Structural Acoustics

Structural and acoustical optimization of segment plate based shell structures

Master Thesis Project in Architecture 2023

Herman Ehrnberg & Simon Wikström

Chalmers School of Architecture

Department of Architecture and Civil Engineering

Examiner: Kengo Skorick

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Abstract

This thesis aims to present a novel approach to the optimization of cassette-based shell structures covering an auditorium through a combination of acoustical and structural optimization techniques. The research is divided into three phases: theory, geometry, and design.

Phase 1 focuses on the theoretical foundation of the research, including the principles of acoustics, ray tracing, evolutionary algorithmic iterations, and cassette-based shell structures. This phase provides the necessary knowledge and understanding to develop a methodology for the optimization of shell structures that incorporates both acoustic and structural considerations and aims to establish a strong theoretical foundation that informs the optimization process in subsequent phases.

In Phase 2, the focus shifts to geometry optimization, where iterative optimization is conducted on the geometry of the shell structure. According to the methodology developed in Phase 1 the process involves the integration of acoustical theory, ray tracing, and evolutionary algorithmic iterations. The outcome of Phase 2 is a grasshopper component that can create an optimized auditorium design based on simple input parameters such as an approximate stage and seating area.

Finally, Phase 3 focuses on the final design of the auditorium based on the results of Phase 2. Materiality and effect are of critical importance in this phase. The aim is to create a visually pleasing and functional auditorium that meets the acoustic and structural performance requirements.

This project aims to add value to shell structures by integrating acoustical theory, ray tracing, and evolutionary algorithmic iterations to optimize both acoustical and structural properties. The thesis's goal is to provide a new methodology for optimizing shell structures that can be applied in various contexts, such as concert halls and theatres. The research presents a valuable contribution to the field of architectural design as well as to architectural acoustics and structural engineering by presenting a new approach to optimization that considers both acoustic and structural performance.

Keywords : optimization, shell-structures, ray-tracing, acoustics, auditorium design

Table of Contents

Introduction

Gridshells are incredibly efficient load bearing systems, as they are highly material effective (Schling et al., 2018), however, from experience shell structures are often limited due to budget restraints as their construction can pose a challenge due to thier complex geometry. Due to their efficient material usage one can argue they're a great alternative for the concerns regarding environmental impact. Today, most shell structures are novel and are designed by the largest architectural and structural firms. However, as material efficient and aesthetically pleasing as they are, they often lack additional value, something that this thesis aims to find.

Considering the double curved shape of a shell structure, combined with its versatility in shape, it seems highly applicable for acoustical venues. Although an acoustical analysis of a shell structure might be simple enough, it's important to keep in mind that the original value of the structure is its material effectiveness, which directly relates to its structural optimization.

Today there exists programs that can analyse a space acoustically, as well as programs that can analyse a structure structurally, but none that can do both analyses, and none that works towards quick optimizations. A problem that exists within acoustical architecture is that the entire model may have to be changed between each analysis, if the values are not satisfactory, which creates an unnecessarily lengthy process.

Aim

Therefore the aim of this project is to create a design tool that does not exist today, combining both the structural optimization with the acoustic, while still having a material focus on the aesthetics of the structure. This design tool will also have the focus of shortening the process time of finding an optimized solution by working with Evolutionary Algorithmic Iterations as a method, creating a tool that skips the need for manual iterations between each analysis. As a final objective, this thesis will end in a design project in the form of an auditorium created with the help of the design tool and the basis in the theory of the thesis.

This formulates the thesis main research question as:

"Can a cassette based shell structure be found that is optimized for both structure and acoustics, while still having aesthetics and material in focus?"

Method

The method used in this thesis takes its basis in the theory presented in Phase 1. This theory is developed through an extensive literature study, in combination with existing knowledge already possessed by the design team. The final design project is created with the help of a design tool that is constructed throughout the thesis. This design tool combines the use of Ray-tracing, in combination with acoustical analysis theory, with Evolutionary Algorithmic Iterations to find a structure optimized acoustically as well as structurally by changing a certain number of input parameters describing its geometry. The acoustics and the structure are analysed several times with different focus areas to eventually create a general shape, which is used as a mold for the final design.

The team believes that open source research and normalization of shells is needed, that working with its potential within acoustics adds another benefit to help outweigh the inherent negatives concerning monetarily costs. As the availability of robotics is increasing we believe that unique-element-based structures will become more common and that future auditoriums will become far more viable than what they are today.

As the project will be aimed at making shell structures more viable by adding an extra layer of value through acoustics, buildability and costs cannot be compromized, as that reduces the overall value of the shell. Because of this, a lot of focus is expected to be directed at the design of the cassettes themselves, and how they can be produced at a large scale.

Delimitations

The acoustic simulations of the project will be slightly limited as the team lacks background in this field as well as the time and experience needed to properly explore this. Instead, basic custom ray trace simulations will be performed as the means of optimization, as a proof of concept. The exact function of the structure will not be looked into, and any detailed calculations of its strength, will not be performed, especially in regards to joints. The feasibility and buildability of the structure will be approximated from the optimization in the computer programs used.

Reading Instructions

The thesis is divided into three different phases to increase understanding, Phase 1 is focused on theory, Phase 2 on Geometry and Phase 3 on Design. To browse only the design work, without understanding of the process or theory itself, Phase 1, and also Phase 2 to some degree, may be skipped by the reader.

Phase 1

Theory

When analysing the acoustics of a room there exists a massive amount of acoustical parameters that might be taken into consideration. However, these parameters can in general be divided into five different groups that corresponds to their subjective characteristics. These groups are classified as Reverberance, Loudness, Clarity, Balance and Envelopment. (Mahalingam, 1998)

For the project of an auditorium the first three groups are of the most importance, meaning the Reverberance, Loudness and Clarity, hence, these are what we will be analysing.

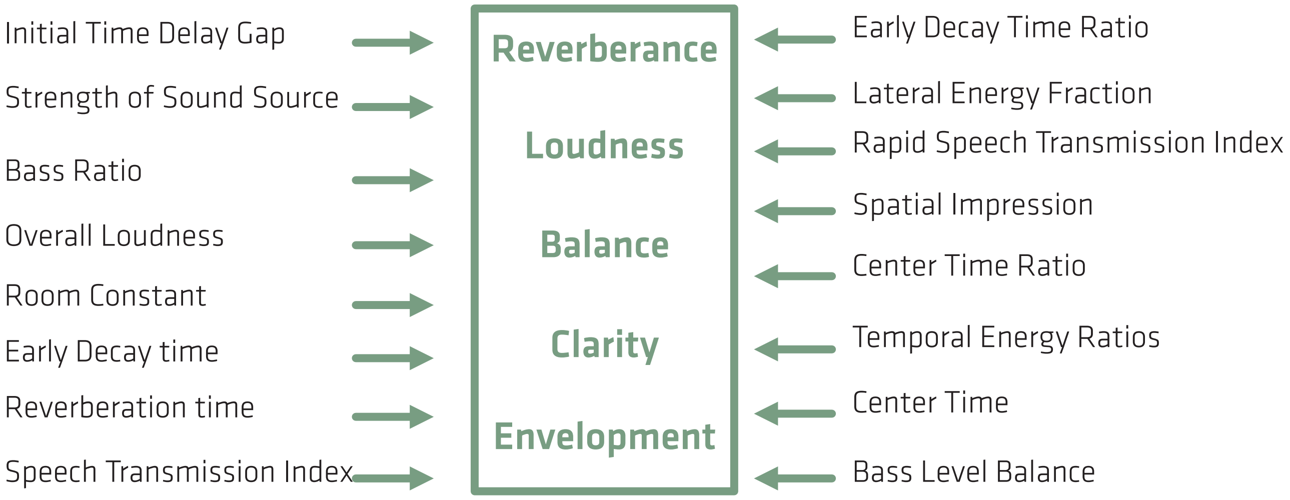


Figure 01, Acoustical Parameters

Reverberance, or Reverberation, is the measurement of the persistence of sound in a certain space after the original sound has been removed (Mahjoob & Malakooti, 2008). When sound is created from a source in a space it gives birth to a large amount of echoes. These echoes build up and then slowly starts to decay as the sound is absorbed by the different surfaces inside the space, as well as the air, creating reverberation. The reverberation has a big influence on the experienced acoustics of a room, and is of big importance for different performances. This study looks into the reverberation time, RT60, which is the time it takes for the sound strength to decay by 60dB below the level of the direct sound. The optimal value of RT60 varies for different performances according to the table in Figure 02.

When reverberation time is calculated the early decay needs to be taken into account. As the initial drop of 5dB can be affected by many factors the calculation of RT is normally performed from -5dB. This means that RT60 would be calculated from -5dB to -65dB.

Reverberation time is considered a global parameter, which means that it is highly affected by the room as a whole and not by local reflections. Therefore it is preferred as an average over a number of source receivers instead of specific receiver locations.

Performances	**RT60**
Symphonic	1.4-2.2s
Theatre	0.7-1.0s
Opera	1.3-1.8s

Figure 02, Goal Values for Reverberation Time RT60 (Zhang, 2005)

Clarity is a comparison between the ratio of the energy in the early sound and that in the reverberant, or later, sound, expressed in dB (Ahnert & Schmidt, 2011). It measures to which degree the individual sounds stand apart from one another. If the clarity is too low, the fast parts of the music melt into eachother, and are as such not readable or distinguishable anymore. Clarity is measured in different ways depending on the performance. For speaking performances, such as theatre or lectures, the first 50ms of sound is important, and clarity is hence measured in C50. However, for musical performances the first 80ms are of importance and clarity is hence measured in C80. The goal values for the different types of clarity can be seen in the following the table in Figure 03.

C50	**C80**
>-2dB	-3dB to +8dB

Figure 03, Goal Values for clarity C50 and C80 (Ahnert & Schmidt, 2011)

Loudness, or Sound Strength, is the subjective perception of sound pressure, how loud the sound is percieved. It is important that the loudness of the auditorium is high enough to be heard by the entire audience, at is also important to have an evenly distributed loudness throughout the room. It is however important to note that the total loudness depends mostly on the initial sound strength of the performance. Loudness is measured in dB.

The amount of sound energy reaching the stage is also important, escpecially for the performers, and is measured as Stage Support (ST1) in dB. Goal values for these parameters can be found in the table in Figure 04.

ST1
-15dB to -12dB

Figure 04, Goal values for Stage support (Ahnert & Schmidt, 2011)

Brilliance refer to the reverberation time at low frequencies relative to that of higher, or middle frequencies (Ahnert & Schmidt, 2011). Above 500Hz, the reverberation time should be the same for all frequencies, but at low frequencies an increase in the reverberation time creates a warm sound, while a decrease would create a more brilliant sound. The brilliance of a room is measured by the Bass Ratio (BR), goal values for the Bass Ratio can be found in the table in Figure 05.

Performance	**Bass Ratio**
Music	1.0-1.3
Speech	0.9-1.0

Figure 05, Goal Values for Bass Ratio (Ahnert & Schmidt, 2011)

To be able to calculate these properties as easy as possible a connection between them is sought. The connection found is that they all depend in some way on the amplitude of the sound waves (or simply, the energy carried by each wave) as well as the velocity of, and time and distance travelled by the waves. Therefore the properties are all broken down into these parameters, giving the following equations.

To be able to calculate these properties in a more direct way, the sound waves are simplified as sound rays, travelling linear through the air, with a value of sound energy as a representation of their amplitude as waves.

