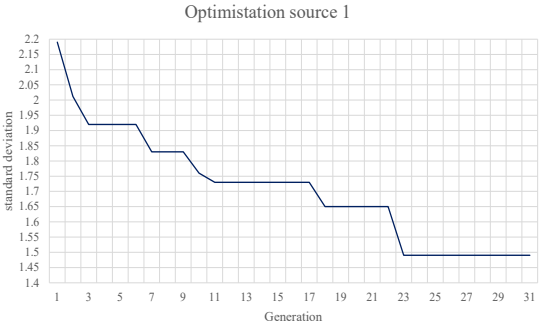


Figure 65: Algorithmic optimisation graph per generation for source 1

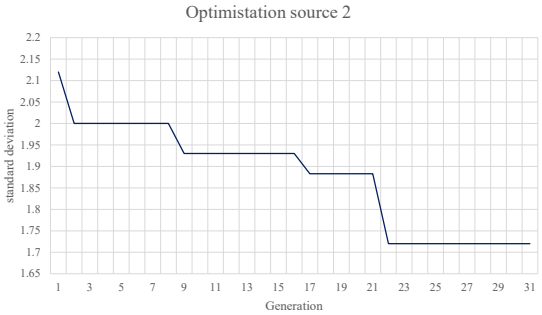


Figure 66: Algorithmic optimisation graph per generation for source 2

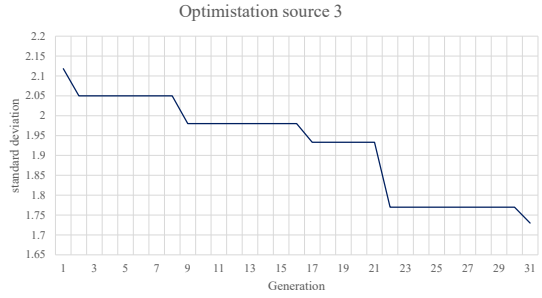


Figure 67: Algorithmic optimisation graph per generation for source 3

Std: 2.191

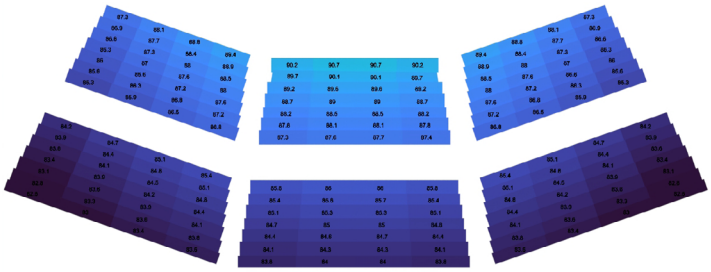
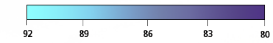


Figure 68: Source 1, no reflectors.



Std: 1.441

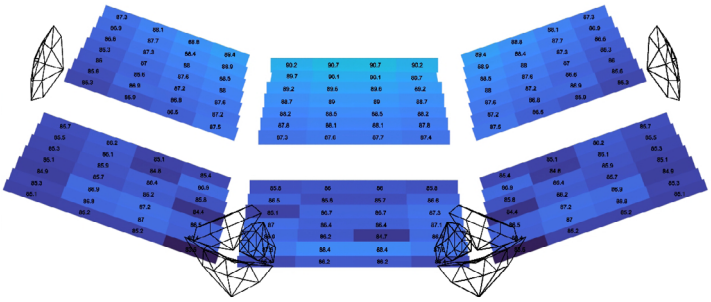
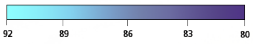


Figure 69: Source 1, lateral reflectors



Std: 2.120

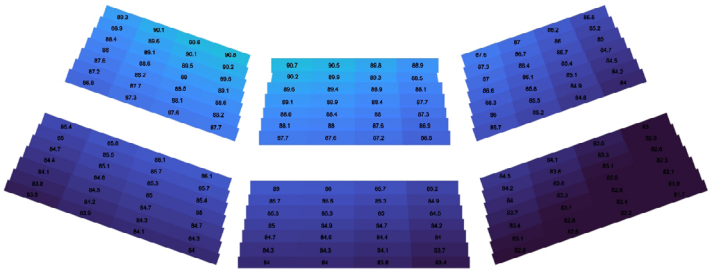
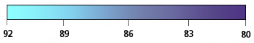


Figure 70: Source 2, no reflectors.



Std: 1.907

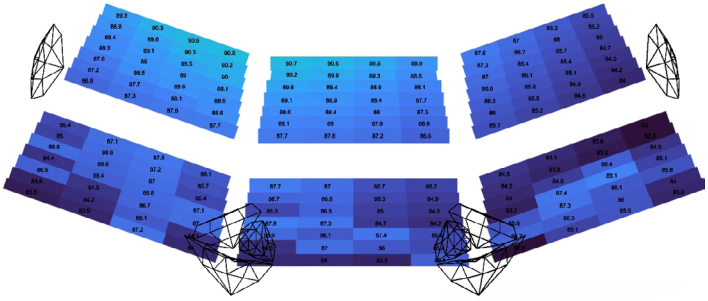
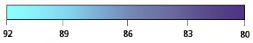


Figure 71: Source 2, lateral reflectors



Std: 2.118

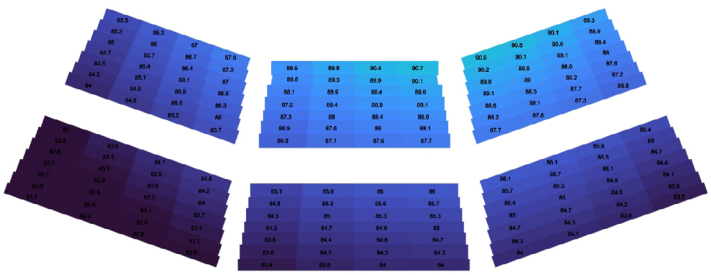
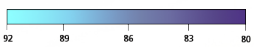


Figure 72: Source 3, no reflectors.



Std: 1.904

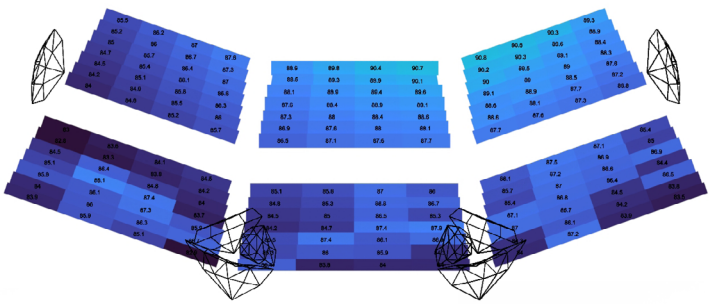
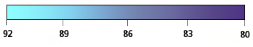


Figure 73: Source 3, lateral reflectors



5.5.3.2 Evaluation

Acoustic requirements				2.5
Criteria	**Insufficient (1)**	**Partial meets (2.5)**	**Meets requirements (4)**	**Score**
SPL uniformity	Standard deviation not meaningfully reduced relative to baseline. Rear and lateral zones remain strongly underserved. No clear improvement in SPL distribution visible in results plot.	Measurable reduction in std dev relative to baseline. Improvement visible in parts of the seating area but distribution remains uneven across all zones.	Clear reduction in std dev relative to baseline. Improvement is consistent across rear and lateral zones. Results plot shows a visibly more uniform SPL gradient across the full audience area.	2.5
Spatial requirements				3
Criteria	**Insufficient (1)**	**Partial meets (2)**	**Meets requirements (3)**	**Score**
Sightline integrity	Structure enters or blocks the sightlines of a significant portion of the audience. Audience members cannot see the stage unobstructed from one or more seating zones.	Structure marginally intrudes on sightlines for a small number of seats, or sits at the boundary of the sightline volume but does not cause full obstruction.	Structure clears all audience sightlines entirely. Every seat has an unobstructed view of the stage. Sightline bounding volume constraint is satisfied in the parametric model.	3
Preservation of openness	The structure encloses or strongly encloses the audience area. The sky is significantly obstructed. The sense of being in an open outdoor space is compromised.	Openness is partially maintained. Some zones feel enclosed or the sky view is noticeably reduced, but the space does not feel fully enclosed.	The audience area remains open. Sky is visible. The outdoor spatial character of the venue is preserved and the structure does not read as an enclosure.	3
Contextual integration	The structure reads as a purely technical apparatus with no visual connection to the forest context. Form and material are incompatible with the character of the venue.	Some formal or material connection to the setting. The structure is not entirely out of place but does not integrate naturally.	Form and material integrate with the setting. The structure is architecturally legible as part of the venue rather than a technical element. It does not compete with the stage for attention.	3
Technical requirements				3
Criteria	**Insufficient (1)**	**Partial meets (2)**	**Meets requirements (3)**	**Score**
Structural feasibility	The structural concept presents significant unresolved engineering challenges that are not addressed by the design.	The structural approach is plausible but includes one or more unresolved challenges. Engineering issues are identified but not fully resolved within the design.	The structural concept is sound and buildable. Column-mounted or otherwise self-supporting configuration. Wind load and installation challenges are addressed or do not present problems within the design logic.	3

Parametric compactness	The parametric model is poorly structured or not parametrised. Many redundant variables, or key geometric properties are fixed and cannot be adjusted by the optimizer.	The parametric setup is functional but not efficient. The design space is workable but larger than necessary, or some key parameters are missing or poorly defined.	All relevant geometric properties are exposed as a compact set of sliders. The optimizer has direct and meaningful control over the design with a minimum number of variables. The model can be recalibrated for other venues.	3
Principle of restraint	The design uses more material or structural complexity than the acoustic function requires. Elements are present that serve no acoustic or structural purpose.	Mostly restrained but includes some redundant elements, or material choices add visual weight without a clear acoustic or structural justification.	All material and geometric choices are minimal and purposeful. Nothing is present that does not serve acoustic or structural function. The intervention is as light as possible.	3
Total score				**8.5**

Table 5: Rubric score of iteration 3

With a total score of 8.5 out of 10, the third iteration represents a clear step forward from both previous designs. For the first time, all three pillars score at or above the midpoint simultaneously, confirming that the synthesis of acoustic logic from iteration 1 and spatial language from iteration 2 produced a design that is coherent across all evaluation criteria.

The perfect spatial and technical scores of 3 out of 3 reflect that the lessons of the first two iterations were fully absorbed. The tree-column structure and enlarged panel geometry clear all audience sightlines, preserve the open character of the venue and integrate naturally with the forested setting of the Bostheater. The parametric setup is the most efficient of the three iterations, with the five-point profile curve of the central canopy giving the optimizer a compact and expressive design space and the sequential two-stage optimization strategy reducing the complexity of the search.

The acoustic score of 2.5 out of 4 reflects a design that achieves meaningful and consistent improvement across all three source positions but does not fully resolve the off-axis decay problem. The central source result, a reduction in standard deviation from 1.845 to 1.300 dB, is the strongest acoustic result of the three iterations. The lateral sources show a clear improvement but remain less uniform, a limitation that is accepted as a characteristic of a single reflector system operating across multiple source positions rather than a flaw in the design concept itself

The progression from 6.2 to 6.0 to 8.5 across the three iterations illustrates the research through design process at work. Each iteration identified a specific shortcoming that directly motivated the next design decision, culminating in a final design that satisfies the spatial and technical requirements fully while delivering a measurable and consistent acoustic improvement across the audience area.

5.5.4 Final design visualisation

5.5.4.1 Materialisation

The reflector panels are fabricated from matte glass. Glass was selected as the panel material based on four criteria that are each very important for an outdoor installation: lifespan, UV resistance, scratch resistance and weight. Unlike polymer alternatives such as acrylic or polycarbonate, which will turn yellow and lose surface clarity under prolonged UV exposure, glass retains its optical and acoustic properties without surface treatment or needing replacement. Its scratch resistance makes sure that the panel surfaces remain geometrically consistent over time The weight of glass, while greater than polymer panels, is manageable within the structural logic of the design and contributes to the stability of the canopy under wind loading, reducing the risk of panel vibration and the acoustic consequences that would follow.

The matte finish on the glass panels serves a visual purpose. The matte finish eliminates the mirror-like reflections that clear glass would produce at certain sun angles, preventing the panels from becoming a source of glare or visual distraction for audience members. The structure remains legible as a designed object in the landscape without competing with the stage for the audience's attention.

The structural frame is constructed from stainless steel hollow sections. Stainless steel was chosen for its corrosion resistance in an outdoor environment subject to rain, humidity and temperature cycling across seasons. The profile of the hollow sections is important to the visual character of the design: the frame reads as a light skeleton rather than a heavy structural presence, which allows the glass panels to stand out of the visual appearance of the reflector. The column base rises from a foundation and branches up through a steel skeleton that distributes the load out towards the sides of the reflector, whichs follows the structural logic of a tree.

The connection between the steel frame and the glass panels is realized through point fixings at the panel corners. This detail keeps the framing lines clean and unobstructed, maintaining the clarity of the geometric language across the full surface of the reflector. It also allows the individual panels to be replaced if that is required.