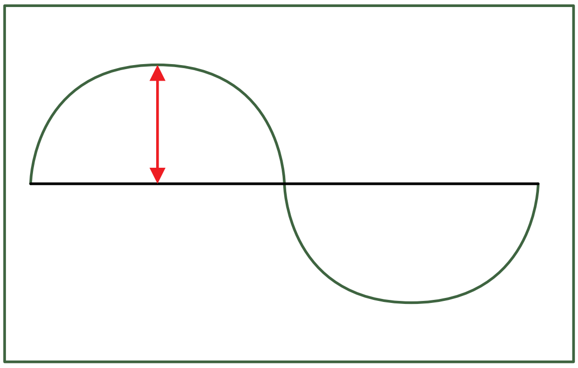


Figure 06, Amplitude of a sound wave

Clarity, Stage Support & SPL calculations

Clarity is as mentioned earlier calculated from the early sound energy reaching the receiving location compared to the late sound energy reaching the same location. For speaking, the first 50ms are counted as early and for music, the first 80ms. Hence the values C50 and C80, respectively, are calculated according to Equation 1 & 2.

$$C_{50} = 10 \times log(\frac{E(0-50ms)}{E(50ms-end)})$$

Equation 1, Clarity, C50

$$C_{80} = 10 \times log(\frac{E(0-80ms)}{E(80ms-end)})$$

Equation 2, Clarity, C80

Stage Parameters shows how the acoustics influence the experience for the musicians playing on a stage. The Stage Support is calculated in dB according to Equation 3 for the energy reaching 1m from the performer.

$$ST1 = 10 \times log_{10} \times \frac{E_{20-100ms}}{E_{5ms}}$$

Equation 3, Stage Support, ST1

The Sound Pressure Level, or the loudness, is calculated with the sound energy of the receiving location in comparison to a reference value which is equal to the intensity of the lowest sound which can be heard by human ears at a frequency of 1000Hz (Ahnert & Schmidt, 2011). This value, E0, is equal to 1 * 10^-12 W/m2. Hence the sound pressure level is calculated according to Equation 4.

$$SPL = 10log_{10}(\frac{E}{E_0})$$

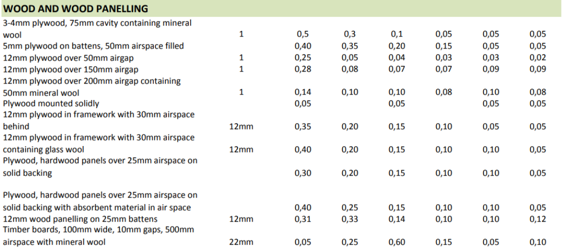
Equation 4, Sound Pressure Level, SPL

As can be seen in the equations the sound energy present at the acheiving location is of the highest importance, however, this value will not be the same as the value of the initial sound energy as the rays lose energy due to several different occurences while travelling. The three most pronounced energy losses are those of scattering, absorption and attenuation. (Cox et al., 2006)

Sound scattering, is when the sound ray hits a surface that is not entirely smooth and therefore reflects in several different directions. When calculating the remaining energy from a reflection a scattering coefficient is taken into acount for the energy lost in different directions than the main direction.

Sound absorption is when the sound energy is absorbed into the reflective surface due to pores. The lost energy is taken into account with an absorption coefficent. Both the absorption and the scattering coefficient are material dependant as well as frequency dependant and signifies how much energy is lost through absorption and scattering respectively. The scattering coefficient as also, however, dependant on the shape of the surface, as a smoother surface will give less scattering.

Values of absorption coefficients of different materials can be found in the table “Absorption Coefficients” (Acoustic Project Bureau, 2003), with a few examples in Figure 07.



WOOD AND WOOD PANELLING							
3-4mm plywood, 75mm cavity containing mineral wool	1	0,5	0,3	0,1	0,05	0,05	0,05
5mm plywood on battens, 50mm airspace filled		0,40	0,35	0,20	0,15	0,05	0,05
12mm plywood over 50mm airgap	1	0,25	0,05	0,04	0,03	0,03	0,02
12mm plywood over 150mm airgap	1	0,28	0,08	0,07	0,07	0,09	0,09
12mm plywood over 200mm airgap containing 50mm mineral wool	1	0,14	0,10	0,10	0,08	0,10	0,08
Plywood mounted solidly		0,05		0,05		0,05	0,05
12mm plywood in framework with 30mm airspace behind	12mm	0,35	0,20	0,15	0,10	0,05	0,05
12mm plywood in framework with 30mm airspace containing glass wool	12mm	0,40	0,20	0,15	0,10	0,10	0,05
Plywood, hardwood panels over 25mm airspace on solid backing		0,30	0,20	0,15	0,10	0,10	0,05
Plywood, hardwood panels over 25mm airspace on solid backing with absorbent material in air space		0,40	0,25	0,15	0,10	0,10	0,05
12mm wood panelling on 25mm battens	12mm	0,31	0,33	0,14	0,10	0,10	0,12
Timber boards, 100mm wide, 10mm gaps, 500mm airspace with mineral wool	22mm	0,05	0,25	0,60	0,15	0,05	0,10

Figure 07, Example values for and absorption coefficients for various frequencies and materials (Acoustic Project Bureau, 2003)

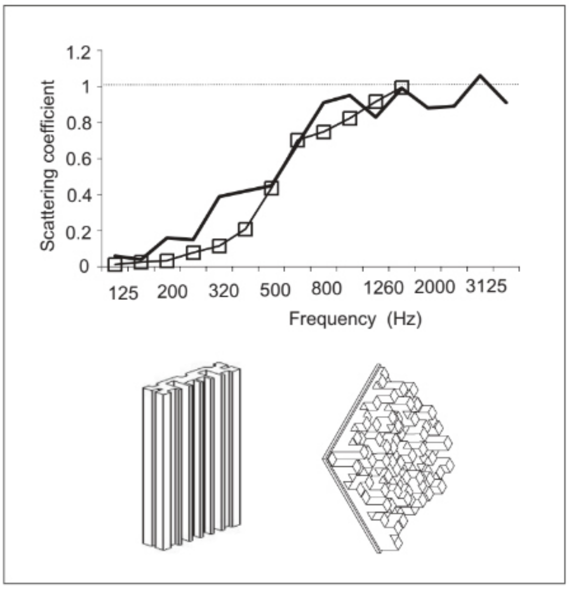


Figure 08, Scattering Coefficients for different frequencies for two different kinds of diffusers (Cox et al., 2006)

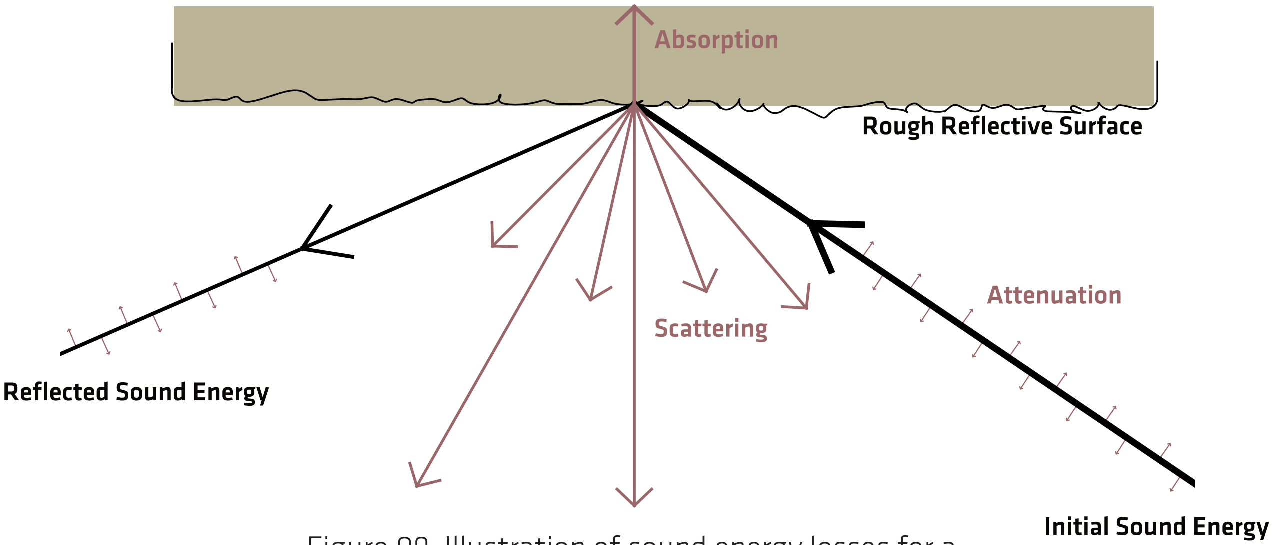


Figure 09, Illustration of sound energy losses for a single sound ray

Attenuation is the sound energy losses due to travelling through air and depends on several factors such as the pressure, temperature and relative humidity of the air, as well as the frequency of the sound waves (ISO, 1993). Even though the calculations are done with the simplification of sound rays, they will still need to take the original frequency of the waves into account.

The attenuation coefficient is measured in dB/m and different values can be seen in the table in Figure 10.

Frequency, Hz	Relative Humidity %			
	30	40	50	60
63	0.00019	0.00015	0.00012	0.00010
125	0.00060	0.00051	0.00044	0.00038
250	0.00141	0.00138	0.00131	0.00121
500	0.00251	0.00262	0.00272	0.00278
800	0.00386	0.00379	0.00390	0.00406
1000	0.00500	0.00465	0.00466	0.00480
1250	0.00674	0.00592	0.00571	0.00574
1600	0.00977	0.00810	0.00745	0.00724
2000	0.01411	0.01120	0.00988	0.00928
2500	0.02081	0.01600	0.01364	0.01239
3150	0.03156	0.02375	0.01971	0.01740
4000	0.04889	0.03642	0.02966	0.02563
5000	0.07353	0.05482	0.04423	0.03771
6300	0.11139	0.08398	0.06762	0.05722
8000	0.16834	0.13002	0.10529	0.08893
10000	0.24187	0.19358	0.15883	0.13469

Figure 10, Attenuation coefficients of air at 20 degrees Celcius in dB/m (ISO, 1993)

The energy reaching the receiver can as such be calculated by the initial energy leaving the sound source, the attenuation coefficient of the air, and the absorption and scattering coefficient of the reflective surfaces according to Equation 5.

$$E = E_0 \times e^{-h \times d} \prod_i (1 - \alpha_i - s_i)$$

Equation 5, Sound energy calculation

Where E is the sound energy at the receiving location,

E_0 is the initial sound energy,

e is the constant e = 2.718,

h is the attenuation coefficient in dB/m,

d is the distance travelled by the ray,

$\prod_i$ is the multiplication summation for the reflective surfaces,

α_i is the absorption coefficient for the i-th surface,

s_i is the scattering coefficient for the i-th surface.

The reverberation time can be calculated in two different ways, one quicker estimation that does not depend on the exact geometry of the room, but on its volume and absorption, and one that depends on the decaying of sound energy in the room (Odeon, 2021). The quicker estimation is calculated according to Equation 6. Where V is the total volume of the room, Si is the surface area of material i and alphai is the absorption coefficient of material i.

$$RT60 = \frac{0.161 \times V}{\Sigma(-S_i \times ln(1-\alpha_i))}$$

Equation 6, Reverberation Time, RT60

The other method depends on the decaying sound energy of the room and can therefore be calculated according to earlier theory with rays carrying sound energy instead of sound waves. Here the output diagram of receiving location should show a decaying curve measuring the sound energy in that spot. The decay curve shows how energy decays in time after a continous sound source has been switched off depending on the total sound pressure level and on the time. For the estimation of Reverberation time there should be one decay curve for each freqency band.

For this decay curve not only the reverberation time is important, but also the curvature of the curve as it indicates how straight the decay curve is, and therefore how evenly the sound drops in the room. It is defined according to Equation 7.

$$C = 100(\frac{T_{30}}{T_{20}} - 1)$$

Equation 7, Curvature of the sound decay curve, C

Ideally the curve should be as straight as possible, however, values of curvature below 10% are perfectly acceptable, while higher than 15% are not recommended (Odeon, 2021).

The bass ratio also depends on the reverberation time, and the comparison of RTs for different frequencies. A higher reverberation time for the lower frequencies compared to the higher frequencies gives a higher Bass Ratio, and therefore a warmer sound, while the opposite would give a more brilliant sound. The Bass Ratio is calculated according to Equation 8.

$$BR = \frac{RT_{125Hz} + RT_{250Hz}}{RT_{500Hz} + RT_{1000Hz}}$$

Equation 8, Bass Ratio, BR

The Speech Transmission Index (STI) indicates how well speech is understood and is calculated in dB according to Equation 9.

Where SIIi is the Speech Intelligibility Index for the i-th frequency band according to Equation 10.

Where wi is the weighting factor for the i-th frequency band and Di is the modulation depth of the i-th frequency band.

Di is calculated according to Equation 11, where S is equal to the sound pressure level of each frequency band.

The weighting factors used can be found in the international standard IEC 60268-16: This is a set of weighting factors developed by the International Electrotechnical Commission (IEC).

Values for the weighting factors for each frequency band can be seen in the table in Figure 11, note that the factors are used to give more weight to the frequency bands that are more important for speech intelligibility.

$$STI = \frac{1}{7} \times \Sigma SII_i$$

Equation 9, Speech Transmission Index, STI

$$SII = \Sigma(w_i \times D_i)$$

Equation 10, Speech Intelligibility Index, SII

$$D = \frac{S_{max} - S_{min}}{S_{max} + S_{min}}$$

Equation 11, Modulation Depth, D

Frequency (Hz)	Weighting Factor wi
125	0.2
250	0.2
500	0.2
1000	0.2
2000	0.1
4000	0.05
8000	0.05

Figure 11, Weighting factors, w (IEC 60268-16)

Subjective scale	STI value
Bad	0.00-0.30
Poor	0.30-0.45
Fair	0.45-0.60
Good	0.60-0.75
Excellent	0.75-1.00

Figure 12, Goal values for STI (IEC 60268-16)

When analysing the acoustics of a room with regards to the different materials of the different elements of the room there are many different parameters to take into consideration. As has been mentioned earlier there are various material dependent coefficients that describes different acoustical events that takes place in and around them, such as absorption and diffusion (scattering). But there are also other considerations that needs to be made according to material. Especially in regards to the shell structure, which will need to be buildable, but also the regards of effect and aesthetics in general.

Figure 13, CNC-milled timber prototypes (Peters et al., 2020)

There are several novel material analyses for acoustic properties in combination with various digital fabrication methods and techniques, some of which might be highly interesting when it comes to the combination of acoustics and segment based shell structures. Some examples are the robotically-controlled nozzle-extruded polyurethane foam (Bonwetsch et al., 2008), the robotically fabricated mass timber acoustic surfaces (Peters et al., 2020), the 5-axis CNC milling of MDF structural cells (Peters et al., 2013), as well as the robot-controlled folding and welding of a plastic (Vomhof et al., 2014). There also exists a built project that has merged acoustic performance with digital fabrication that includes 6000m2 of sound scattering CNC-milled gypsum panels, namely the Elbphilharmonie Hamburg by architects Herzog and DeMeuron.

Figure 14, CNC-milled gypsum panel for the Elbphilharmonie Hamburg by architects Herzog and DeMeuron. Image from Hasenkopf Industrie Manufaktur

As mentioned earlier, this project makes use of a simplified theory where the sound waves are instead thought of as rays, with values of sound energy instead of amplitude and sorted into frequency bands. For the calculations a method called ray-tracing is therefore used, taking advantage of the earlier simplification.

Ray-tracing is a simplified geometrical method where the analysis is foused on rays travelling linear through space from one point to another. The ray-tracing techniques are derived from image synthesis, and lighting and thermal simulation (Mahjoob & Malakooti, 2008).

As input for this project there are in general two different types of surfaces, with different properites. Reflecting surfaces and receiving surfaces. The reflecting surfaces are those of the stage and the cassette based shell structure, while the receving surfaces are those of the seating area.

When a ray-trace analysis is started a large quantity of rays are leaving the sound source in the center of the stage simultaneously to simulate an instantaneous blast of sound. The rays are allowed to be reflected on the reflecting surfaces as they travel across the room. The quantity and the quality of the rays terminating at the destination surfaces gives the result necessary for the acoustic calculations according to the theory.

The quality of a ray refer to the amount of sound energy it contains, as well as its travelled time and distance.

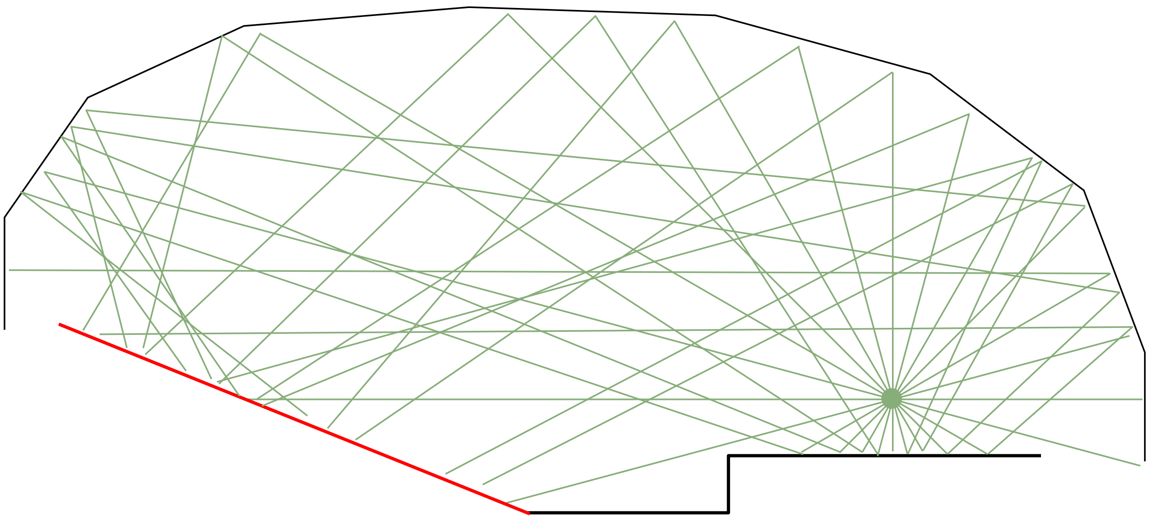


Figure 15, 2D illustration of Ray-Tracing

A certain quantity of rays are sent out with a base Sound Energy value, velocity and frequency.

Traveling through the air they lose energy due to the air's attenuation.

When they hit a reflective surface they lose energy due to the surfaces' absorption coefficient and scattering coefficient.

When the rays hit a receiving surface they stop, their sound energy is noted, the time it took for them to travel there is noted, the distance it took for them to travel there is noted.

From these values the various Acoustical Parameters are calculated.

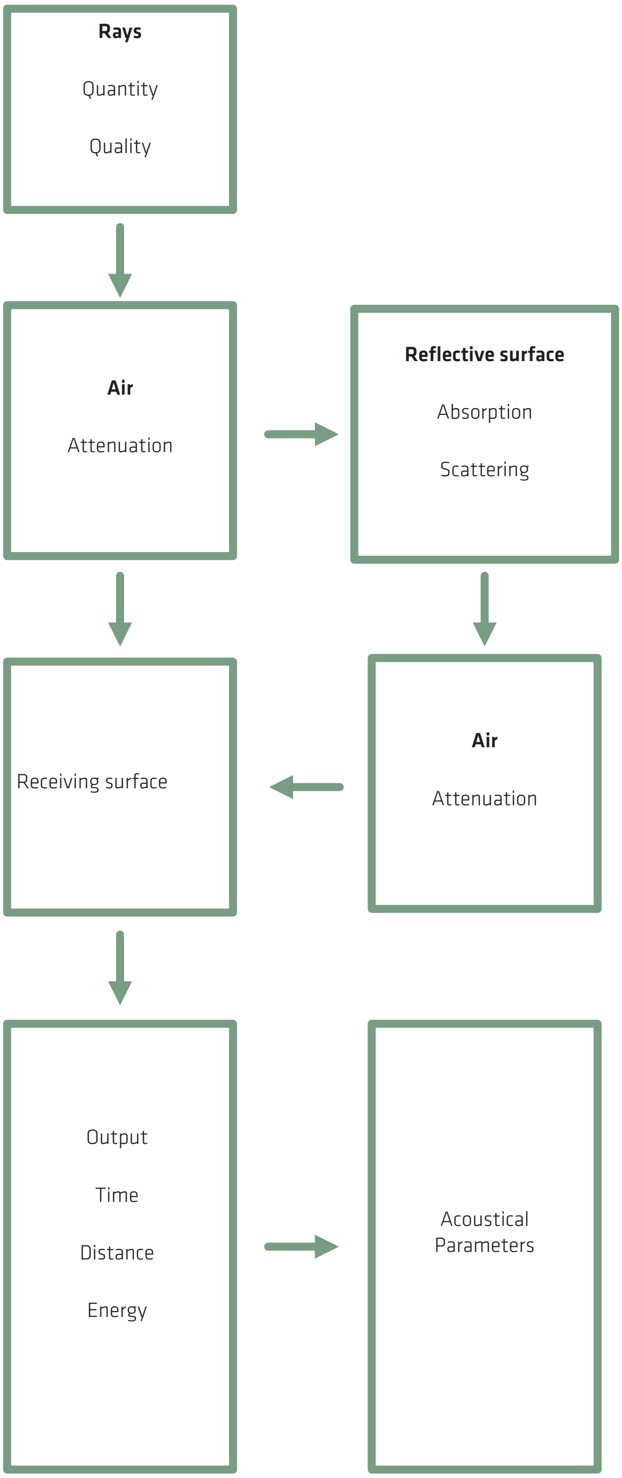


Figure 16, The ray-tracing method

A shell structure in construction and architecture can generally be described as a curved plate that transmits applied forces in tensile, shear and compressive stresses that act in plane with the surface (Deloney, 2021). For distributed loads the most efficient shape of the shell is curved in two directions, creating a smooth, flowing surface which can be found by dynamic relaxation algorithms, which is the primary method for developing the overall geometry of grid shells such as the courtyard roof of the British Museum.

The advantage of load-bearing shell structures is that they eliminate the need for interior columns and walls, providing unobstructed space and flexibility for interior design and they provide a distinct architectural expression (Deloney, 2021). However, they require careful planning and engineering to ensure that the bearing capacity is distributed evenly in accordance to the loads across the shell and that it can resist all the forces acting on the building.

While load-bearing shell structures can be categorized into different types, the specific categorization may vary depending on the criteria used. One way to categorize load-bearing shell structures is based on their construction method. In this context, load-bearing shell structures can be categorized into three main types: overlapping continuous members gridshells, short element gridshells, and cassette-based systems.

Overlapping continuous member gridshells refer to shell structures where the curved surface is formed by long-spanning members that work in compression, tension and/or active bending. These long-spanning members are typically made of engineered timber or composite materials. This construction method is commonly used in large-scale shell structures such as Frei Otto's Multihalle. Long span member gridshells offer a low degree of design flexibility and are suitable for large spans. They are relatively cheap to construct but require skilled labor. The grid of laths are typically layed flat and pushed into its supports and the final shape is formed and stiffened (Tayeb et al., 2019).

Short element gridshells refer to shell structures where the curved surface is formed by a grid of smaller, modular elements. These elements can be made of timber, steel, or other lightweight materials, and are typically connected together in a steel connection. This construction method is commonly used in a variety of scales of shell structures, such as experimental pavilions or the courtyard roof of the British Museum. Short element gridshells are lightweight, easy to assemble, and offer a high degree of design flexibility. However, each connection typically vary in angles making them relatively expensive to manufacture (Tayeb et al., 2019).

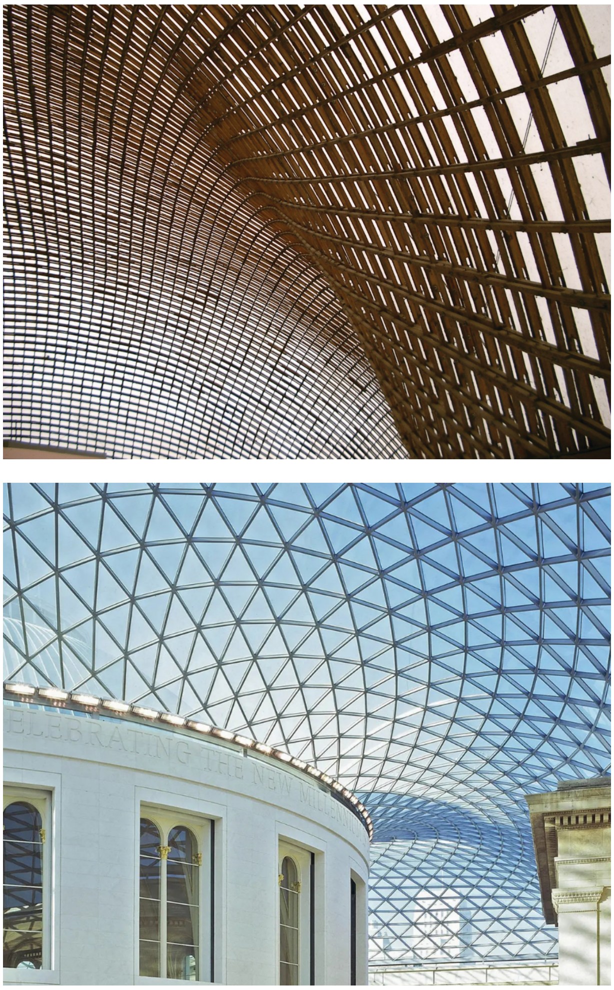


Figure 17, Top: Multihalle Mannheim by Frei Otto, 1975 (Schling et al., 2018) Bottom: British Museum glass ceiling (The Guardian, 2020)

Cassette-based systems refer to shell structures where the curved surface is formed by a series of pre-fabricated panels or cassettes that are connected together on site (Robeller et al., 2016). These cassettes are typically made of lightweight materials such as composite materials, stone or timber, and are designed to be easily assembled into the desired shell shape. This construction method was recently used in a double-layered timber plate shell (Robeller et al., 2016) as well as the Landegsgartenschau Pavilion (Li & Knippers, 2014). Cassette-based systems are highly modular, easy to assemble, can be stiff enough to slightly differ from the formfinding models allowing a very high degree of design flexibility and can include cladding, insulation etc. The main drawbacks are that they typically require a long, carefull planning stage. The prefabrication of the cassettes needs to be highly automated and the capacity of the joints need to be verified for many different angles. To reduce complexity for manufacturing complexity is often introduced in the planning stage as each cassette needs to consist of only planar elements cut by a saw.