A light source is positioned at the centre of the reflector structure, at the branching point of the steel frame. During daytime performances and events, the structure functions only as a passive acoustic structure. After dark, the integrated lighting adds a new dimension: the matte glass panels distribute light outward and downward across the audience area, casting am ambient glow that is coming from the geometry of the panels. The same faceting that redirects sound during a performance redirects light in the evening, making the structure a spatial and atmospheric landmark within the venue rather than an object that disappears into the background once its acoustic function is no longer the primary concern.

all three simultaneously, the optimizer searches for a reflector geometry that produces consistent acoustic improvement regardless of where on the stage the sound source is located.

5.5.4.2 Visualisations of the final design



Figure 74: Render at night (made with AI assist)

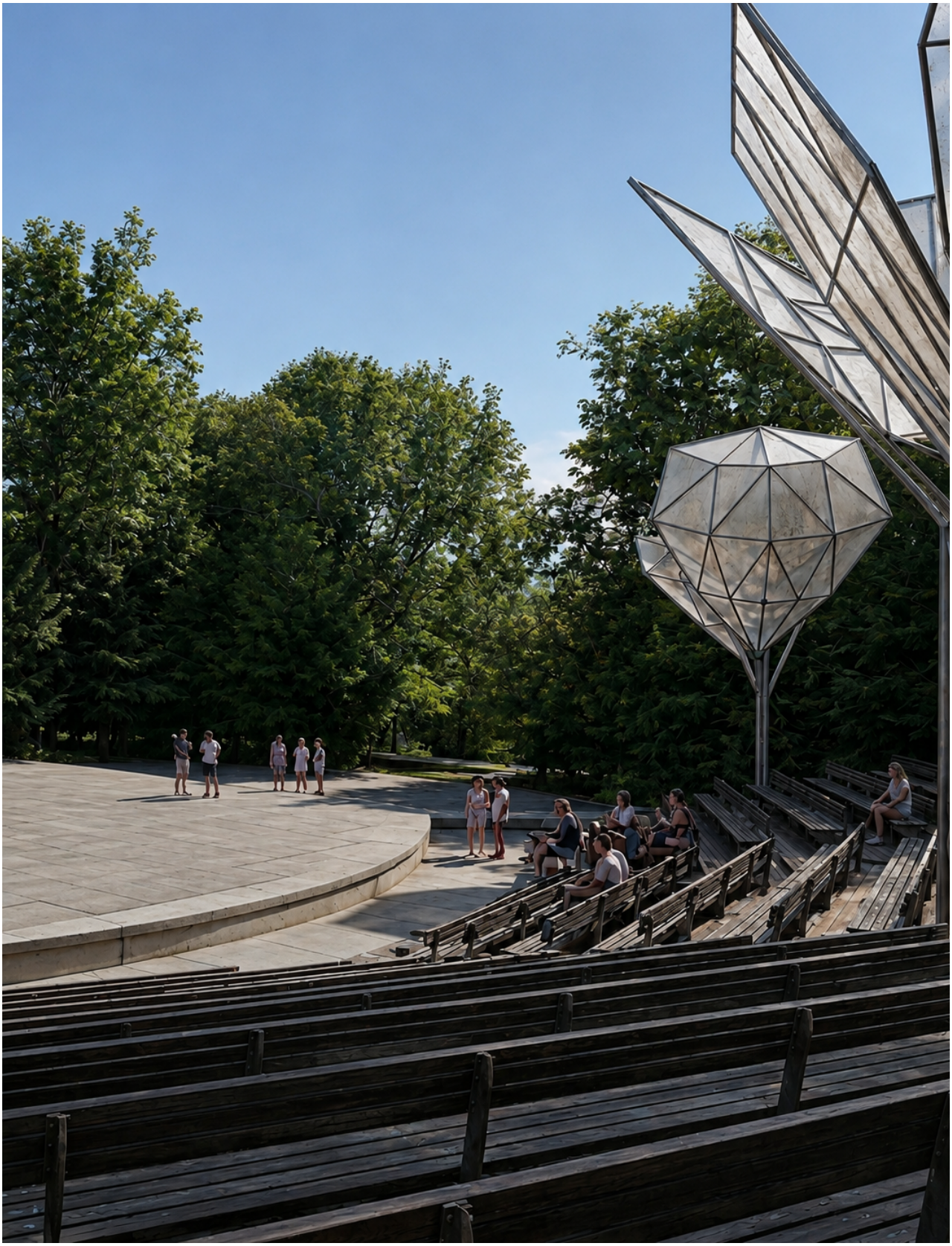


Figure 75: Render by day (made with AI assist)

6. CATT Simulation

The optimization workflow developed in chapter X runs on Aeolus, which is a ray-tracing plugin for Grasshopper, to evaluate acoustic performance during the generative design process. Aeolus is good for the demands of iterative optimization, it operates under a number of simplifications that limit its accuracy as a validation tool. To establish a more reliable simulation of the final reflector design, the optimized geometry was also simulated in CATT-Acoustic. This chapter describes the CATT model setup and presents the simulation results for both the baseline and reflector conditions across two source positions and two audience configurations.

6.1 Model Setup

6.1.1 Geometry

The CATT model is built from the Rhino geometry of the Amsterdamse Bostheater developed in chapter 4. The stage, tribunes and ground plane were exported as surfaces and imported into CATT-Acoustic using the dxf2geo-tool. The reflector geometry, the optimized tree structures from iteration 3, were introduced as an additional layer, which allowed simulations to be run with and without the reflectors used by turning this layer on or off. Around the geometry of the Amsterdamse Bostheater and the reflectors, a large box was modelled, to simulate the outdoor environment. The box was made so large that the rays which are reflected from the inside of the box will not have impact the receiver points. The box was also given a material which was fully absorbent. In figure 67, the CATT model is shown.

6.1.2 Material absorption

Different absorption coefficients were assigned to each surface category in the model. The stage platform was modelled as a hard concrete surface with low absorption across all frequencies. The reflector surfaces also assigned coefficients with a low absorption coefficient. The enclosing box was assigned a uniform absorption coefficient of 0.99 across all octave bands. An overview of the absorption coefficients of the model used per surface category is provided in table 2.

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Podium, circulation space	0.1	0.1	0.1	0.1	0.1	0.1
Surrounding box	0.99	0.99	0.99	0.99	0.99	0.99
Reflector	0.01	0.01	0.01	0.01	0.01	0.01

Table 6: Absorbtion coefficients used in CATT model

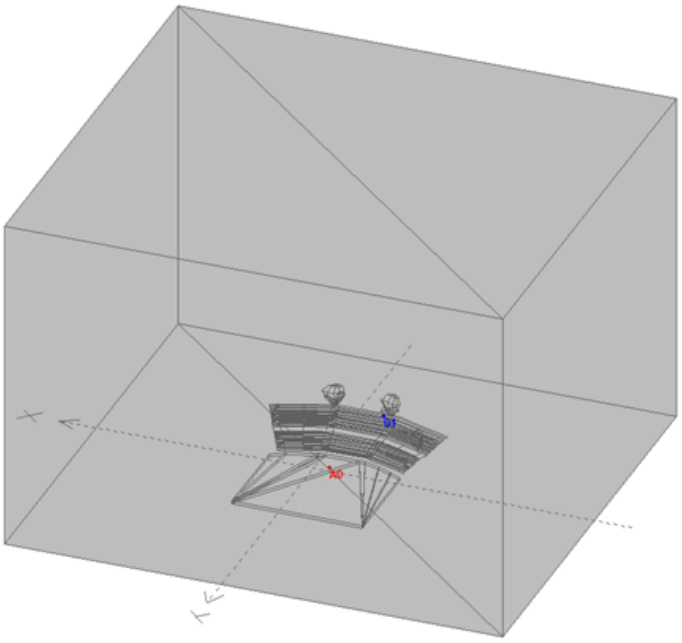


Figure 76: 3D view of the CATT model.

6.1.3 Audience absorption

Two simulation configurations were evaluated for each scenario: one without an audience present and one with a full audience occupying the seating area. The presence of an audience has a significant effect on the acoustic behaviour of an outdoor venue. As established by Beranek (1960) and discussed in the literature review, a seated audience functions as a large absorptive surface rather than as a collection of individual absorbers. Its absorbing power scales with the floor area it occupies and remains broadly consistent regardless of seating density within a normal range. These coefficients were assigned to both the horizontal and vertical planes in the audience area. In figure 68, these planes are shown. The absorption coefficient which was used for the audience area is shown in table X.

The effect of the audience is not straight forward in an outdoor context. Unlike in closed rooms where audience absorption reduces reverberation time, the biggest effect outdoors is a reduction in ground reflection from the seating area itself. The audience plane suppresses the reflection that the ground surface would otherwise have, which reduces the average SPL across the receiver grid while tending to increase the standard deviation.

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Audience	0.5	0.7	0.85	0.95	0.95	0.85

Table 7: Audience absorbtion coefficient used in CATT model

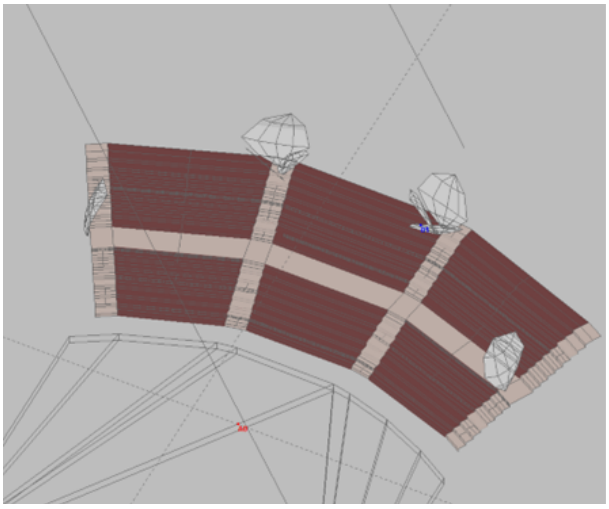


Figure 77: Audience planes in the catt model.

6.1.4 Source and receiver Configuration

Two source positions were used: source 1, positioned at the centre of the stage and source 2, positioned to the left from the stage. Both sources were modelled as omnidirectional point sources at stage height. The receiver grid covered the full seating area of the Bostheater at a uniform spacing, with receiver points positioned at seated ear height. A total of 250,000 rays were used for each simulation run, a quantity established during calibration as sufficient to produce stable SPL values at all receiver positions without excessive computation time.

Although three source positions were used during the optimization phase, the CATT validation uses only two. The third source position was omitted here because the final reflector geometry is symmetric through the theater's central axis. During optimization, all three positions were necessary: the lateral reflectors on either side of the seating area were being shaped simultaneously and a source on one side could influence the performance of reflectors on the other side. In the CATT model, the symmetry of the model means that source to the right of centre would produce a mirrored result to that of source 2. Simulating it separately would add no new acoustic information and source 1 and source 2 together are sufficient to show the full range of the design's acoustics.

6.2 Validation against field measurements

Before evaluating the effect of the reflectors, the baseline CATT model, without reflectors and without an audience, was validated against the on-site measurements measured at the Amsterdamse Bostheater, which are described in chapter 3. During initial simulations, all receiver points produced SPL values around 5 dB higher than the corresponding field measurements. This systematic offset indicated that the source level in the model was set too high relative to the loudspeaker used during the on-site measurement campaign. The source level was therefore reduced by 5 dB, after which the simulated values aligned consistently with the measured data. The measured SPL values at each point were then compared to the adjusted CATT outputs. The comparison is summarized in appendix 1.

Across most measurement points, the CATT model reproduces the measured values within 1.5 dB, except point 12. This is since there is a small canopy situated in the real theater. This results in more reflections at this receiver point.

The model proves a consistent correspondence with the physical measurements, confirming that its geometric and material parameterization is a valid basis for evaluating the effect of the reflectors.

6.3 Simulation results

6.3.1 Baseline condition: no reflectors, no audience

Table 4 presents the standard deviation and average SPL for both source positions with no reflectors and compares the CATT-Acoustic and Aeolus results. The figures confirm a similarity between the two simulations for the baseline condition: the standard deviation values differ by less than 0.05 dB for both sources. The results of the CATT baseline condition are plotted in figure 69 and 70.

	CATT	**Aeolus**
Std, source 1	2.207 dB	2.191 dB
Std, source 2	2.418 dB	2.118 dB

Table 8: Std results of the baseline condition

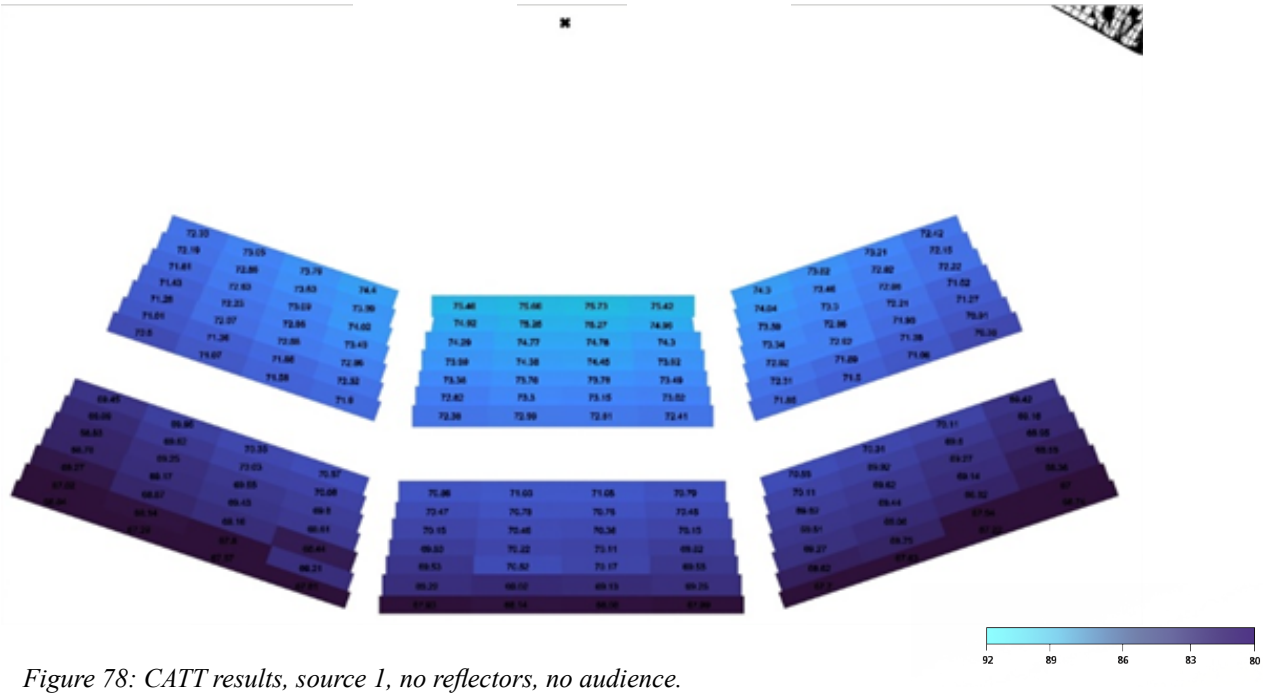


Figure 78: CATT results, source 1, no reflectors, no audience.

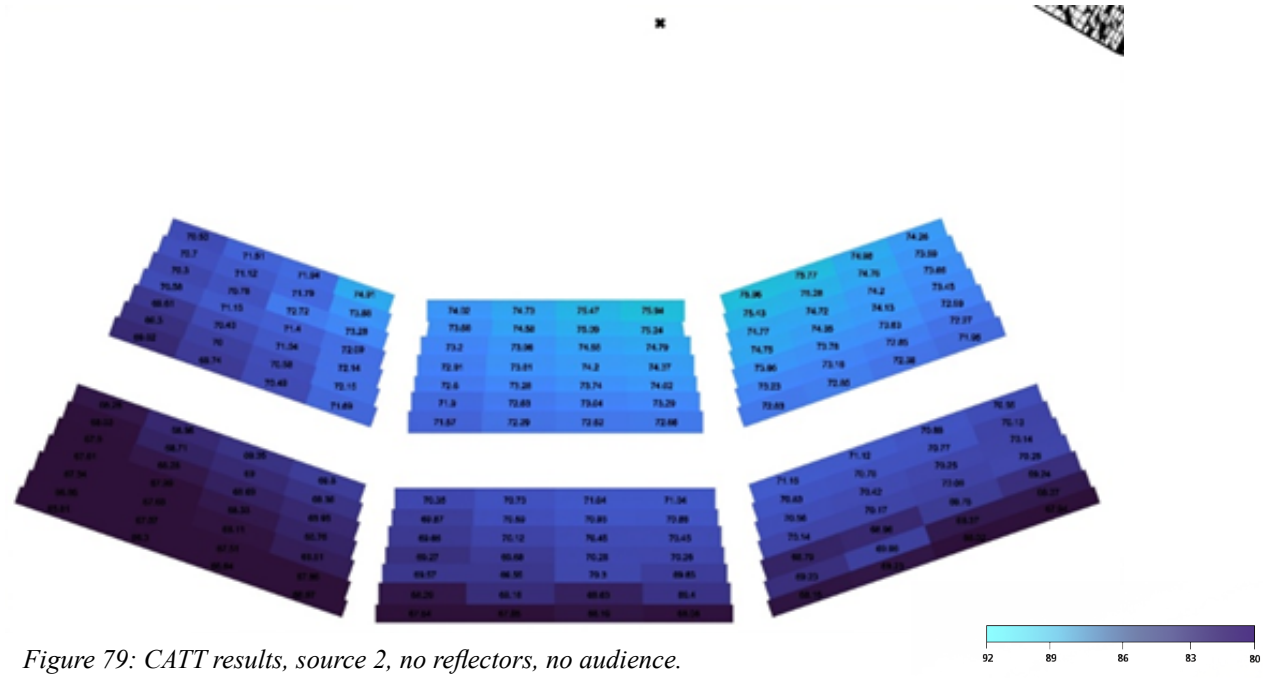


Figure 79: CATT results, source 2, no reflectors, no audience.

6.3.2 Effect of the reflectors: with reflectors, no audience

Table 5 shows, that with the optimized reflector geometry, the CATT simulation produces a clear and consistent improvement in SPL uniformity for both source positions. For source 1, the standard deviation reduces from 2.207 dB to 1.559 dB, an improvement of 0.648 dB, while the average SPL increases slightly from 71.12 to 71.88 dB. For source 2, the standard deviation reduces from 2.418 dB to 1.941 dB, an improvement of 0.477 dB, with a corresponding average SPL increase from 71.07 to 71.67 dB.
The results are plotted in figures 71 and 72, which show the SPL distribution heatmaps

across the receiver grid for each condition. The comparison between the no-reflector and with-reflector heatmaps shows a visible reduction in the colour gradient from front to rear of the audience: the darker zones at the rear and sides of the audience area in the baseline condition are partially filled in, consistent with the redirection of energy toward the lower-SPL zones.

Comparing the CATT results with the Aeolus optimization outputs in Table X, the improvement in standard deviation is somewhat smaller in CATT than in Aeolus for both sources. For source 1, Aeolus predicted a standard deviation of 1.441 dB with reflectors, compared to 1.559 dB in CATT, a difference of 0.118 dB. For source 2, the Aeolus result of 1.904 dB compares to the CATT result of 1.941 dB.

	CATT, no refl.	**CATT, with refl.**	**Aeolus, no refl.**	**Aeolus, with refl.**
Std, source 1	2.207 dB	1.559 dB	2.191 dB	1.441 dB
Std, source 2	2.418 dB	1.941 dB	2.120 dB	1.904 dB
Avg SPL, source 1	71.12 dB	71.88 dB	-	-
Avg SPL, source 2	71.07 dB	71.67 dB		

Table 9: Results of the reflectors

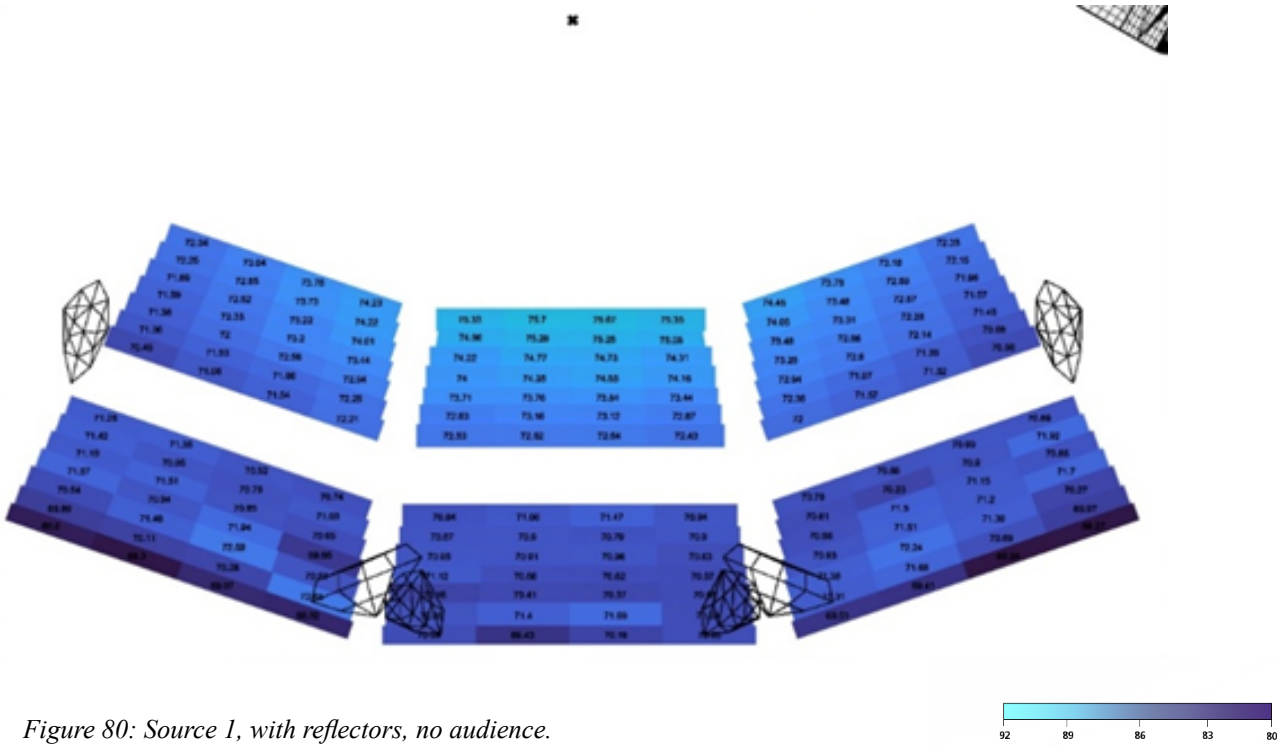


Figure 80: Source 1, with reflectors, no audience.

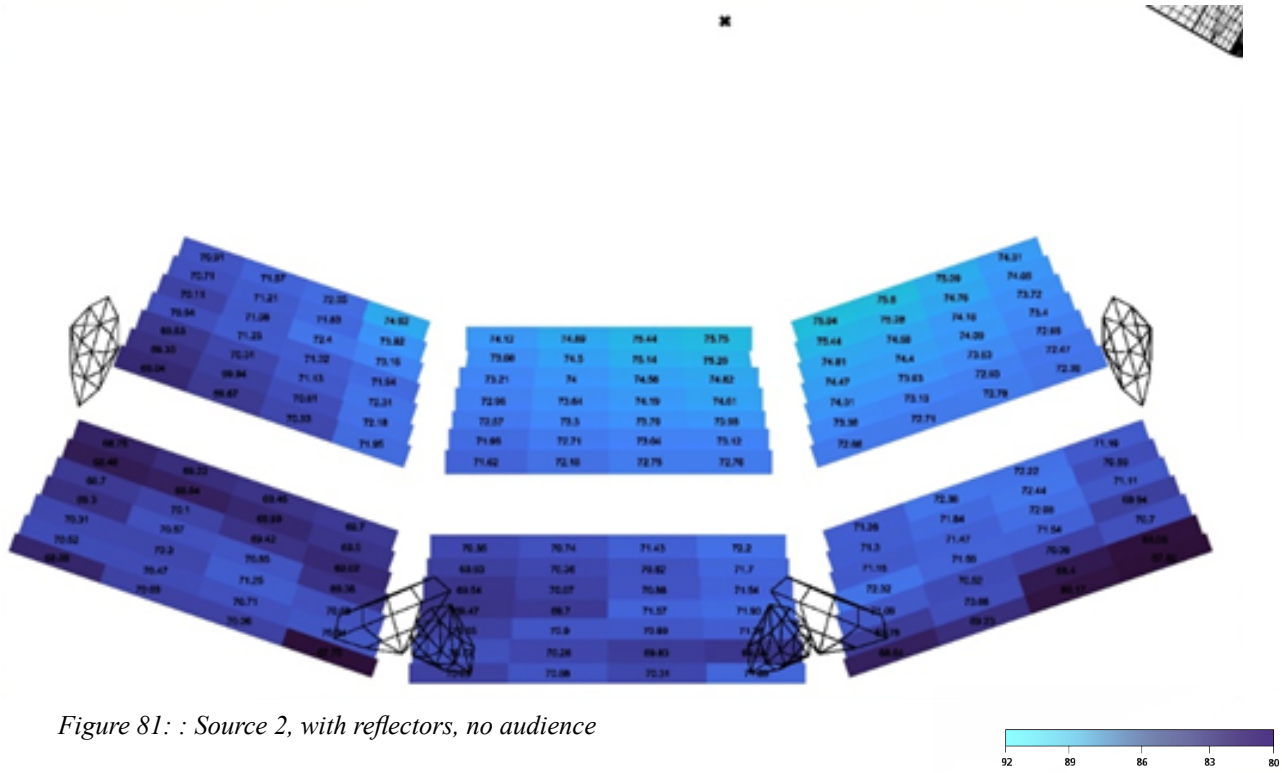


Figure 81: : Source 2, with reflectors, no audience

6.3.3 Effect of the audience: with audience

The addition of audience planes introduces a consistent shift in the acoustic results. For the no-reflector condition, the standard deviation increases slightly with the audience present: from 2.207 to 2.238 dB for source 1, and from 2.418 to 2.451 dB for source 2. The average SPL decreases by approximately 0.5 - 0.6 dB across both sources. Both effects are consistent with the theoretical role of the audience as an absorptive surface: by suppressing the reflection from the seating area, the audience reduces the total energy reaching the receivers.