In this project, cassette based shell structures are implemented on the shells of the auditorium after it has been optimized both acoustically and structurally. As it is a type of structure that is highly applicable to most types of double curved shapes it should be the most suitable type of structure for this project. There are, however, various types of cassette based shell structures that all follow the basic rules of planar sides and even distribution of loads. This project will look into the type of cassettes that might be suitable for an auditorium-type building, i.e. cassettes that in generall fill the entire structure, but gives the possiblity for rotation, hollowing and pitting. This to give the opportunity for different values of absorption and scattering throughout the structure. The structure should also strive for being as symmetric as possible to ease construction by having several indistinguishable cassettes.

Figure 18, Different types of cassette based shell structures

Evolutionary algorithmic iterations is a method of iterations where the geometry that is being iterated evolves due to its earlier generations (Cohoon et al., 2003). There are several different types and methods of evolutionary algorithms, but in general they all work in the same way. The method studied and used in this thesis is a genetic algorithm method with a survival selection process. In general the method works as follows.

A gene pool of different values describes and creates the geometry in question, a simple example would be in the way that a cube is described and created by the values of its width, height and depth.

A fitness function searching for a goal value is then implemented on the geometry. For the cube the function might be its volume, and the goal value 100mm3.

A number of maximum iterations per generation is chosen, a higher number is usually connected to a better end result, but also to a slower process.

Then the iterations start. For the first generation seemingly random combinations of values for the gene pool are iterated, and therefore many different geometries and volumes. When the maximum number of iteration is reached, the process stop.

The program then finds the iterations with the function values closest to the goal value, saves these geometries for reproduction, and starts the next generation with the gene pools describing the geometries with these values.

Then the iteration in the next generation starts, this time with the best results from the earlier generation as starting values, and only small differences in the genes compared to this iteration. This means that all iterations in this generation is in some way similar to the geometries with the starting values. When maximum iterations are reached, the fitness function is calculated, and the iterations with the best values are picked out and brought to the next generation.

And so the process proceeds, for as many generations as necessary.

However, a risk with this type of iteration exist. It is highly possible that the algorithm does not end up at the best possible value, but instead at a local maximum value.

If the best iterations from the first generation is not close enough to the best possible value the system might find only the best similar solution, since all upcoming generations will evolve from the original values. And if there exist inferior solutions that lies “genetically” inbetween this local maxima and the total maxima, the algorithm will never iterate past these, since its always looking for a better solution than the previous, and therefore never reach the best possible value.

There does, however, exist a possible solution for this problem, namely, mutations. A mutation is a random mix of values for the gene pool being thrown into a generation. This random mix might prove a better solution than those of the generation, and therefore entirely take over the evolution, making the algorithm jump out of a local maximum value, and instead strive for a better solution.

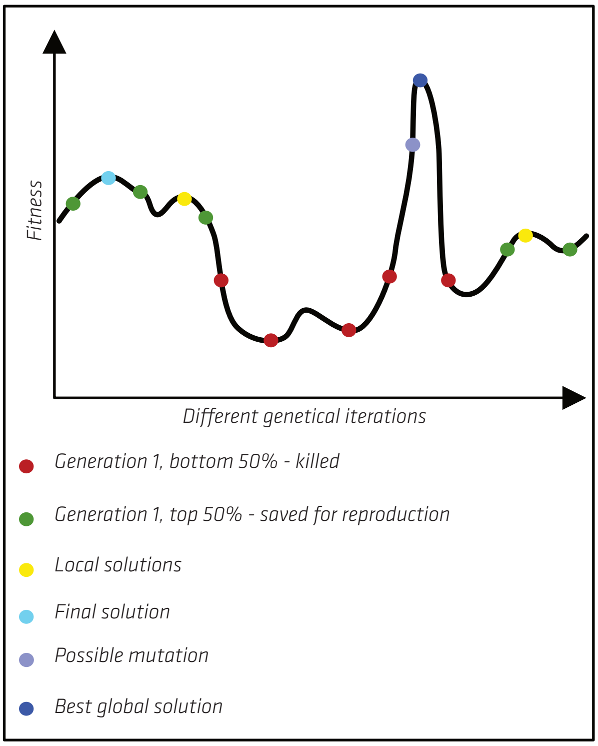


Figure 19, Local maxima and mutations

The general idea of the system used in this thesis is built on the theory presented above. The input is presented in the shape of an approximate stage, a sound source and a seating area which are used to create a flat base geometry.

This geometry is raised as a wall and roof structure by several different parameter values, which in this case is the gene pool.

Then the initial generation of random geometries is iterated. On these geometries the ray tracing analysis is performed and from that the acoustic analysis with the goal values following the acoustical theory.

The best geenes are kept for the next generation, and on it goes until satisfactory values has been found. Mutations are implemented when necessary.

When the absolute best result is found, it is developed into a cassette based structure according to the theory above, and from there developed into a final auditorium design.

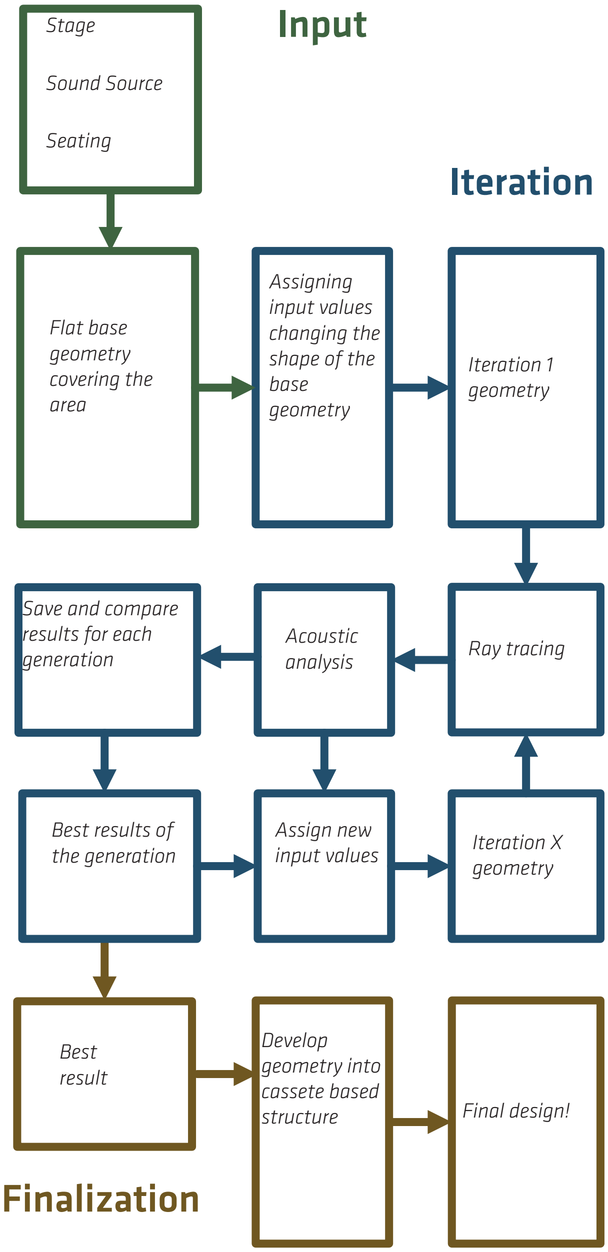


Figure 20, The general iterative method

The component that is the outcome of this thesis works according to the methods presented above. It starts from simple input values in form of geometry and numerical values and goes through an iterative optmizing process. As an output it gives not only the best solution but also the result of the analysis in the form of acoustical diagrams and graphs.

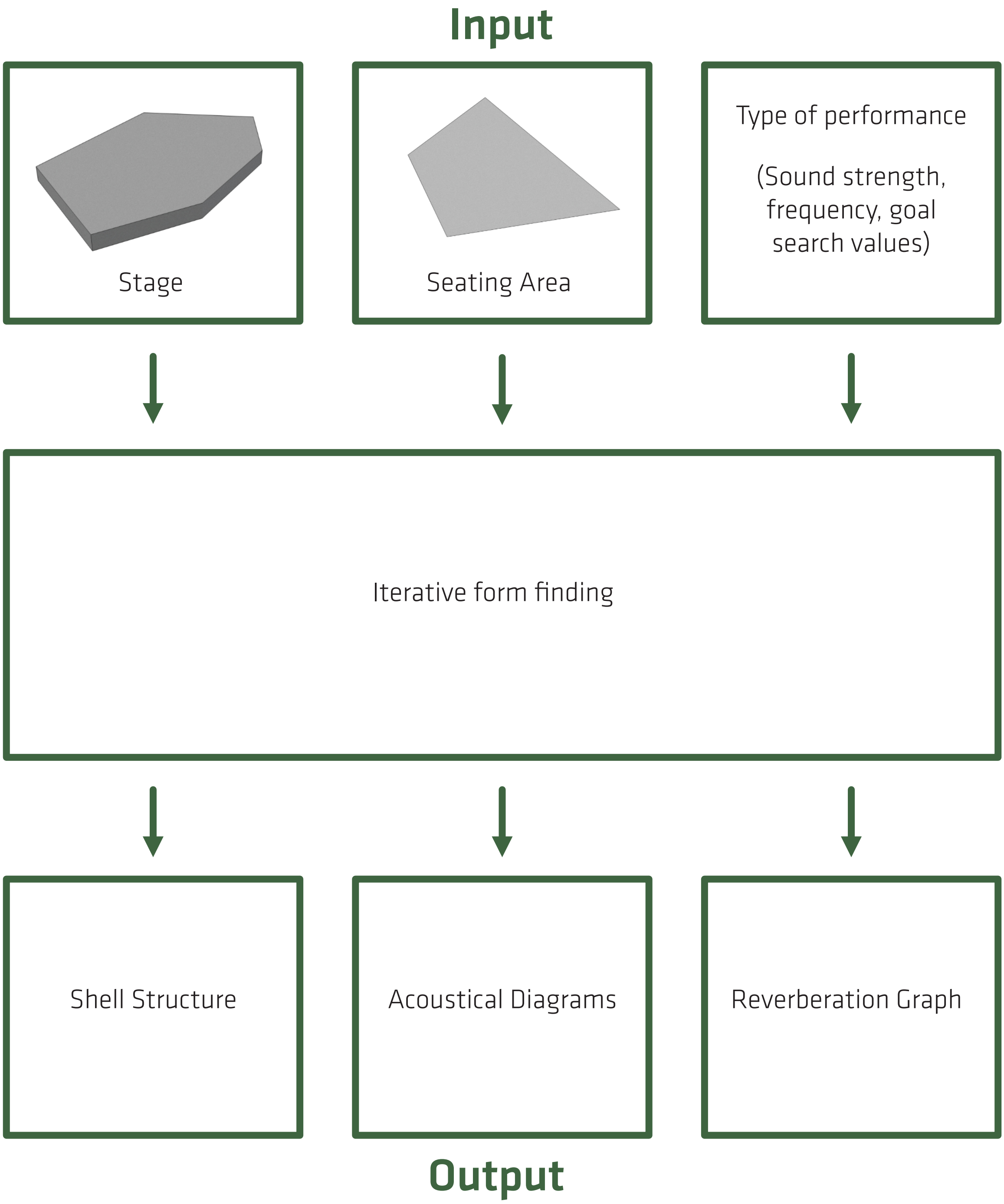


Figure 21, The general idea of the component

Phase 2

Geometry

Ray tracing is a computational method that simulates how sound waves propagate through a virtual 3D environment by tracing the paths of individual sound rays. Based on theory, the interactions between these rays and surfaces and their material can be modeled to predicts how sound will propagate and be perceived in a given space. The information needed from each ray is its distance traveled between each reflection and what surfaces it reflected on. Based on this the energy and timings are calculated which is all that is needed to get approximated acoustical values for the given space, following the theory in Phase 1.

Rhino has a library containing a RayCast function, however it does not keep track of which surfaces has been reached and reflected on by the rays. To get that information the script would need to compare the reflection location to all surfaces and choose the closest one. This is very computationally heavy which is not acceptable for a the iteration process and because of this another method was developed.

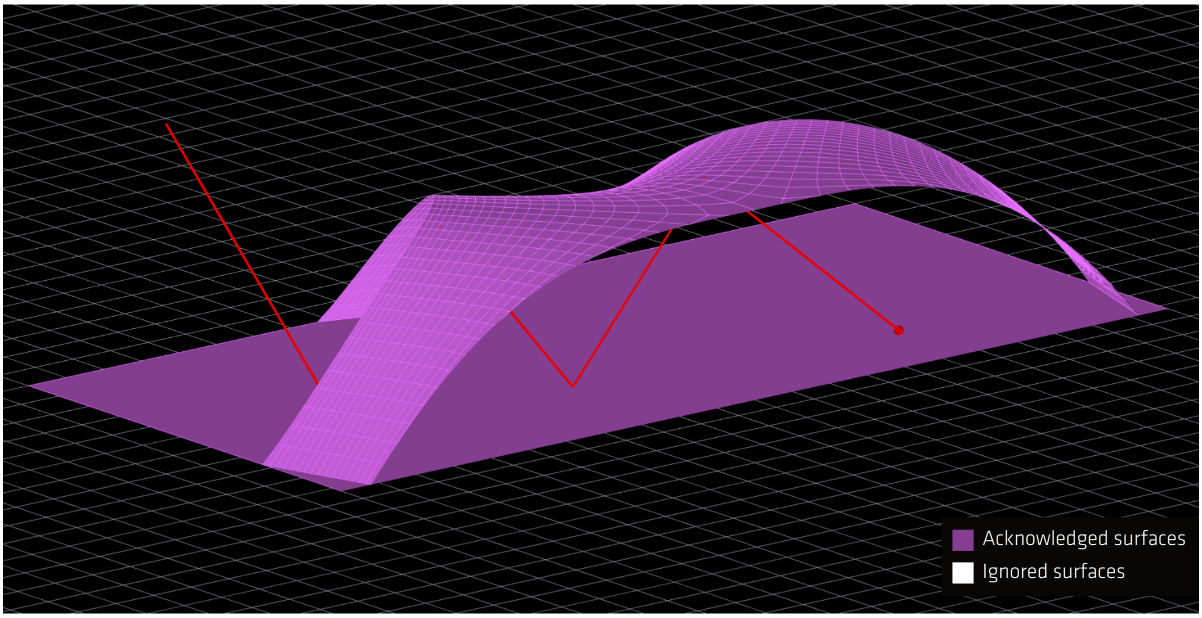


Figure 22, Simulation of Rhino RayCast function with a single ray

The method used is based on voxels (pixels in 3D) instead. Each voxel contains data about what surfaces it intersects with. This lightens the computational load as each ray can only see its relevant surfaces. It uses an algorithm commonly used within computer graphics to traverse the voxels along its direction. When a voxel contains surfaces the ray is cast onto those and only those surfaces. If it reflects it repeats, if not it continues traversing according to the algorithm.

Each time the ray reaches a surface its energy decreases based on the distance traveled and the absorption coefficient of the reached surface. If it reaches a receiver surface, data containing where on the surface it reflected, the rays energy and when in time it reflected is saved.

Casting thousands of rays in all directions, all relevant acoustical properties are simulated and can as such be displayed and evaluated.

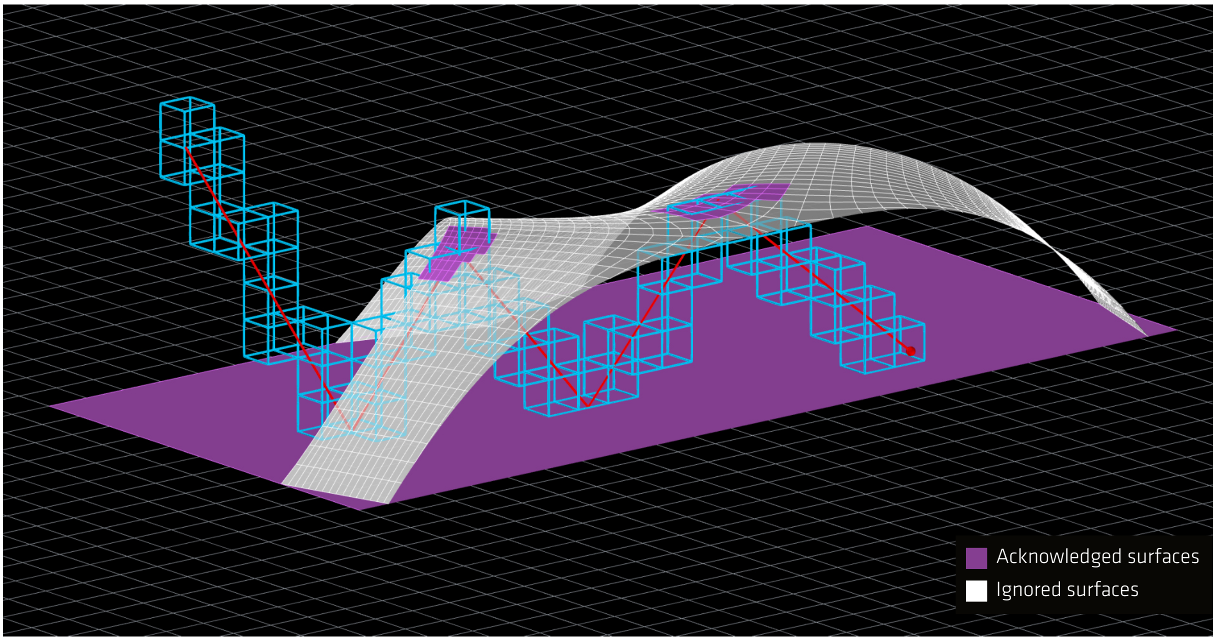


Figure 23, Simulation of the Voxel-based RayTracing component with a single ray

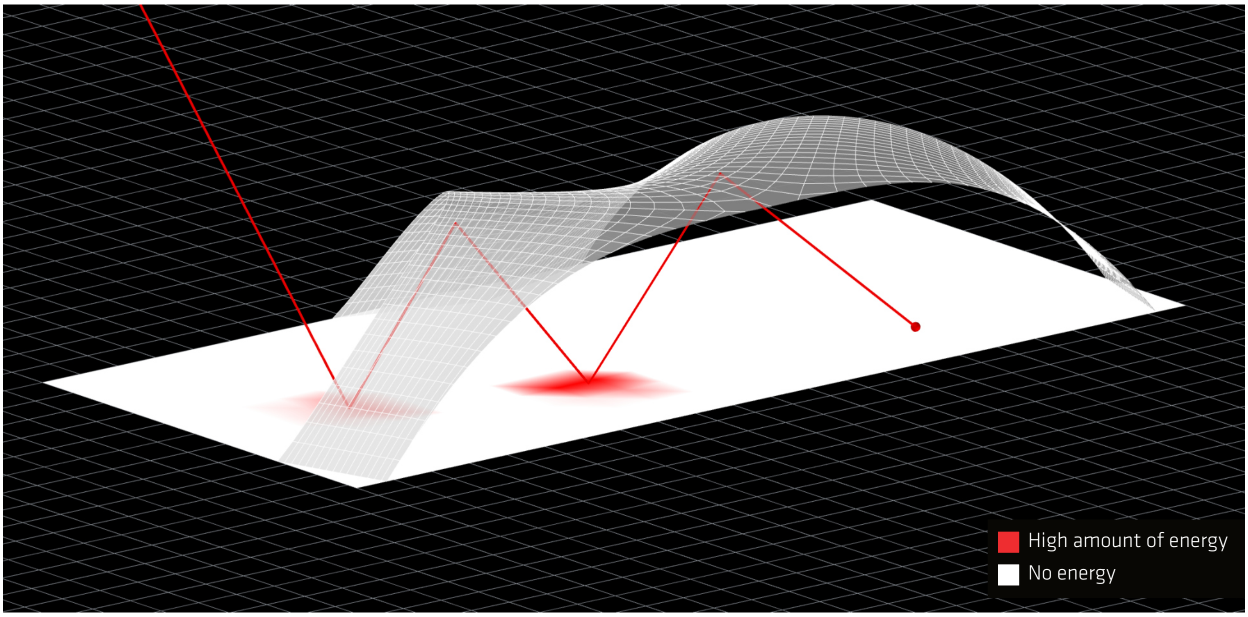


Figure 24, Simulation of the energy in each impact of the ray on the receiving surface, a higher density of color represents more energy. As can be seen the energy of the ray decreases with each reflection.

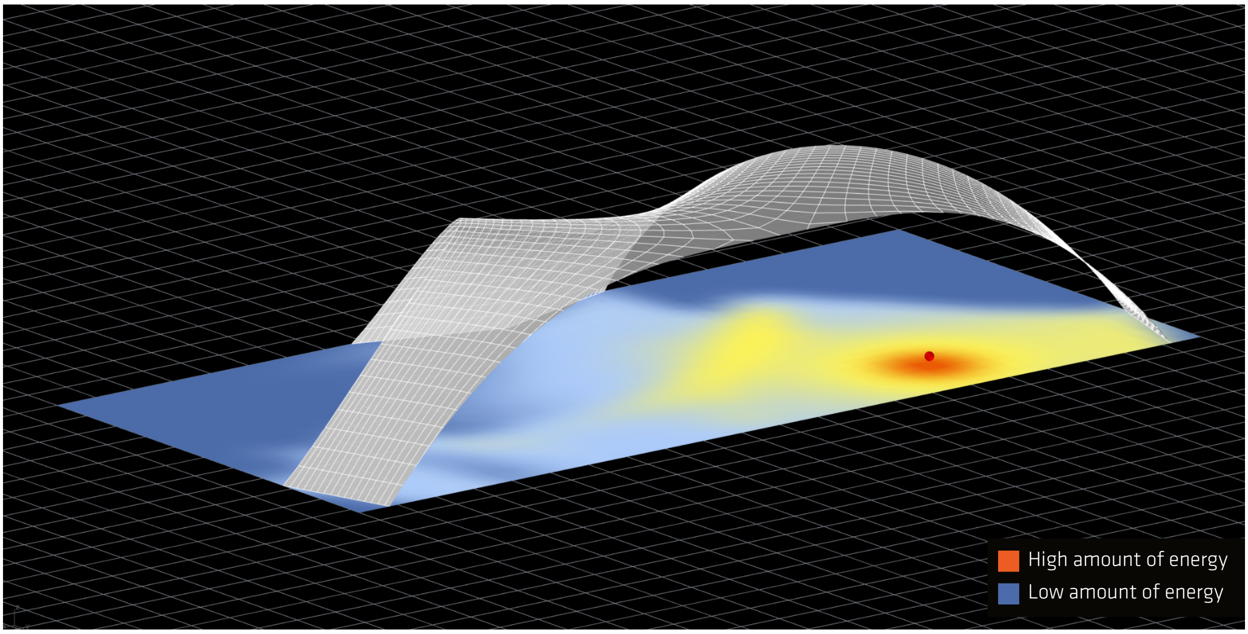


Figure 25, Simulation of the Sound Pressure Level in this particular case, using the Voxel-based RayTracing component

During the construction of the component several tests were made to see how it works, what could be improved and to create a general understanding of ray tracing as a method of acoustic analysis. The ray-tracing component was then combined with the acoustical theory to give a direct response on the acoustical properties of the room in the form of acoustical diagrams. These diagrams represent Sound Pressure Level (SPL) distributed over the seating surface. However, their values are in this stage of no importance.