With the reflectors in place and the audience as well, the standard deviation reduces to 1.594 dB for source 1 and 2.012 dB for source 2. The improvements compared to the audience baseline are 0.644 dB and 0.439 dB, which are comparable in magnitude to the no audience simulation.

	No audience, baseline	**No audience, with reflectors**	**With audience, baseline**	**With audience, with reflectors**
Std, source 1	2.207 dB	1.559 dB	2.238 dB	1.594 dB
Std, source 2	2.418 dB	1.941 dB	2.451 dB	2.012 dB
Avg SPL, source 1	71.12 dB (A)	71.88 dB (A)	70.56 dB(A)	71.32 dB(A)
Avg SPL, source 2	71.07 dB (A)	71.67 dB (A)	70.47 dB(A)	71.07 dB(A)

Table 10: Results of the audience

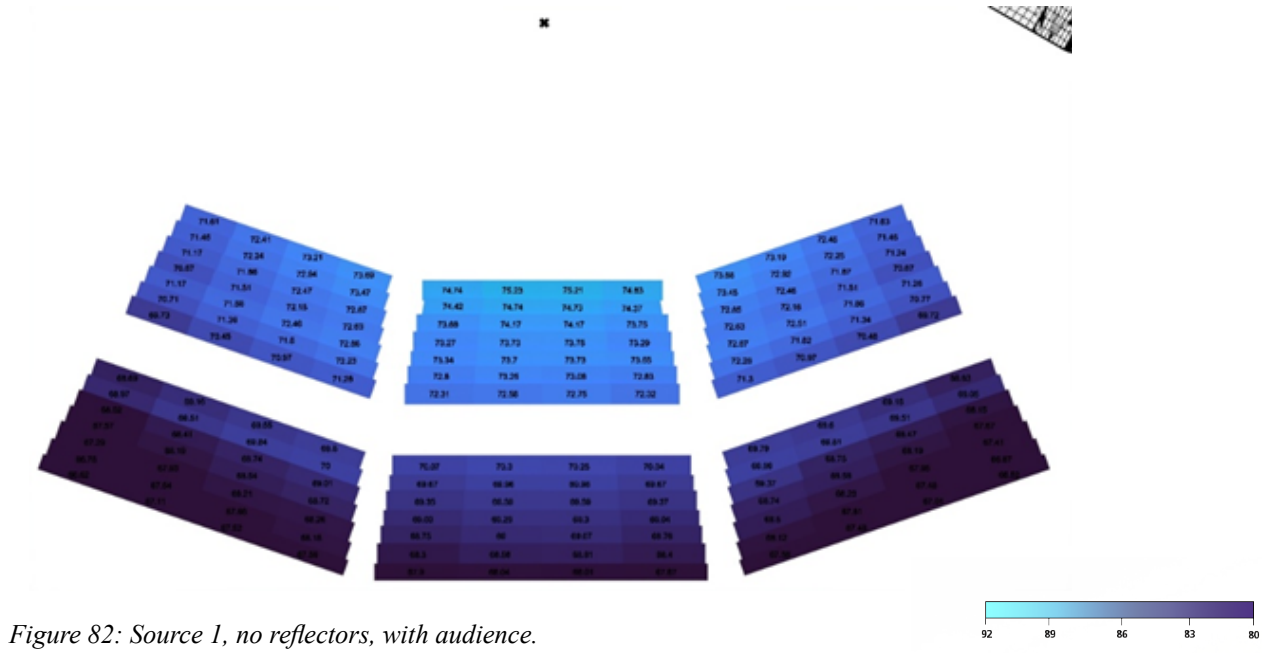


Figure 82: Source 1, no reflectors, with audience.

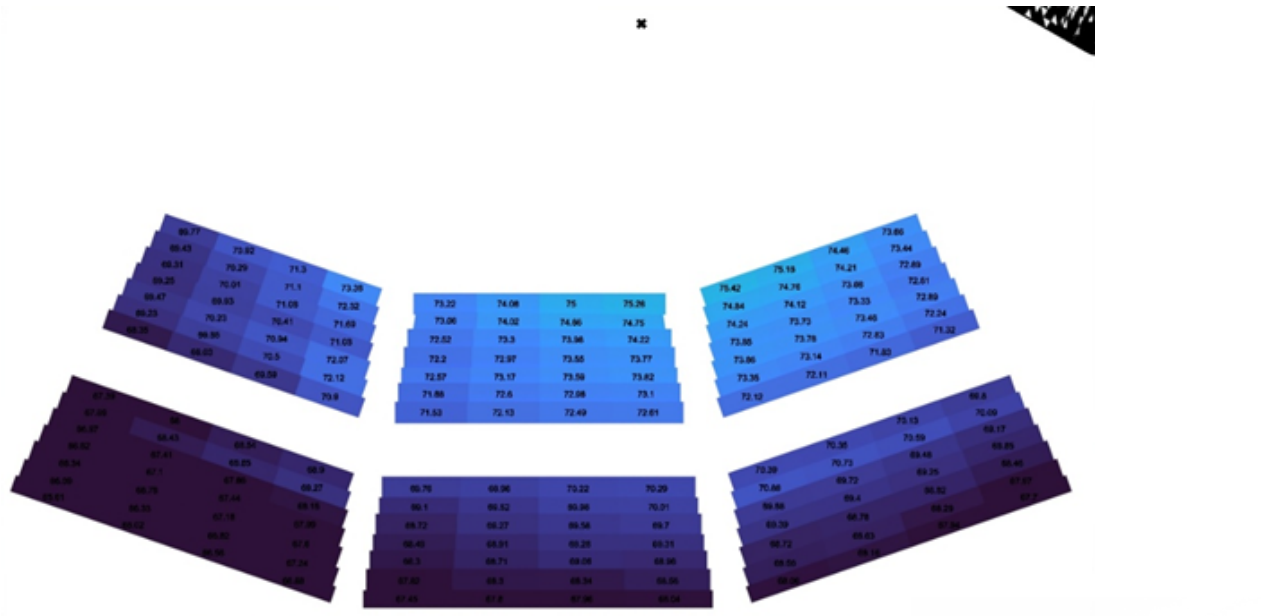


Figure 83: Source 2, no reflectors, with audience.

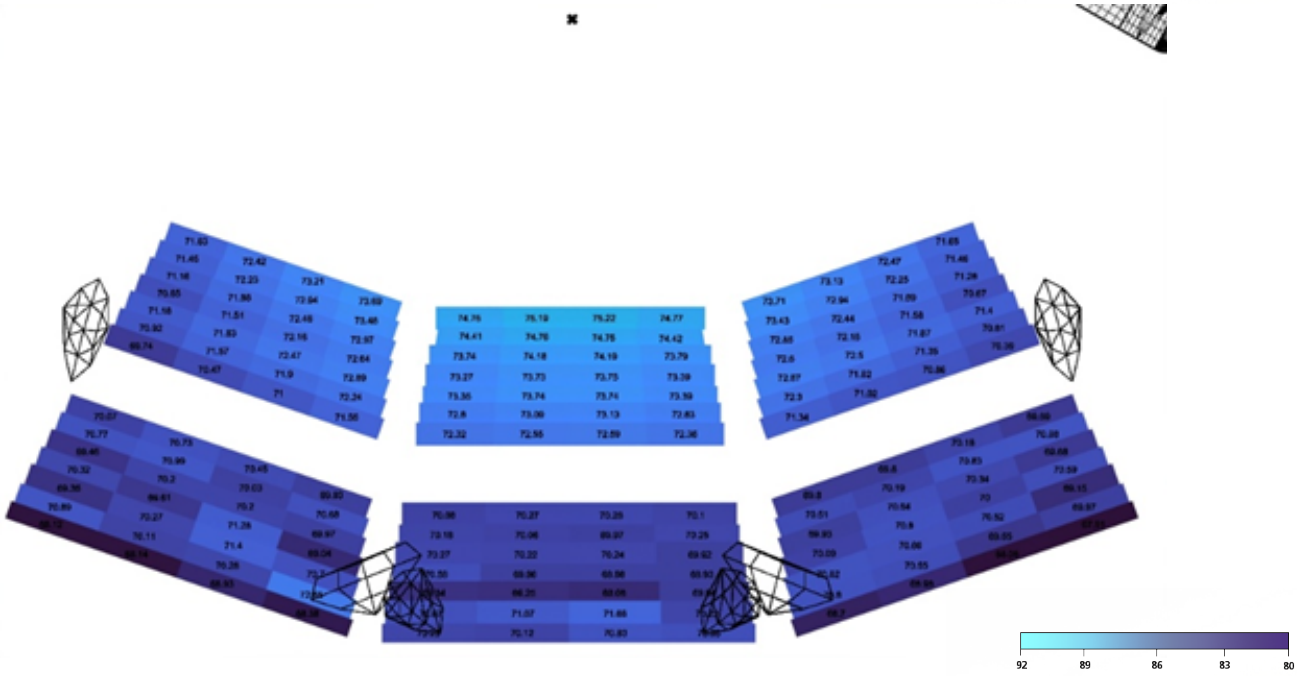


Figure 84: Source 1, with reflectors, with audience.

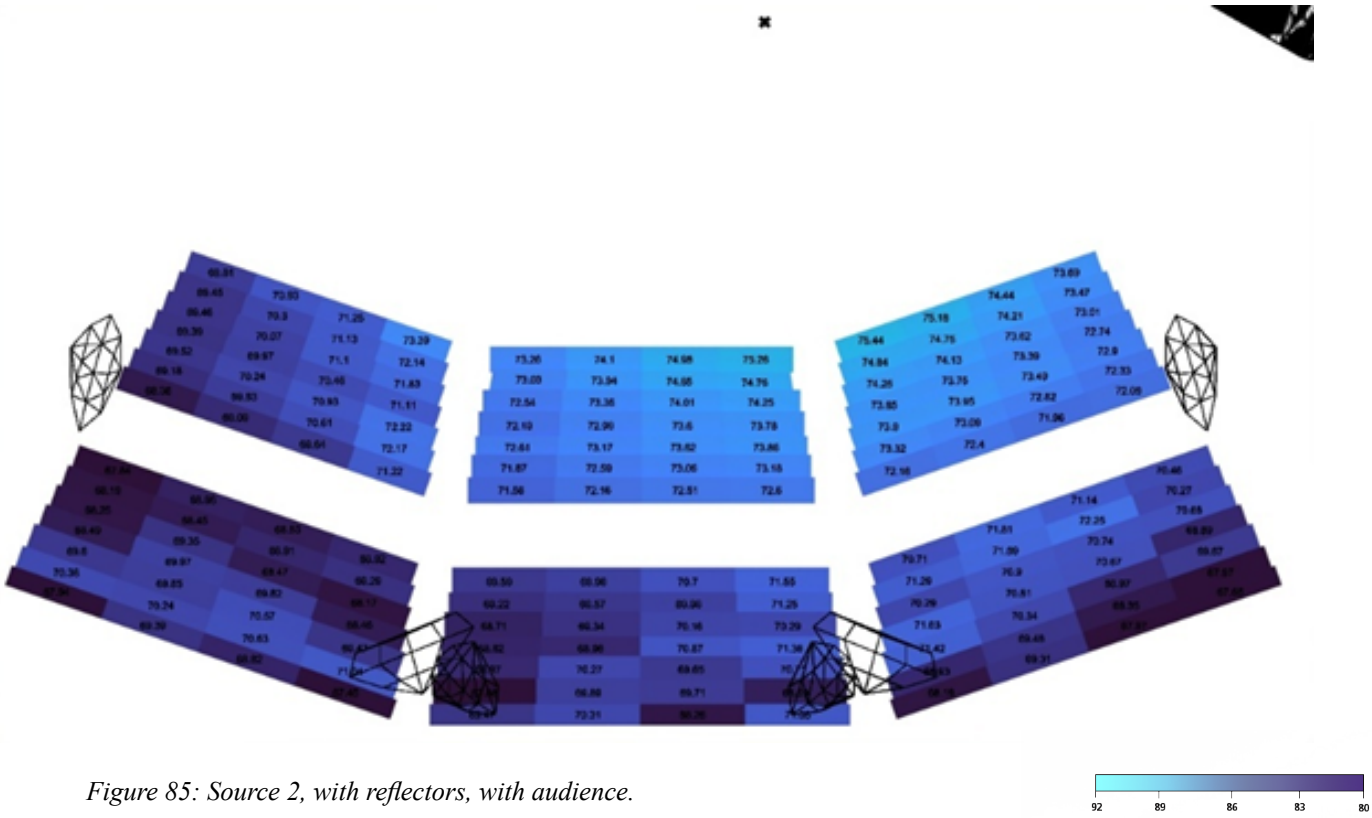


Figure 85: Source 2, with reflectors, with audience.