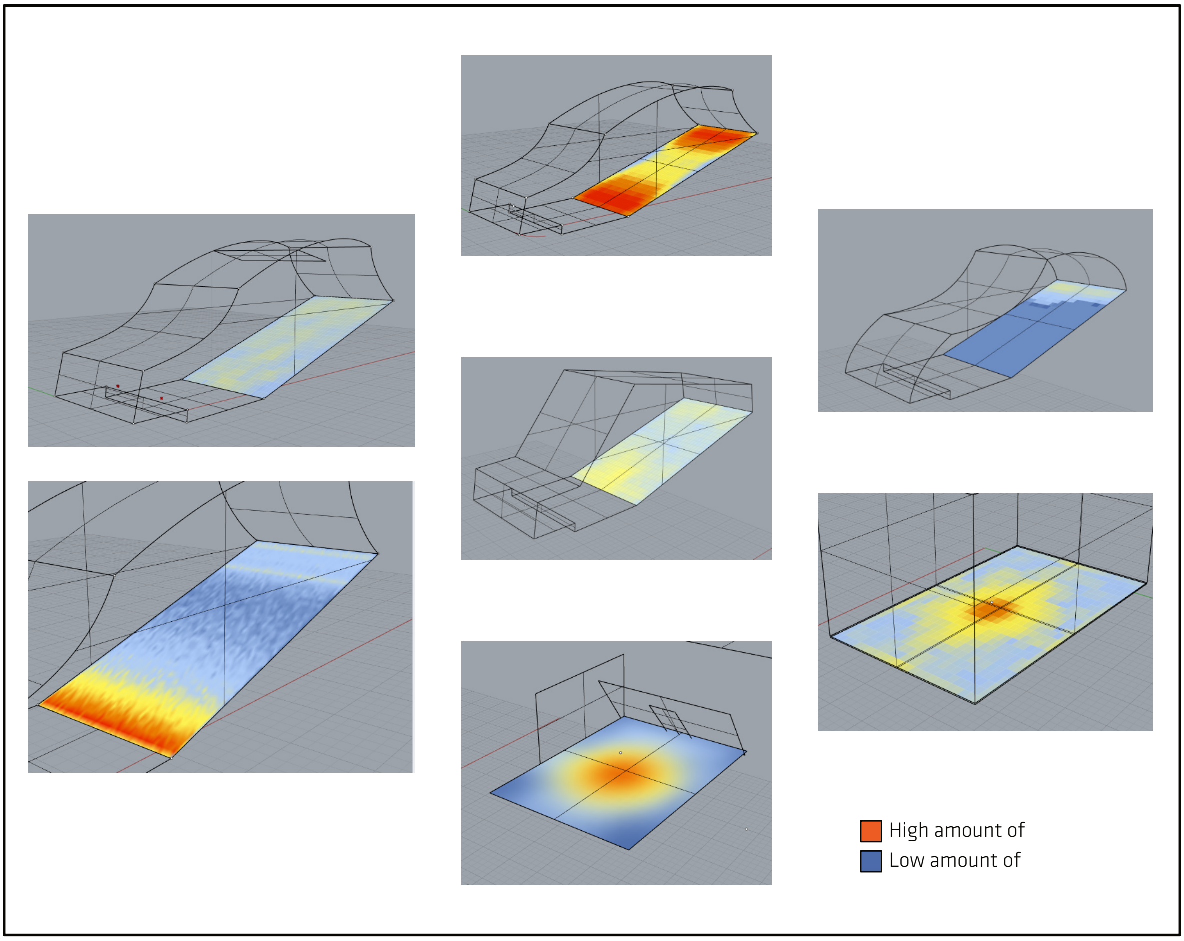


Figure 26, Ray-tracing testing

The component was tested on a 3D-model of Göteborgs Konserthus to test its probability on one of the best shoebox-type auditorium in the world, but also to create the possibility to learn what it is that makes the acoustical properties of this venue as good as they are. The acoustic parameters that was being tested was the Sound Pressure Level as well as the Clarity (C50, C80). In this test it was clear to see that the distribution of the Sound Pressure was quite even thoughout the hall and that the Clarity had large zones with very good values. What was also noticed was that the big reflector in the back of the hall, as well as the reflective nooks on its side walls helped massively with the good acoustical values.

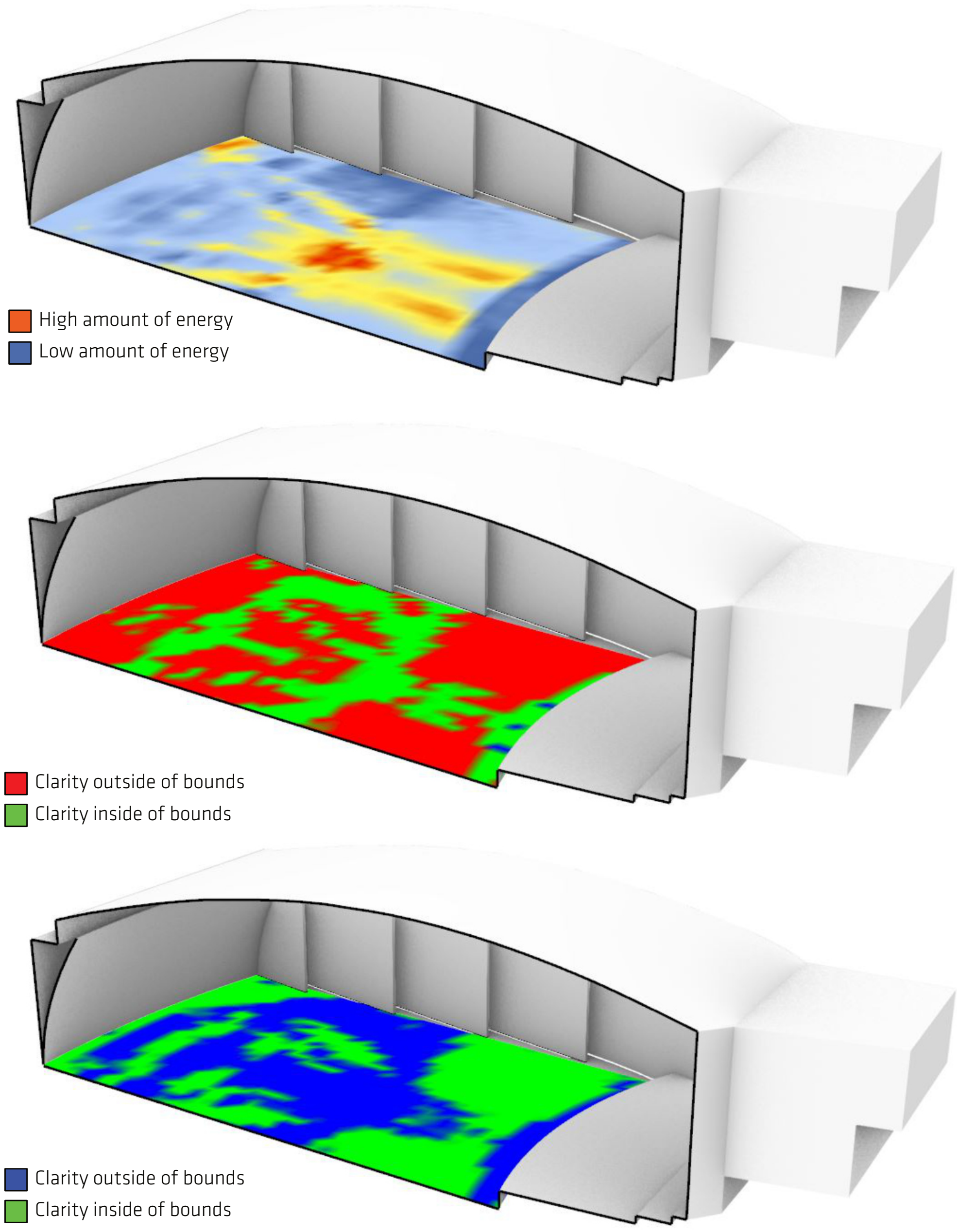


Figure 27, Acoustical analysis of Göteborgs Konserthus. SPL, C80 and C50 respectively.

Form-finding

The form-finding component that was used when iterating for the final auditorium shape takes its base in a parametric Grasshopper script that should be able to create a large amount of versatile shapes from the simple inputs of an approximate stage and seating area. For this project, the process was done in several steps before landing on the solution that seemed most suitable and versatile.

Firstly the shape was made as a mesh with a Kangaroo-form finding method. Although this method provided a lot of different shapes, the auditorium as a whole lacked a certain flair, and the mesh itself was quite difficult to control.

Secondly the shape was made as a mesh resting on top of side walls. This provided a more easily changeable shape, as well as a more aesthetic overall-look, however, the total geometry did not seem versatile enough. In this phase of the process, some trials on rotating and resizing the panels of the mesh was made. These ideas were brought further into the process.

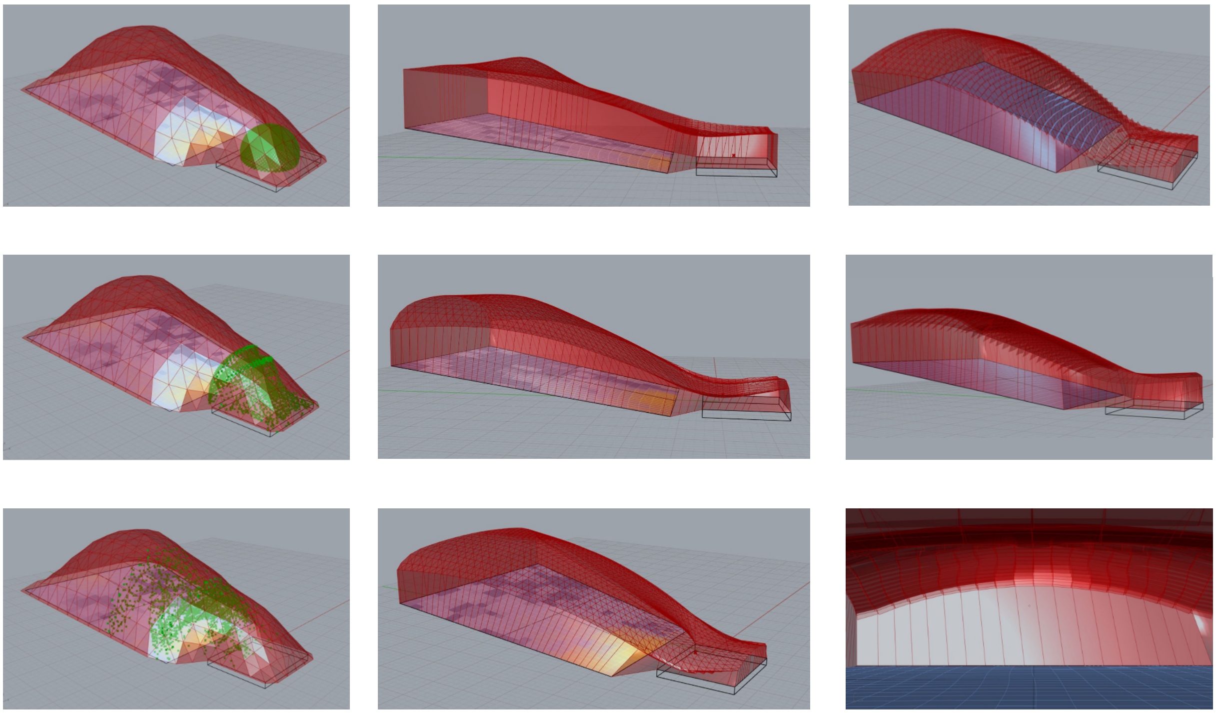


Figure 28, Process images

As the Ray-tracing testing was being performed on Göteborgs Konserthus an idea was born. The idea of creating a parametric Grasshopper model that could, with the exact parameters, look almost the same as the concert hall, and therefore have similar acoustical properties. The concert hall was therefore analysed in a structural way and a model with the possibility of mimicing its structure was created. This model was instead of a mesh based on the principle of loft surfaces, to be able to mimic the several orthogonal corners of the concert hall.

This model was then evolved as more and more features were added to it making it highly versatile in all aspects possible besides the simple input data. The shape was based on an approximate stage, a seating area and the principle of a shoebox-type auditorium.