6.3.4 Effect of other acoustic parameters

Beyond SPL uniformity, three additional acoustic parameters were evaluated for the with-audience condition using source 1: Clarity (C80), Sound Strength (G) and Lateral Fraction (LF). These parameters were not used as optimization objectives but are assessed here as secondary indicators of how the reflector geometry influences the broader acoustic character of the venue.

6.3.4.1 Clarity (C80)

The introduction of the reflectors produces a modest improvement in C80 uniformity, with the standard deviation reducing from 2.680 dB to 2.465 dB. The average C80 value increases marginally from 14.16 dB to 14.33 dB. Both baseline and reflector conditions sit well above the preferred range for music performance, which is typically cited between − 2 and + 4 dB for concert hall contexts. This is expected in an open-air setting where the absence of a reverberant field means that virtually all received energy arrives as direct sound or early reflections, producing inherently high clarity values throughout the audience area.

The spatial distribution of the C80 change, shown in figure 78, reveals that the improvement is not uniform across the grid. The seats that benefit most are concentrated in the back and

lateral zones, where baseline C80 values were already the lowest, in the range of 9 - 12 dB. The decrease which is observed at front positions occurs only at seats where baseline values go over 17 dB, a range in which further increases carry no perceptual significance. The reflectors are therefore redistributing early energy in a spatially targeted way, reducing the spread of C80 across the audience rather than shifting its absolute level.

	With audience, baseline	With audience, with reflectors
Std, source 1	2.680 dB	2.465 dB
Avg C80, source 1	14.16 dB	14.33 dB

Table 11: Results of C80

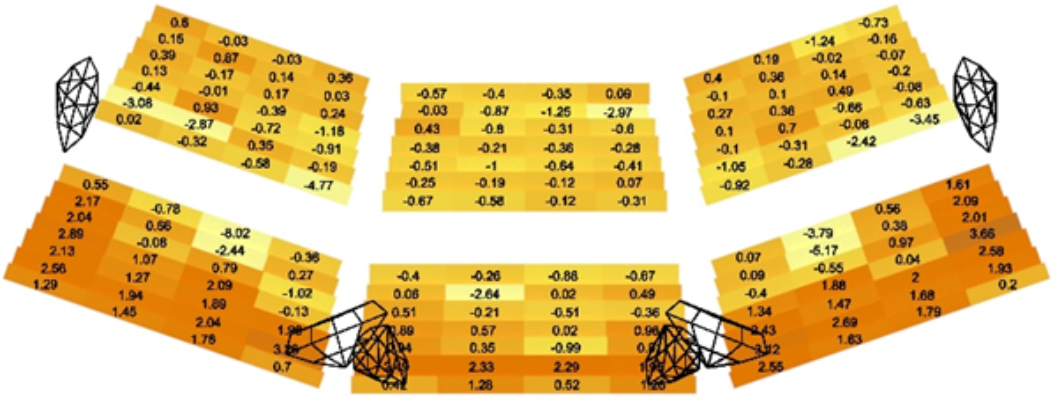


Figure 86: Source 1: difference in C80, with or without reflector..

6.3.4.2 G-strength (G)

The G-strength results show the clearest secondary improvement of the three parameters which are evaluated. For this evaluation of G, frequencies 250 - 4k Hz were used. The standard deviation reduces from 2.261 dB to 1.662 dB, a reduction of 0.599 dB that closely resembles the SPL standard deviation. The average G increases from 3.610 dB to 4.380 dB, an improvement of 0.770 dB. Unlike the SPL, G is normalised against a free-field reference level at 10 metres, which makes it independent of the source level used in the simulation.

All receiver positions produce negative G values in the baseline condition, which is expected outdoors where the absence of enclosing surfaces means that energy at distance falls below the free-field reference level. The reflectors reduce the magnitude of this deficit across the back and lateral audience zones, making G values less negative where the decay was the highest.

	With audience, baseline	With audience, with reflectors
Std, source 1	2.261 dB	1.662 dB
Avg G, source 1	3.610 dB	4.380 dB

Table 12: Results of G

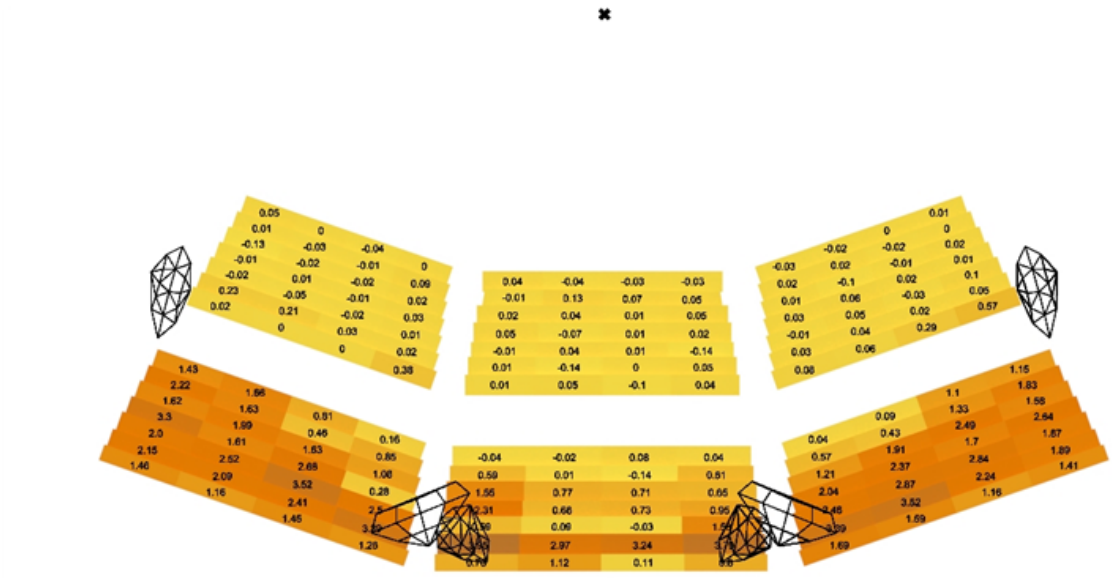


Figure 87: Source 1, difference in G-strength, with or without reflector.

6.3.4.3 Lateral Fraction (LF)

The LF results require different interpretation. The introduction of the reflectors produces a big increase in both the average LF and its standard deviation: the average rises from 2.854 % to 13.340 % and the standard deviation increases from 3.748 % to 13.848 %. These values are way higher than the range of 0.10 % to 0.35 % cited for concert hall contexts and indicate that the crowd-integrated reflector geometry is generating a significant proportion of lateral energy at a subset of receiver positions.

	With audience, baseline	With audience, with reflectors
Std, source 1	3.748 %	13.848 %
Avg LF, source 1	2.854 %	13.340 %

Table 13: Results of LF

This outcome is a direct consequence of the tree-column placement within the audience zone. Unlike ceiling reflectors or acoustic shells, which deliver energy from above or the front, the lateral reflector panels are positioned at the sides of the seating area at close range to adjacent receivers. This geometry produces strong lateral energy at seats close to the reflective structures, which can be seen in the high standard deviation: the effect is spatially concentrated rather than uniformly distributed. In the baseline outdoor condition, lateral energy is near to zero across the entire audience area because of there are no enclosing surfaces. Any increase in LF therefore represents a gain in spatial impression relative to the baseline, even where values exceed the indoor reference range.

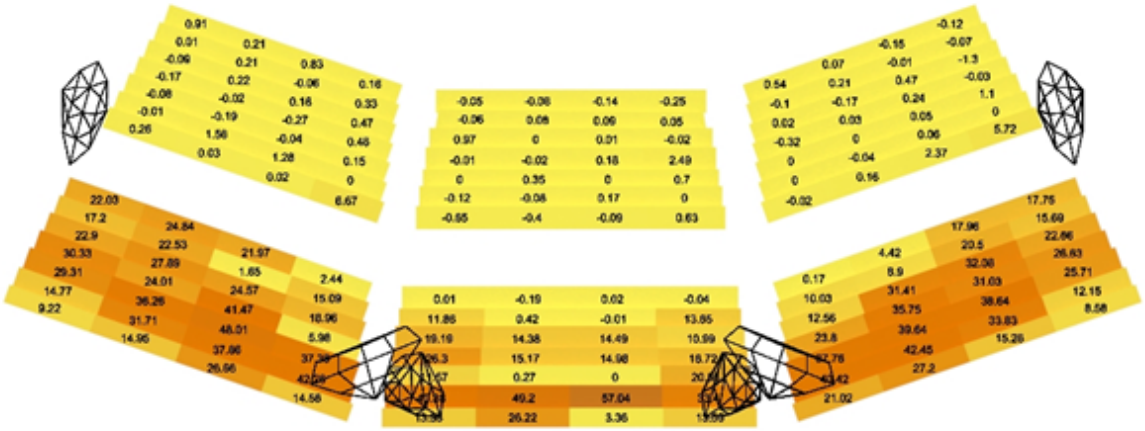


Figure 88: Source 1, difference in LF, with or without reflector.

6.3.5 Time-trace video

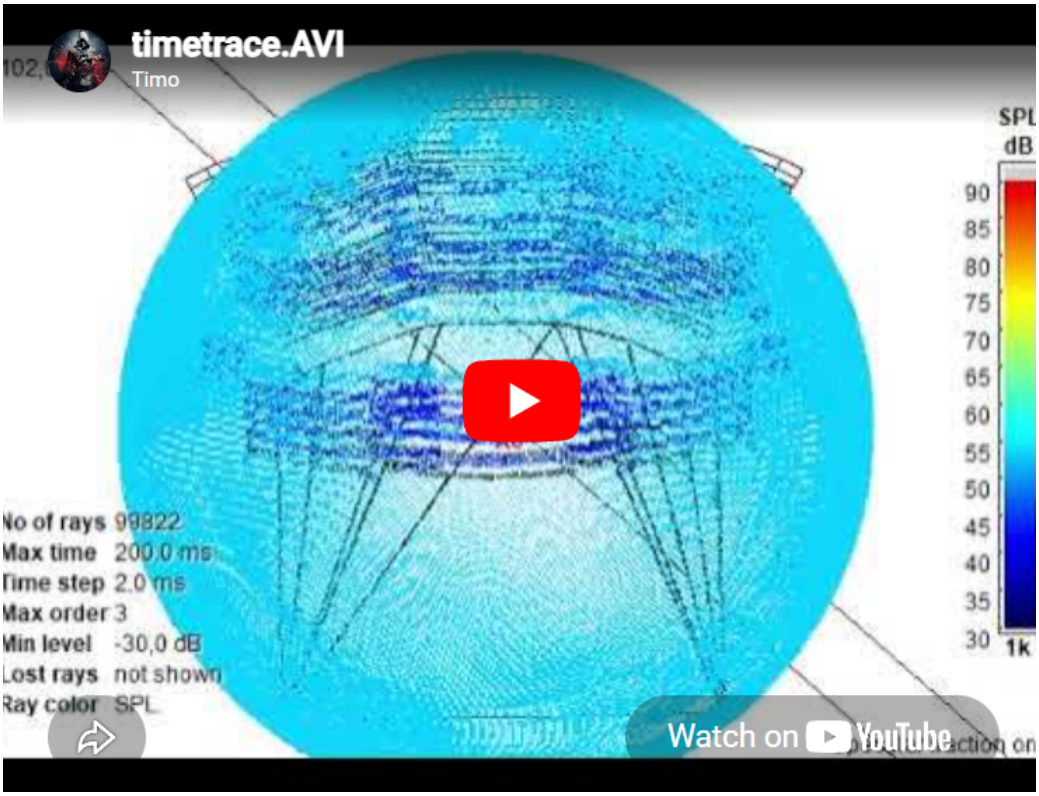


Figure 89: Time trace video

To support the interpretation of the simulation results, a time trace video was exported from CATT-Acoustic. This video visualises the propagation of individual sound rays through the venue over time, making it possible to observe both the arrival sequence and the timing of reflections at specific receiver positions.
The video shows that the direct sound reaches the receivers at the back of the audience area at around 100 ms after the source sends the impulse. This delay is consistent with the physical distance between the stage and the rear seating zone. At approximately 140 ms, a second wave of energy arrives at the same receivers. This is the reflected sound redirected by the crowd-integrated reflector panels.

The 40 ms gap between the direct sound and the reflected sound is acoustically significant. In room acoustics, early reflections are defined as those arriving within 80 ms of the direct sound, and it is this early energy that contributes to perceived clarity and spatial impression. A reflection arriving 40 ms after the direct sound falls well within this window, which means it is integrated by the listener as useful early energy rather than perceived as an echo. This explains the improvement in C80 observed at the rear seating positions in the simulation results: the reflectors are not simply adding more sound energy to the back of the audience, they are delivering it at the correct moment to reinforce the early part of the impulse response.

7. Discussion

7.1 The effectiveness of the computational workflow

TThe central question of this thesis is whether a performance-based computational workflow can produce a passive, crowd-integrated acoustic structure that meaningfully improves SPL uniformity in an open-air theater. The results of the CATT-Acoustic validation confirm that the answer is yes, but with important nuance. The optimized reflector geometry reduces the standard deviation of SPL across the audience area by 0.648 dB for the central source position and 0.477 dB for the off-axis position, in a venue where the baseline gradient spans approximately 8 - 9 dB from front to back. These improvements are real, consistent across source positions, and robust to the presence of a full audience.

The just-noticeable difference for level changes under controlled conditions is approximately 1 dB, which places the standard deviation reduction measured here below the threshold of individual perceptibility at any single seat. This is a limitation that should be stated directly. However, the standard deviation is a measure of the distribution across all seats simultaneously and a reduction in standard deviation does not mean that every seat improves by the same amount. The heatmap comparisons show that the largest gains are concentrated where they are most needed: at the back and lateral parts of the audience area, where the baseline SPL deficit is greatest. At these positions, the reflectors deliver local improvements of up to 3 dB, a difference that is clearly hearable and acoustically significant. The smaller reduction in standard deviation is therefore not a ceiling on what individual audience members gain; it is a statistical consequence of the fact that the front rows, which were already well-served, change little. The workflow is doing exactly what it was designed to do: targeting the bad parts of the audience area and bringing them closer to the level of the rest.

The magnitude of the improvement is also a result of the scale and placement of the reflecting surfaces, not a fundamental ceiling created by the workflow itself. The design space explored in this thesis was tightly constrained by sightline requirements, structural logic and the spatial envelope of a specific venue. A structure with greater surface area, more aggressive panel angles would be expected to produce larger improvements at the cost of bigger visual obstruction. The workflow is capable of optimizing such a structure equally well. The result in this thesis reflects the design boundaries applied, not the limits of the computational approach.

A pattern that is worth addressing is the visual similarity between the candidate solutions produced by the second optimization stage. Across the Pareto front, the generated geometries go toward a narrow range of panel configurations, giving the impression that the optimizer is returning effectively the same solution in multiple variants rather than exploring a diverse set of designs.

This result is most likely a consequence of the parameterization of the lateral reflector panel. The leaf is defined by a limited set of geometric variables that control its position, orientation and curvature. Because the parameter space is tightly constrained by the architectural boundary conditions encoded in the first optimization stage, the number of geometrically distinct configurations that the algorithm can evaluate is limited. When the acoustic objective function responds strongly to only a small subset of those parameters, the optimizer converges quickly toward a similar family of solutions regardless of the starting population.

This is not necessarily a failure of the workflow. The results may reflect that the design space for the reflector, as currently parameterized, contains a genuine optimum that the algorithm is reliably finding. However, it does suggest that the parameterization of the leaf could be extended in future iterations. Introducing additional degrees of freedom would expand the design space and allow the optimizer to explore solutions that are both acoustically competitive and architecturally more varied. Whether such solutions exist and what they look like remains an open question that the current parameterization cannot answer.

7.2 The contribution of the computational workflow

Beyond the acoustic result itself, the workflow developed in this thesis represents a methodological contribution to performance-based design for outdoor acoustic structures. The sequential multi-objective optimization strategy, in which lateral and central reflector components are optimized in successive stages, each taking the previous output as its starting condition, addresses a practical problem that a single-stage optimization could not: the combined parameter space of a fully integrated crowd structure is too large for an evolutionary algorithm to navigate reliably within a feasible computation time. By decomposing the problem into acoustically ordered stages, the workflow achieves multi-source robustness across three simultaneous objectives while remaining compatible with iterative architectural design development. A full optimization run (30 generations of 250 iterations) completes within a time frame that allows the designer to evaluate results, adjust constraints, and re-run without breaking the design process. This is an achievement for an outdoor acoustic problem of this complexity, and it is the workflow that is transferable to other venues and other design configurations.

7.3 The Aeolus–CATT difference

A consistent pattern across all simulation scenarios is that Aeolus overestimates the acoustic improvement relative to CATT-Acoustic. For the central source, Aeolus predicted a post-optimization standard deviation of 1.441 dB, compared to 1.559 dB in CATT, a discrepancy of 0.118 dB. The direction of this discrepancy is predictable: Aeolus, having been used as the optimization environment, will tend to find solutions that exploit whatever simplifications its model introduces. The magnitude of the discrepancy is small enough that the Aeolus-based workflow remains a valid optimization tool, but it underscores the importance of independent validation. A workflow that is optimized and validated within the same simplified environment would risk overstating its own results. The two-tool approach adopted here, Aeolus for optimization, CATT for validation, is therefore not only a methodological usage but a safeguard against this bias.

A further implication is that the baseline correspondence between Aeolus and CATT, which was found to be within 0.05 dB for the no-reflector standard deviation, does not guarantee equivalent accuracy once geometry is introduced. The introduction of the reflector surfaces creates new specular reflection paths whose energy is handled somewhat differently by the two solvers. Future applications of this workflow should treat the Aeolus-to-CATT difference as a parameter to be characterized for each new design configuration rather than assumed to be negligible.

7.4 The effect of the audience

The presence of a full audience consistently increases the standard deviation of SPL slightly and reduces the average level, as discussed in chapter 6. This finding has practical implications for how the design's performance should be communicated. The acoustic improvement delivered by the reflectors does not change to the audience condition, but the uniformity achieved is somewhat worse when the audience is modelled. Since the venue is only ever used with an audience, the with-audience figures are the operationally relevant ones and should be treated as the primary result.

This also raises a question about the optimization setup. The Aeolus-based optimization was run without an audience model, meaning that the reflector geometry was shaped by a simulated environment that does not fully represent the venue in use. Incorporating audience absorption into the Aeolus workflow would require a more detailed surface model than was used here, but it would produce a more accurate optimization target. This is a straightforward extension of the current workflow and is recommended for future iterations.

7.5 The secondary acoustic parameters

The C80 and G results are positive. Both show a reduction in standard deviation with an improvement in average value, which confirms that the reflectors are improving uniformity across multiple metrics.

The LF result is the most significant finding outside of SPL uniformity and requires the most careful interpretation. The big increase in average LF, from 2.854% to 13.340% is a consequence of the reflector geometry. The lateral reflector, positioned within the audience zone at close range to some seats are delivering energy from the side at distances and angles that produce strong lateral contributions at those positions. This is an effect that would not occur with a ceiling canopy or stage shell and it is a consequence of the crowd-integrated placement.

Whether this means an improvement depends on the reference point. Compared to indoor concert hall benchmarks, values above 0.35% are not ideal and could suggest too much lateral energy at those seats. When compared to outdoor benchmarks, any increase in LF represents a gain in spatial envelopment. The right benchmark for an open-air venue is not the concert hall but the open field. When held to that standard, the LF result is positive. The high standard deviation does suggest that this positive improvement is not well distributed. Future iterations of the design could explore whether panel angles can be adjusted to spread lateral energy more evenly across the audience.

7.6 Limitations

Some limitations of this thesis deserve acknowledgement. First, the geometrical acoustics approach underlying both Aeolus and CATT is unreliable at low frequencies. Ray-tracing methods are generally considered valid in any case above the Schroeder frequncy, where wavelengths are short relative to the dimensions of the reflecting surfaces. Below this threshold, wave effects become significant and are not captured by the model. The bass frequencies that characterize much of the amplified music performed at venues like the Bostheater are therefore outside the scope of this simulation and the uniformity improvements demonstrated here should be understood as applying to mid and high frequencies only.

Second, the field validation is based on a single measurement campaign conducted in January, without an audience and under specific weather conditions. Outdoor acoustic measurements are sensitive to wind, temperature gradients and ground moisture, all of which affect sound decay and were not characterized during this thesis. The good correspondence between the measured values and the CATT baseline is encouraging, but a more robust validation would require measurements across multiple conditions and

seasons.

Third, the workflow has been calibrated and validated exclusively for the Amsterdamse Bostheater. The parametric structure of the design is intended to be transferable to other open-air venues by recalibrating the geometric constraints and re-running the optimization, but this transferability has not been demonstrated. Different venue geometries, stage configurations and acoustic environments would require both a new measurement and a new optimization run. The performance of the workflow in those settings is unknown.

7.7 Societal impact

The acoustic uniformity of the improvement is the most significant societal contribution of this work. The SPL gradient that characterizes most open-air venues is not acoustically neutral. It produces a worse listening experience for audience members seated further from the stage. The crowd-integrated reflector system directly targets this inequality: by design, the structures intercept sound energy that would otherwise escape and redirect it toward the rear and lateral zones of the audience area where the deficit is greatest. Local improvements of up to 3 dB at these positions represent a perceptible and meaningful improvement in listening quality for the audience members who currently receive the worst acoustic experience in the venue.

This principle of acoustic equity is not often mentioned explicitly in the literature on venue acoustics, which tends to optimize for average or peak performance rather than for the experience of the worst-served seats. The uniformity objective that drives this thesis reframes the design problem: instead of asking how good the best seats can be, it asks how close the worst seats can get to the best. That is a fundamentally different and arguably more socially valuable question and the computational workflow developed here provides as a method for answering it in the context of any open-air performance venue.

8. Conclusion

8.1 Main research question

This thesis set out to answer a single central question: which performance-based computational design workflow can optimize a passive, crowd-integrated acoustic structure for maximizing acoustic uniformity in large outdoor performance venues? The answer, demonstrated through the design, optimization and validation carried out at the Amsterdamse Bostheater, is the following. A Grasshopper-based workflow combining Aeolus ray-tracing simulation with a sequential multi-objective Octopus optimization, validated independently in CATT-Acoustic, is capable of generating a crowd-integrated reflector geometry that produces a measurable improvement in SPL uniformity across the audience area. The optimized structure reduces the standard deviation of SPL by up to 0.648 dB across the full audience grid, with local improvements of up to 3 dB at the back and lateral seating zones. These improvements are consistent across two source positions and are maintained in the presence of a full audience, confirming that the workflow produces a result that holds under realistic performance conditions.

8.2 Acoustic parameters

The first sub-question asked which acoustic parameters are most relevant for defining and optimizing uniformity in an open-air performance context. The literature review and measurement campaign together confirm that SPL standard deviation across the audience area is the most appropriate primary metric for this purpose. Unlike reverberation-based parameters such as RT or C80, which describe the decay of sound energy and are largely irrelevant in the absence of a reverberant field, SPL standard deviation directly quantifies the spread of level across the audience. Sound Strength (G) functions as a secondary metric, capturing whether the reflectors are adding energy to the audience area or merely redistributing it.

Sound Strength (G) functions as a secondary metric, showing if the reflectors are adding energy to the audience area or redistributing it. The CATT results confirm that the optimized design improves both: standard deviation decreases and average values increase, which indicates that the reflectors are returning energy to the audience rather than shifting it between places. This is consistent across SPL, G and C80. The LF results introduce an additional parameter. The crowd-integrated placement generates lateral energy at positions that would receive no lateral energy in a normal open-air theater. This produces a gain in spatial impression that is not apparent in prior acoustic shell research. The metrics for open-air uniformity research are SPL standard deviation as the first objective, G as a confirmation and LF as a measure of the spatial impression gain that crowd-integrated reflector produces. C80 was evaluated but showed limited response in the absence of

a reverberant field. This confirms that clarity-based parameters are not meaningful optimization targets in this context.

8.3 Constraints

The second sub-question asked which architectural constraints must be integrated into the computational workflow to make sure that the designed structure is realistically usable. Three categories of constraint were to be essential.
The sightline envelope: no reflective surface may occupy the volume between any seat and the stage, a condition that was encoded in Grasshopper as a bounding volume derived from the seat positions and stage edge of the Bostheater.

The panel collision check: because the optimizer treats each panel as an independent variable, it can generate configurations where surfaces from different parts of the structure intersect, producing geometries that are acoustically evaluated but physically unrealizable. An explicit collision check was therefore applied to exclude such configurations from the Pareto front.

The slider range: every optimization variable was assigned minimum and maximum values derived from the structural and spatial logic of the venue, preventing the algorithm from ever generating a geometry that exceeds the permissible parameter space. Encoding these constraints within the optimization loop rather than checking solutions afterward was essential: it ensured that every candidate the algorithm evaluated was architecturally valid, allowing the full computational budget to be spent exploring the feasible design space rather than filtering out infeasible results.