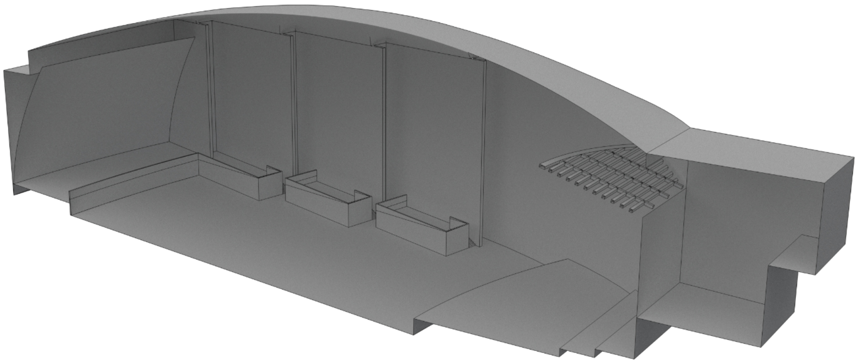


Figure 29, Göteborgs Konserthus

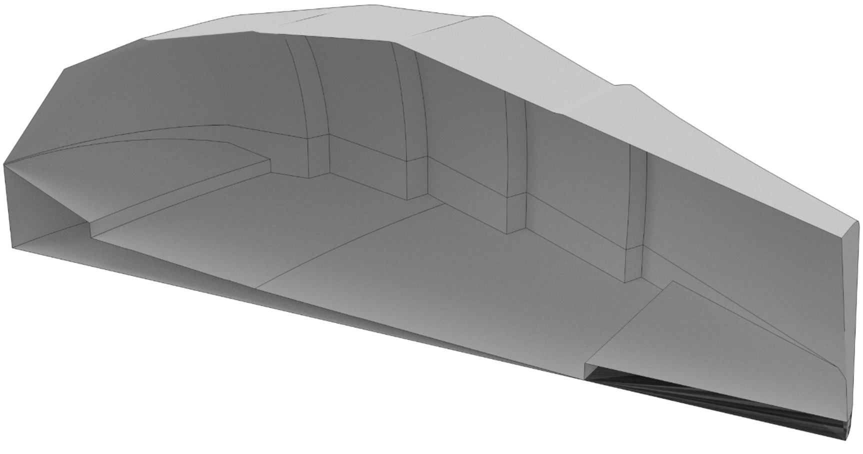


Figure 30, Conceptual Imitation

This new model gave the opportunity for many different shapes of a shoebox-type auditorium as its versatility was very high. However, its drawbacks was that it had to be based on a loft-type structure and was only applicable for a shoebox-type auditorium. It was also not very dependant on the user as it would create an exact shape out of basically no input. These types of properties seemed very applicable for the usage of non-designers, as no actual design work is necessary, however it might not be as applicable for designers.

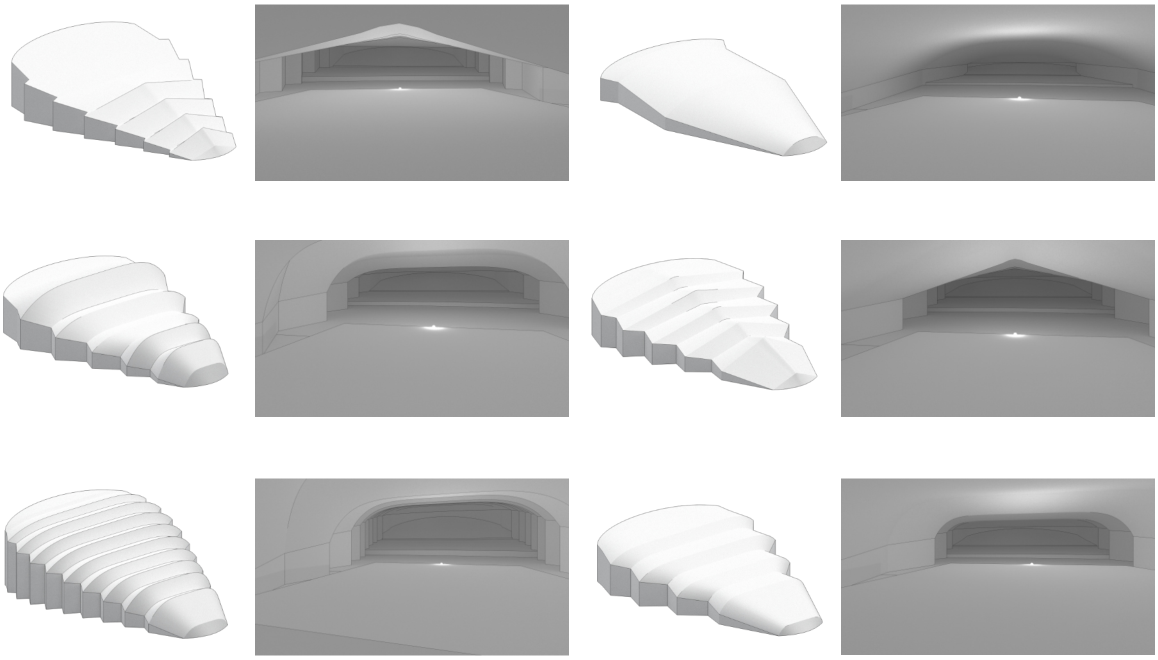


Figure 31, Versatile examples

The Grasshopper script modelling the shoebox structure was divided into several clusters to increase understanding and to make backtracking easier. The geometry was in general controlled by the input in the form of two geometric shapes (the approximate stage and the seating surface) as well as 14 different numerical parametric inputs, in the form of sliders. As these sliders vary, the shape of the entire geometry change in many different ways. Since there are such a big amount of parameters there is also a big amount of different combinations, and therefore a huge amount of different shapes. These inputs are divided into three groups, Reflectors, Seating and Overall.

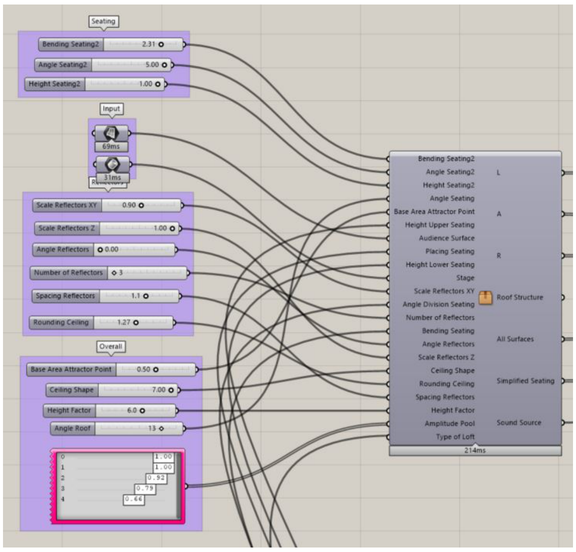


Figure 32, Input parameters

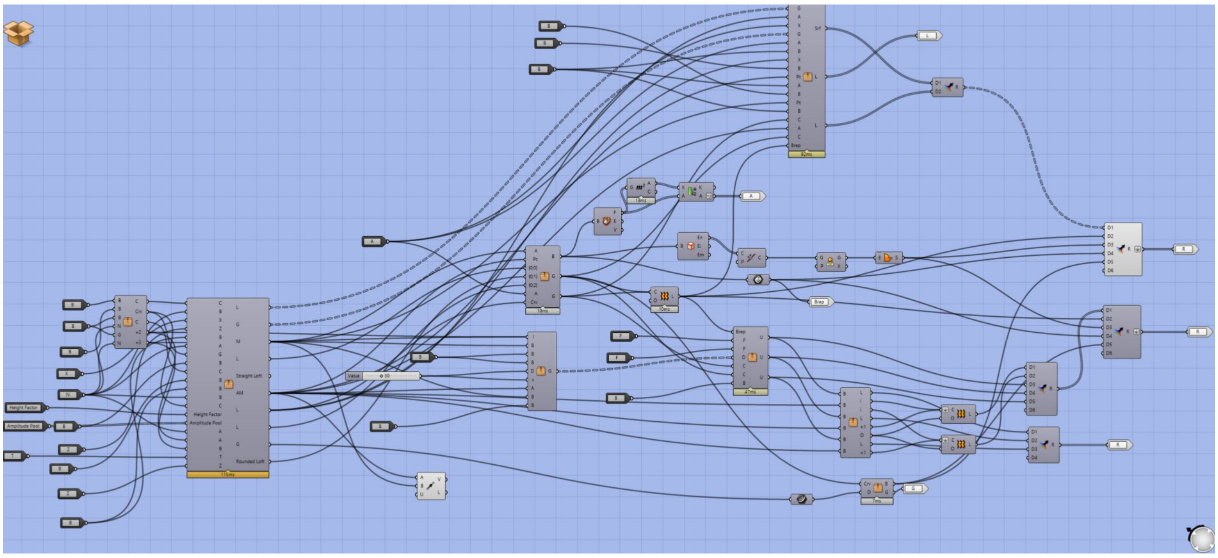


Figure 33, Different clusters controlling different parts of the geometry

The Reflector group controls the different lofts, that works as reflectors of the roof and the wall structure. In this group there are 6 parameters.

The first scales the reflectors in the XY plane, which in general means the scale of the reflectors on the side walls.

The second scales the reflectors in the Z direction, which in general means the scale of the reflectors on the ceiling.

The third decides the angle of the reflectors, they can vary from orthogonal towards the stage to orthogonal towards the back wall, and everything inbetween.

The fourth decides the number of reflector, and as such also the number of seating surfaces.

The fifth decides the spacing inbetween the reflectors, if they are evenly spaced, or if their spacing depends on a function.

The sixth decides the shape of the roof inbetween the reflectors, in the longitudal direction, which can vary from flat to increasingly rounded.

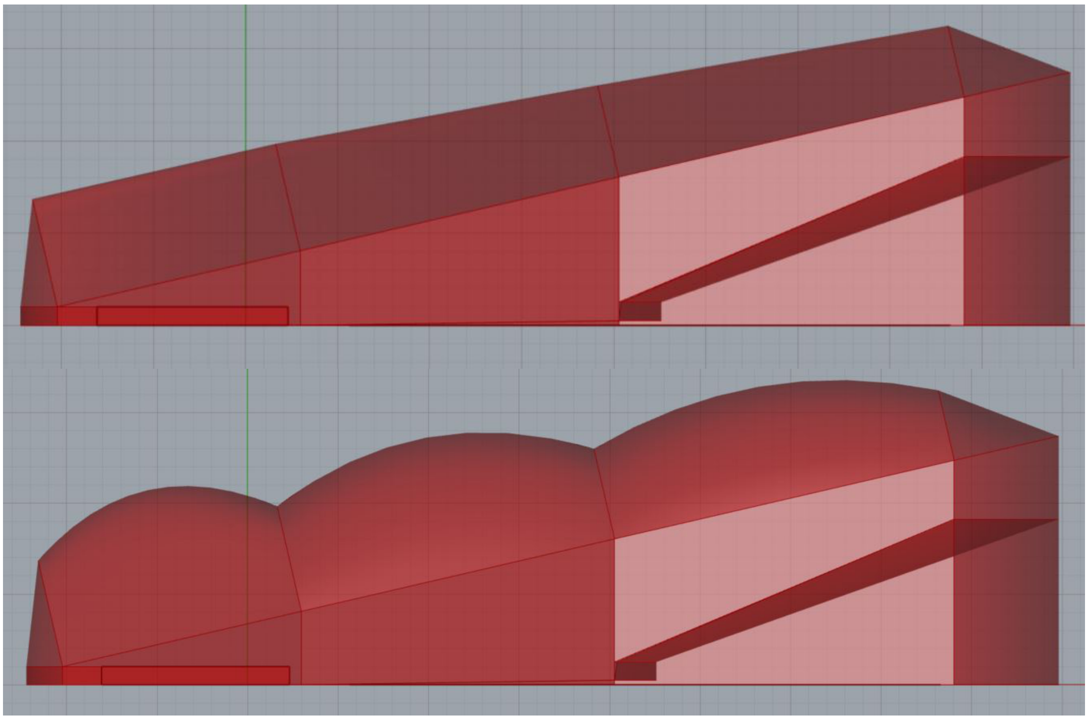


Figure 34, Varying shape of the roof

The Seating group controls the seating area, in this group there are 3 parameters.

The first decides the bending of the seating in the XY-plane, it can vary from linear to increasingly bent.

The second decides the angle increase of the seating, in general how much the angle of the seating increases between each seating surface, from the stage - backwards.

The third decides the height of the walls inbetween each seating surface.