8.4 The reflector design

The third sub-question asked how the crowd-integrated reflector should be designed and parameterized to be both acoustically effective and architecturally coherent. The answer came through three design iterations, each of which contributed a distinct lesson.

The first iteration established that a purely engineered approach produced acoustic improvements but no coherent architectural character. The second iteration introduced an architectural language based on tree-column forms integrated into the audience zone, but demonstrated that surface area is a needed addition for acoustic effectiveness: a geometrically good design that is too small will not move the objective function. The third and final iteration merged these findings: the tree-column language of iteration 2 was retained and scaled to provide needed surface area and the sequential optimization was applied to the resulting geometry to converge on the final panel angles. The result is a structure that satisfies the sightline and collision constraints, maintains the open spatial

character of the Bostheater and delivers the acoustic improvements confirmed by the CATT validation.

The key design principle that emerged across all three iterations is that crowd-integrated reflectors must be conceived as architectural elements from the outset, not as acoustic devices that are given architectural form.

8.5 The limits of Geometrical Acoustics

The fourth sub-question asked what the limits of geometrical acoustics simulation are as a design tool for this application and how reliable its results are compared to measured conditions. Two limits were identified.

The first limit is the frequency threshold. Ray-tracing methods are valid only above approximately 500 Hz, where wavelengths are short relative to the dimensions of the reflecting surfaces. Below this threshold, wave effects including diffraction around panel edges and interference between reflections become significant and are not captured by either Aeolus or CATT. The uniformity improvements demonstrated in this thesis therefore apply to mid and high frequencies only and the behaviour of the structure at the bass frequencies that dominate amplified music at venues like the Bostheater remains uncharacterized.

The second limit is the gap between the optimization environment and the validation environment. Aeolus consistently overestimates the acoustic improvement relative to CATT, by 0.118 dB for the central source standard deviation. This discrepancy is predictable, Aeolus was used as the optimization environment and will tend to find solutions that exploit its own simplifications. These were small enough that the workflow remains valid, but it confirms that independent validation in a separate solver is not optional. The field validation against on-site measurements confirms that the CATT model is a reliable representation of the Bostheater's acoustic environment, with the large majority of simulated values falling within ±1.5 dB of the physical measurements and provides the empirical grounding that the simulation-only workflow cannot supply on its own.

8.6 Recommendations for future research

Three directions for future work follow directly from the limitations identified above.
The optimization workflow should be extended to use an audience absorption model. The current Aeolus-based optimization was run without an audience present, meaning that the reflector geometry was shaped by a simulated environment that does not represent the venue in use. Incorporating audience absorption into the optimization loop is a straightforward extension of the current workflow and would produce a more accurate optimization.

The transferability of the workflow to other venues should be demonstrated. The Bostheater served as a good case, but the claim that the workflow is adaptable to other open-air configurations has not been tested. Applying the same parametric approach to a venue with a different geometry would both validate the generality of the method and reveal which aspects of the workflow require venue-specific recalibration.

Third, the low-frequency behaviour of the structure should be investigated using wave-based simulation methods. This is particularly relevant for the amplified music genres most commonly performed at venues like the Bostheater, where the perceptual impact of the bass register is substantial.

In response to the design philosophy

The design philosophy, which was established at the start of this thesis, drew a clear distinction between improving acoustic uniformity and replicating indoor acoustics. The goal was never to enclose the audience or introduce artificial reverberation, but to recover the early reflections that indoor spaces provide naturally and that open-air venues lose to the sky. The crowd-integrated reflector system developed in this thesis pursues that goal within a tight constraint set and delivers a result that is acoustically validated, architecturally sound and directly targeted at the audience members who needs it most.
The open-air theater remains open. The sound simply travels a little further.

9. Reflection

Looking back at the process, the project sits at an intersection within Building Technology. The research is technical in its methods but the design questions it raises are architectural ones: how should a structure that lives inside an audience look, how does it relate to the spatial experience of the venue and how can acoustic performance and architectural quality be achieved together rather than traded off against each other. The project ended up leaning more toward the technical side, which was in part a consequence of the scope and in part a consequence of where the most difficult problems lay. The design process did carry genuine architectural thinking, particularly in the second and third iterations where the tree-column design started, but the optimization framework determined what was possible.

The relationship between the designer and the algorithm deserves reflection. Throughout the optimization process, the sense of control was real: the boundary conditions, the parameterization, the objective functions, and the sequential structure of the workflow were all deliberate choices that shaped what the algorithm could and could not find. But the algorithm also imposed its own limits. Because the optimization was targeting a single receiver point per iteration, it converged toward solutions that perform well for a specific source-receiver geometry, while a performance venue contains a complex field of reflections arriving at every seat simultaneously from many directions. The gap between the model and that reality is acknowledged in the discussion, but it points to something broader: the design space explored in this thesis was a simplification and the most interesting acoustic solutions may exist in a more detailed space than the current workflow could navigate within a normal computation time. A future iteration with finer geometric control over individual panel segments and a multi-source, multi-receiver objective function would be the next step.

On the use of artificial intelligence: AI tools were used at several points in this project. AI was used to proofread written sections of the thesis and to produce design visualisation. It was also used to assist in identifying sources during the literature review, though all references were verified for correctness before being cited. The acoustic analysis, simulation workflow, field measurements and design decisions were carried out independently. The use of AI in this project was supplementary rather than generative with respect to the research itself.

The project also raised questions about sustainability that fell outside its scope. In hindsight, a more detailed engagement with the sustainability of the design would have strengthened the work. Questions around the carbon of the glass and steel fabrication, the energy

balance of a passive structure relative to the active reinforcement systems it replaces, and end-of-life disassembly are all relevant to a permanent installation and would have added a dimension to the design evaluation. The scope and time constraints of the thesis made it difficult to pursue this in the depth it deserves, but it is something that, looking back, would have been a worthwhile inclusion. It remains a clear direction for further research.

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11. Appendix

Appendix 1: Comparison simulated values to CATT-Acoustic

Point	Measured (dBA)	CATT (dBA)	Difference (dB)
5	75.9	75.77	−0.13
6	74.1	74.78	+0.68
7	72.9	73.99	+1.09
8	71.8	72.69	+0.89
9	71.7	71.08	−0.62
10	71.8	70.43	−1.37
11	71.2	70.03	−1.17
12	72.6	68.17	−4.43
16	73.4	73.40	+0.00
17	72.4	72.83	+0.43
18	71.5	72.30	+0.80
19	70.4	71.59	+1.19
20	70.1	70.17	+0.07
21	69.3	69.51	+0.21
22	69.2	68.99	−0.21
23	69.4	67.38	−2.02
36	72.4	73.24	+0.84
37	71.7	72.68	+0.98
38	70.9	71.78	+0.88
39	70.0	71.30	+1.30
40	69.3	70.10	+0.80
41	69.0	69.41	+0.41
42	68.9	68.98	+0.08
43	68.9	67.42	−1.48

Appendix 2:
CATT GEO FILE

FROMFRONT

ABS default = <5 15 20 20 20 30>
ABS box = <10 10 10 10 10 10>
ABS podium <10 10 10 10 10 10>
ABS reflector <1 1 1 1 1 1>
ABS audience <50 70 85 95 95 85>

CORNERS

0	-91.786819	-70.400551	0.000000
1	70.999214	-70.400551	0.000000
2	70.999214	-70.400551	110.914009
3	-91.786819	-70.400551	110.914009
4	70.999214	78.127510	0.000000
5	70.999214	78.127510	110.914009
6	-91.786819	78.127510	0.000000
7	-91.786819	78.127510	110.914009
8	-17.062014	-26.969849	6.000000
9	-14.839128	-27.337503	6.000000
10	-14.839128	-27.337503	6.400000
11	-17.062014	-26.969849	6.400000
12	-14.699876	-26.504278	6.000000
13	-14.699876	-26.504278	5.600000
14	-16.888552	-25.932596	5.600000
15	-16.888552	-25.932596	6.000000
16	-15.629991	-25.235718	5.600000
17	-15.629991	-25.235718	5.200000
18	-16.737123	-25.026020	5.200000
19	-16.737123	-25.026020	5.600000
20	-14.522859	-25.445415	5.600000
21	-14.522859	-25.445415	5.200000
22	-16.139574	-24.183987	5.000000
23	-16.139574	-24.183987	4.800000
24	-16.582033	-24.097630	4.800000
25	-16.582033	-24.097630	5.000000
26	-16.139574	-24.183987	5.200000
27	-16.582033	-24.097630	5.200000
28	-15.697114	-24.270344	5.000000
29	-15.697114	-24.270344	4.800000
30	-15.697114	-24.270344	5.200000
31	-15.254655	-24.356701	5.000000
32	-15.254655	-24.356701	4.800000
33	-15.254655	-24.356701	5.200000
34	-14.812196	-24.443058	5.000000
35	-14.812196	-24.443058	4.800000
36	-14.812196	-24.443058	5.200000
37	-14.369737	-24.529415	5.000000
38	-14.369737	-24.529415	4.800000
39	-14.369737	-24.529415	5.200000
40	-15.331925	-23.452765	4.800000
41	-15.331925	-23.452765	4.400000
42	-16.430254	-23.190010	4.400000
43	-16.430254	-23.190010	4.800000
44	-14.233582	-23.715519	4.800000
45	-14.233582	-23.715519	4.400000
46	-14.062959	-22.694382	4.000000
47	-14.062959	-22.694382	4.400000
48	-16.276461	-22.269299	4.400000
49	-16.276461	-22.269299	4.000000
50	-16.125231	-21.364925	3.600000
51	-13.927445	-21.883858	3.600000
52	-13.927445	-21.883858	4.000000
53	-16.125231	-21.364925	4.000000
54	-13.754151	-20.847195	3.600000
55	-13.754151	-20.847195	3.200000
56	-15.966187	-20.432627	3.200000
57	-15.966187	-20.432627	3.600000
58	-13.286775	-18.017824	3.200000
59	-13.286775	-18.017824	2.800000
60	-15.510255	-17.612663	2.800000
61	-15.510255	-17.612663	3.200000
62	-13.137406	-17.123274	2.800000
63	-13.137406	-17.123274	2.400000
64	-15.344499	-16.620586	2.400000
65	-15.344499	-16.620586	2.800000
66	-15.195817	-15.730475	2.000000
67	-12.981370	-16.189745	2.000000
68	-12.981370	-16.189745	2.400000
69	-15.195817	-15.730475	2.400000
70	-14.606019	-14.942847	1.600000
71	-14.606019	-14.942847	2.000000
72	-15.044282	-14.823390	2.000000
73	-15.044282	-14.823390	1.600000
74	-14.167741	-15.062304	1.600000
75	-14.167741	-15.062304	2.000000
76	-13.729478	-15.181758	1.600000
77	-13.729478	-15.181758	2.000000
78	-13.291215	-15.301215	1.600000
79	-13.291215	-15.301215	2.000000
80	-12.852937	-15.420672	1.600000
81	-12.852937	-15.420672	2.000000
82	-12.680985	-14.391440	1.600000
83	-12.680985	-14.391440	1.200000
84	-14.896256	-13.937240	1.200000
85	-14.896256	-13.937240	1.600000
86	-14.156938	-12.254649	0.600000
87	-14.156938	-12.254649	0.800000
88	-14.599717	-12.162112	0.800000
89	-14.599717	-12.162112	0.600000
90	-14.156938	-12.254649	0.400000
91	-14.599717	-12.162112	0.400000
92	-13.714173	-12.347190	0.600000
93	-13.714173	-12.347190	0.800000
94	-13.714173	-12.347190	0.400000
95	-13.271394	-12.439731	0.600000
96	-13.271394	-12.439731	0.800000
97	-13.271394	-12.439731	0.400000
98	-12.828614	-12.532268	0.600000
99	-12.828614	-12.532268	0.800000
100	-12.828614	-12.532268	0.400000
101	-12.385835	-12.624808	0.600000
102	-12.385835	-12.624808	0.800000
103	-12.385835	-12.624808	0.400000
104	-12.531709	-13.497970	0.800000
105	-12.531709	-13.497970	1.200000
106	-14.743897	-13.025935	1.200000
107	-14.743897	-13.025935	0.800000
108	-19.967897	-10.335971	0.400000
109	-25.336061	-8.509826	0.400000
110	-25.336061	-8.509826	0.800000
111	-19.967897	-10.335971	0.800000
112	-25.770891	-9.274852	0.800000
113	-25.770891	-9.274852	1.200000
114	-26.229570	-10.081775	1.200000
115	-26.229570	-10.081775	1.600000
116	-26.210390	-11.024951	2.000000
117	-26.675646	-10.866683	2.000000
118	-26.675646	-10.866683	1.600000
119	-26.210405	-11.024951	1.600000
120	-25.745134	-11.183219	2.000000
121	-25.745150	-11.183219	1.600000
122	-25.279894	-11.341487	2.000000
123	-25.279894	-11.341487	1.600000
124	-24.814638	-11.499755	2.000000
125	-24.814638	-11.499755	1.600000
126	-24.349382	-11.658023	2.000000
127	-24.349382	-11.658019	1.600000
128	-23.884127	-11.816291	2.000000
129	-23.884127	-11.816287	1.600000
130	-23.418871	-11.974559	2.000000
131	-23.418871	-11.974555	1.600000
132	-22.953615	-12.132827	2.000000
133	-22.953630	-12.132823	1.600000
134	-22.488359	-12.291099	2.000000
135	-22.488375	-12.291091	1.600000
136	-22.023104	-12.449367	2.000000
137	-22.023119	-12.449359	1.600000
138	-21.557848	-12.607635	2.000000
139	-21.557863	-12.607627	1.600000
140	-21.092592	-12.765903	2.000000
141	-21.092607	-12.765895	1.600000
142	-20.627337	-12.924170	2.000000
143	-20.627352	-12.924163	1.600000
144	-20.162081	-13.082438	2.000000
145	-20.162111	-13.082431	1.600000
146	-19.696825	-13.240706	2.000000
147	-19.696856	-13.240699	1.600000
148	-19.231569	-13.398974	2.000000
149	-19.231600	-13.398967	1.600000
150	-18.766314	-13.557242	2.000000
151	-18.766344	-13.557235	1.600000
152	-18.301073	-13.715510	2.000000
153	-18.301088	-13.715503	1.600000
154	-17.835817	-13.873782	2.000000
155	-17.835833	-13.873771	1.600000
156	-17.370562	-14.032050	2.000000
157	-17.370592	-14.032039	1.600000
158	-16.905306	-14.190318	2.000000
159	-16.905336	-14.190307	1.600000
160	-16.440050	-14.348586	2.000000
161	-16.440081	-14.348575	1.600000
162	-15.974793	-14.506854	2.000000
163	-15.974824	-14.506843	1.600000
164	-15.509538	-14.665122	2.000000
165	-15.509568	-14.665111	1.600000
166	-15.044312	-14.823379	1.600000
167	-27.126879	-11.660323	2.000000
168	-27.126879	-11.660323	2.400000
169	-27.580202	-12.458137	2.400000
170	-27.580202	-12.458137	2.800000
171	-27.564745	-13.408374	3.000000
172	-28.028368	-13.246669	3.000000
173	-28.028383	-13.246669	3.200000
174	-27.564745	-13.408374	3.200000
175	-27.101107	-13.570075	3.000000
176	-27.101107	-13.570075	3.200000
177	-26.637468	-13.731780	3.000000
178	-26.637468	-13.731780	3.200000
179	-26.173845	-13.893485	3.000000
180	-26.173845	-13.893485	3.200000
181	-25.710207	-14.055186	3.000000
182	-25.710207	-14.055186	3.200000
183	-25.246569	-14.216891	3.000000
184	-25.246569	-14.216891	3.200000
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929	11.726592	-14.540298	3.000000
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931	11.262954	-14.701999	3.000000
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933	10.799315	-14.863704	3.000000
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935	10.335692	-15.025409	3.000000

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949	7.090254	-16.157331	3.000000
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953	6.162978	-16.480740	3.000000
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955	5.699339	-16.642443	3.000000
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957	5.235716	-16.804146	3.000000
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959	4.772078	-16.965849	3.000000
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961	4.308440	-17.127552	3.000000
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963	3.844817	-17.289257	3.000000
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Appendix 3: CATT Reciever file 1

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2 -8.399451 -26.828903 6.9 ; receiver 2
3 -4.055241 -26.828903 6.9 ; receiver 3
4 0.288969 -26.828903 6.9 ; receiver 4
5 -29.905496 -20.949228 6.6 ; receiver 5
6 -25.999981 -22.313277 6.6 ; receiver 6
7 -22.094466 -23.677327 6.6 ; receiver 7
8 -18.188951 -25.041376 6.6 ; receiver 8
9 17.745874 -20.949228 6.6 ; receiver 9
10 13.840358 -22.313277 6.6 ; receiver 10
11 9.934843 -23.677327 6.6 ; receiver 11
12 6.029328 -25.041376 6.6 ; receiver 12
13 -12.634676 -25.926113 6.6 ; receiver 13
14 -8.356174 -25.926113 6.6 ; receiver 14
15 -4.077671 -25.926113 6.6 ; receiver 15
16 0.200831 -25.926113 6.6 ; receiver 16
17 -30.305876 -21.751071 6.9 ; receiver 17
18 -26.328015 -23.140351 6.9 ; receiver 18
19 -22.350153 -24.529632 6.9 ; receiver 19
20 -18.372292 -25.918912 6.9 ; receiver 20
21 18.146254 -21.751071 6.9 ; receiver 21
22 14.168392 -23.140351 6.9 ; receiver 22
23 10.190531 -24.529632 6.9 ; receiver 23
24 6.212670 -25.918912 6.9 ; receiver 24
25 -12.497561 -24.955484 6.4 ; receiver 25
26 -8.305636 -24.955484 6.4 ; receiver 26
27 -4.113712 -24.955484 6.4 ; receiver 27
28 0.078213 -24.955484 6.4 ; receiver 28
29 -17.991321 -24.076439 6.4 ; receiver 29
30 -21.817505 -22.740126 6.4 ; receiver 30
31 -25.643689 -21.403812 6.4 ; receiver 31
32 -29.469874 -20.067499 6.4 ; receiver 32
33 5.831698 -24.076439 6.4 ; receiver 33
34 9.657883 -22.740126 6.4 ; receiver 34
35 13.484067 -21.403812 6.4 ; receiver 35
36 17.310251 -20.067499 6.4 ; receiver 36
37 -12.379543 -24.089015 6.0 ; receiver 37
38 -8.263812 -24.089015 6.0 ; receiver 38
39 -4.148080 -24.089015 6.0 ; receiver 39
40 -0.032349 -24.089015 6.0 ; receiver 40
41 -17.804366 -23.112821 6.0 ; receiver 41
42 -21.542349 -21.806911 6.0 ; receiver 42
43 -25.280333 -20.501000 6.0 ; receiver 43
44 -29.018316 -19.195090 6.0 ; receiver 44
45 5.644743 -23.112821 6.0 ; receiver 45
46 9.382727 -21.806911 6.0 ; receiver 46
47 13.120710 -20.501000 6.0 ; receiver 47
48 16.858694 -19.195090 6.0 ; receiver 48
49 -12.274594 -23.170165 5.6 ; receiver 49
50 -8.226595 -23.170165 5.6 ; receiver 50
51 -4.178595 -23.170165 5.6 ; receiver 51
52 -0.130596 -23.170165 5.6 ; receiver 52
53 -17.620929 -22.201264 5.6 ; receiver 53
54 -21.279962 -20.922321 5.6 ; receiver 54
55 -24.938996 -19.643377 5.6 ; receiver 55
56 -28.598029 -18.364434 5.6 ; receiver 56
57 5.461307 -22.201264 5.6 ; receiver 57
58 9.120340 -20.922321 5.6 ; receiver 58
59 12.779373 -19.643377 5.6 ; receiver 59
60 16.438407 -18.364434 5.6 ; receiver 60
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63 -4.217282 -22.251112 5.2 ; receiver 63
64 -0.254337 -22.251112 5.2 ; receiver 64
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66 -24.602072 -18.792571 5.2 ; receiver 66
67 -21.021444 -20.043111 5.2 ; receiver 67
68 -17.440816 -21.293650 5.2 ; receiver 68
69 16.023078 -17.542032 5.2 ; receiver 69
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72 5.281193 -21.293650 5.2 ; receiver 72
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75 -4.247316 -21.327738 4.8 ; receiver 75
76 -0.351649 -21.327738 4.8 ; receiver 76
77 -17.257817 -20.387393 4.8 ; receiver 77
78 -20.760928 -19.163947 4.8 ; receiver 78
79 -24.264040 -17.940500 4.8 ; receiver 79
80 -27.767152 -16.717054 4.8 ; receiver 80
81 5.098194 -20.387393 4.8 ; receiver 81
82 8.601306 -19.163947 4.8 ; receiver 82
83 12.104418 -17.940500 4.8 ; receiver 83
84 15.607529 -16.717054 4.8 ; receiver 84
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98 -7.876346 -15.773568 3.2 ; receiver 98
99 -4.445790 -15.773568 3.2 ; receiver 99

Appendix 4: CATT Reciever file 2

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02 -22.223414 -12.825325 3.2 ; receiver 102
03 -19.205495 -13.869551 3.2 ; receiver 103
04 -16.187576 -14.913778 3.2 ; receiver 104
05 13.081711 -11.781098 3.2 ; receiver 105
06 10.063792 -12.825325 3.2 ; receiver 106
07 7.045872 -13.869551 3.2 ; receiver 107
08 4.027953 -14.913778 3.2 ; receiver 108
09 -11.075818 -13.909382 2.4 ; receiver 109
10 -7.795677 -13.909382 2.4 ; receiver 110
11 -4.515536 -13.909382 2.4 ; receiver 111
12 -1.235396 -13.909382 2.4 ; receiver 112
13 -15.826895 -13.138940 2.4 ; receiver 113
14 -18.683206 -12.150615 2.4 ; receiver 114
15 -21.539517 -11.162290 2.4 ; receiver 115
16 -24.395828 -10.173964 2.4 ; receiver 116
17 3.667273 -13.138940 2.4 ; receiver 117
18 6.523584 -12.150615 2.4 ; receiver 118
19 9.379895 -11.162290 2.4 ; receiver 119
20 12.236206 -10.173964 2.4 ; receiver 120
21 -10.848747 -12.131379 1.6 ; receiver 121
22 -7.716332 -12.131379 1.6 ; receiver 122
23 -4.583917 -12.131379 1.6 ; receiver 123
24 -1.451502 -12.131379 1.6 ; receiver 124
25 -15.457123 -11.336977 1.6 ; receiver 125
26 -18.151646 -10.404613 1.6 ; receiver 126
27 -20.846169 -9.472248 1.6 ; receiver 127
28 -23.540693 -8.539883 1.6 ; receiver 128
29 3.297500 -11.336977 1.6 ; receiver 129
30 5.992024 -10.404613 1.6 ; receiver 130
31 8.686547 -9.472248 1.6 ; receiver 131
32 11.381070 -8.539883 1.6 ; receiver 132
33 -11.426950 -16.626796 3.6 ; receiver 133
34 -7.918296 -16.626796 3.6 ; receiver 134
35 -4.409643 -16.626796 3.6 ; receiver 135
36 -0.900989 -16.626796 3.6 ; receiver 136
37 -25.666566 -12.596287 3.6 ; receiver 137
38 -22.568650 -13.668249 3.6 ; receiver 138
39 -19.470734 -14.740211 3.6 ; receiver 139
40 -16.372817 -15.812173 3.6 ; receiver 140
41 13.506944 -12.596287 3.6 ; receiver 141
42 10.409027 -13.668249 3.6 ; receiver 142
43 7.311111 -14.740211 3.6 ; receiver 143
44 4.213195 -15.812173 3.6 ; receiver 144
45 -11.208100 -14.872845 2.8 ; receiver 145
46 -7.841851 -14.872845 2.8 ; receiver 146
47 -4.475602 -14.872845 2.8 ; receiver 147
48 -1.109353 -14.872845 2.8 ; receiver 148
49 -24.813551 -10.971861 2.8 ; receiver 149
50 -21.878144 -11.987593 2.8 ; receiver 150
51 -18.942737 -13.003325 2.8 ; receiver 151
52 -16.007330 -14.019056 2.8 ; receiver 152
53 12.653929 -10.971861 2.8 ; receiver 153
54 9.718522 -11.987593 2.8 ; receiver 154
55 6.783114 -13.003325 2.8 ; receiver 155
56 3.847707 -14.019056 2.8 ; receiver 156
57 -10.811913 -12.966615 2.0 ; receiver 157
58 -7.704997 -13.005496 2.0 ; receiver 158
59 -4.598080 -13.044377 2.0 ; receiver 159
60 -1.491164 -13.083258 2.0 ; receiver 160
61 -15.642928 -12.244495 2.0 ; receiver 161
62 -18.419202 -11.283855 2.0 ; receiver 162
63 -21.195476 -10.323214 2.0 ; receiver 163
64 -23.971751 -9.362574 2.0 ; receiver 164
65 3.483306 -12.244495 2.0 ; receiver 165
66 6.259580 -11.283855 2.0 ; receiver 166
67 9.035854 -10.323214 2.0 ; receiver 167
68 11.812128 -9.362574 2.0 ; receiver 168

Appendix 5: CATT Source file

SOURCEDEFS

;natural source
A0 -6.07 1.83 2.5 omni -6.07 5.83 2.5
Lp1m_a = Lp_white 85
A1 -1.07 1.83 2.5 omni -6.07 5.83 2.5
Lp1m_a = Lp_white 85
A2 -11.07 1.83 2.5 omni -6.07 5.83 2.5
Lp1m_a = Lp_white 85

Appendix 6: Grasshopper script (zoom in)