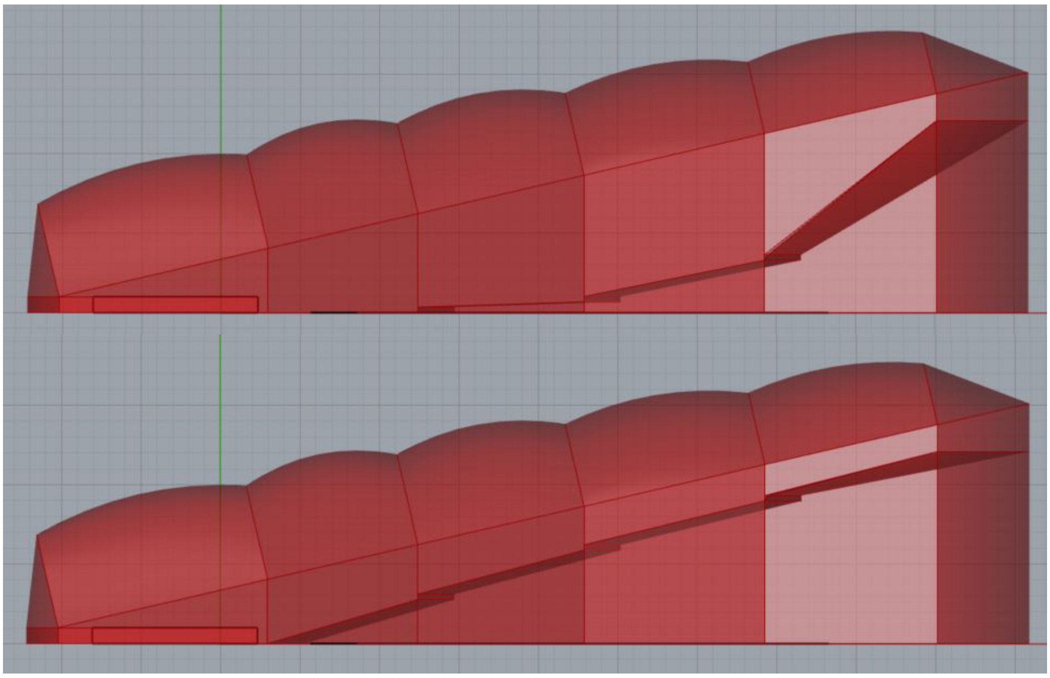


Figure 35, Varying angle of the seating surfaces

The Overall group controls the general shape, in this group there are 5 parameters.

The first controls the general shape of the geometry in the XY-plane.

The second controls the shape of the ceiling in the transversal direction, it can vary from a linear function to increasingly rounded, until reaching the approximate shape of a football goal.

The third controls the overall height of the entire structure.

The fourth controls the angle of the roof and therefore also the general angle of the seating area.

The fifth controls the general shape of the ceiling in the longitudal direction, where it can vary quite freely through several attractor points.

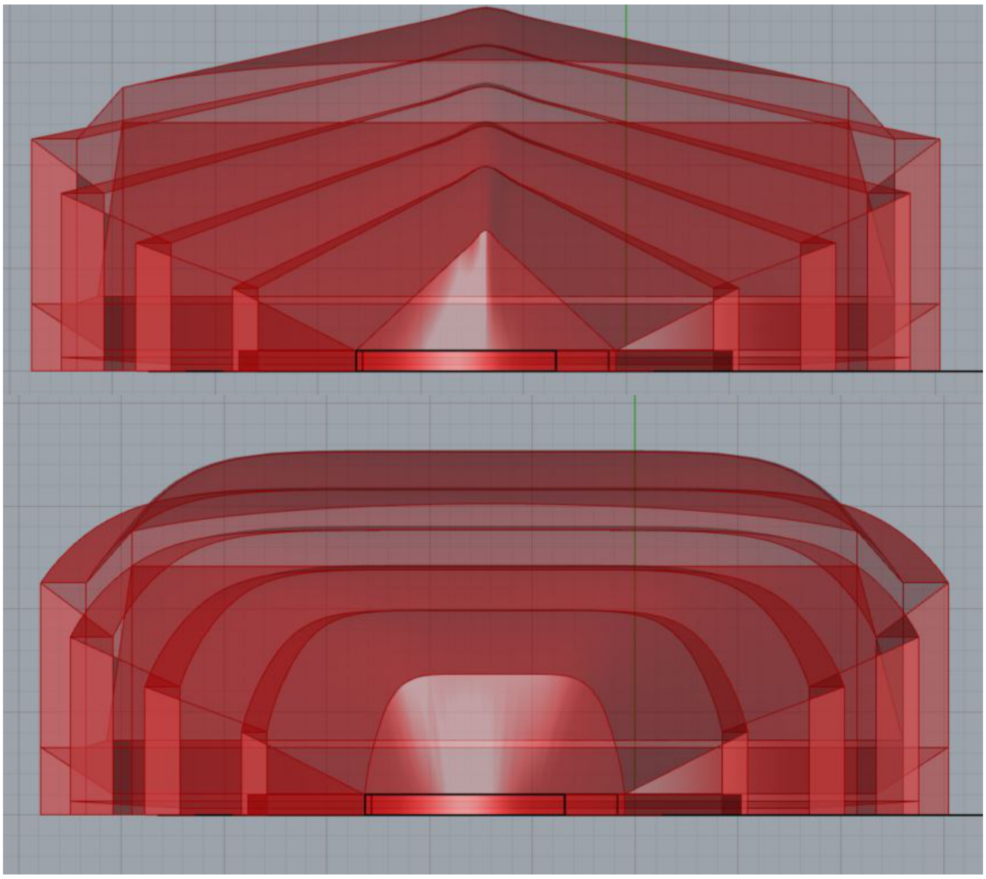


Figure 36, Varying shape of the roof

Due to the certain drawbacks of the shoebox-type auditorium component, ideas were born of creating another component. The drawbacks of the shoebox could be simplified as:

Only being applicable for shoebox type auditoriums, e.t. vineyard-types not possible.

No greater impact on the design from the designer.

A smaller focus on shell structures.

From these drawbacks another component was created, with the focus on vineyard-type auditoriums in combination with shell structures. The ideas of this component was to optimize a finalized design with the help of shell structures, bringing the work of the designer more into the limelight.

With some general lessons learned from the shoebox design, a somewhat different approach was taken with the vineyard concept. The idea is that introducing flexibility to a designed layout can further optimize the acoustics while retaining the architectural intent of the design. For this design many elements were borrowed from Elbphilharmonie, Hamburg. The most prominent ideas are the double layered design and the large hanging, somewhat monumental, acoustically reflective feature.

Figure 37, Interior of Elbphilarmonie in Hamburg
(Herzog & de Meuron, 2016)

The two layers allow for sound to build up harmonics between them while the hanging structure allows for stronger early reflections to the audience, but most importantly the performers. In general, a vineyard style auditorium has problems with early reflections as the roof can be the only surface to provide early reflections back to the stage. The design in this project tries to counteract that with the use of multilayered terrace sections.

The design method of the vineyard differed slightly from that of the shoebox due to the lessons learnt from that process. In the vineyard the celing was thought of as a cassette based structure from the beginning, meaning that the acoustical and the structural optimization could be performed at the same time.

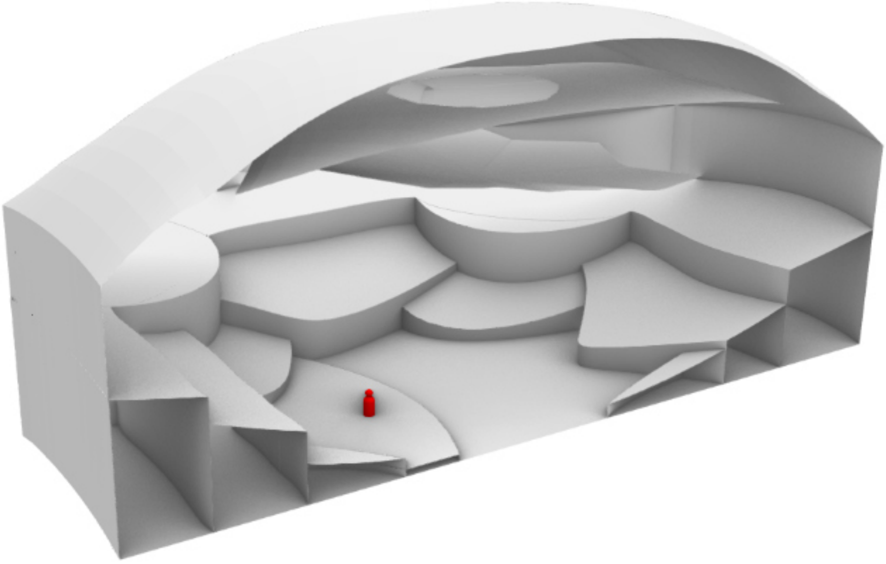


Figure 38, The vineyard-type auditorium

A general mesh topology was designed to be used with a dynamic relaxation algorithm. To gain the required flexibility for the geometry the boundary conditions can change. As the locations of where the shell is connected to the ground different forms are acquired. The transformation used is locked to be within a certain domain, it cannot deviate too much from the original design.

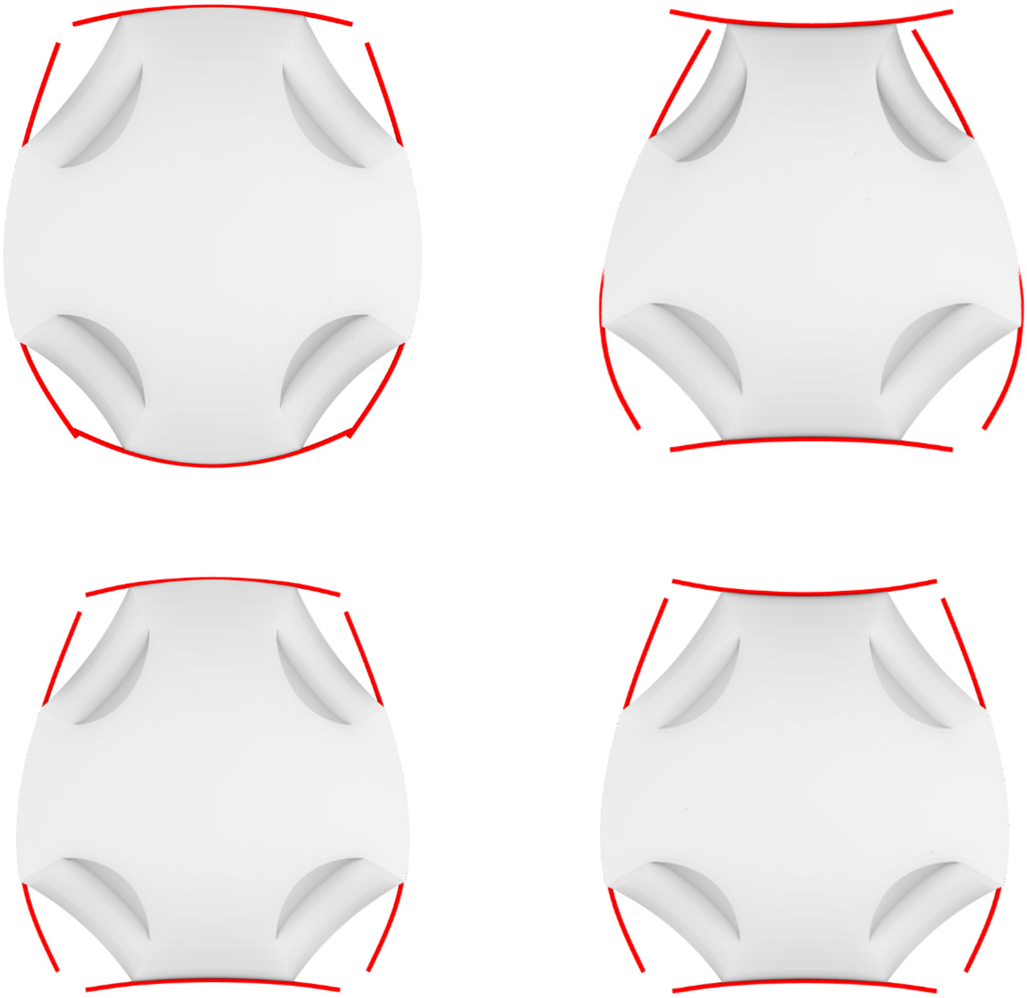


Figure 39, The overal geometry of the vineyard is changed following the boundary curves.

Using the obtained geometry, a general seating layout is designed following the topology of the mesh. This layout can be scaled using a vector field introducing additional flexibility and variability. Three different field strengths are used below, each producing a unique result.

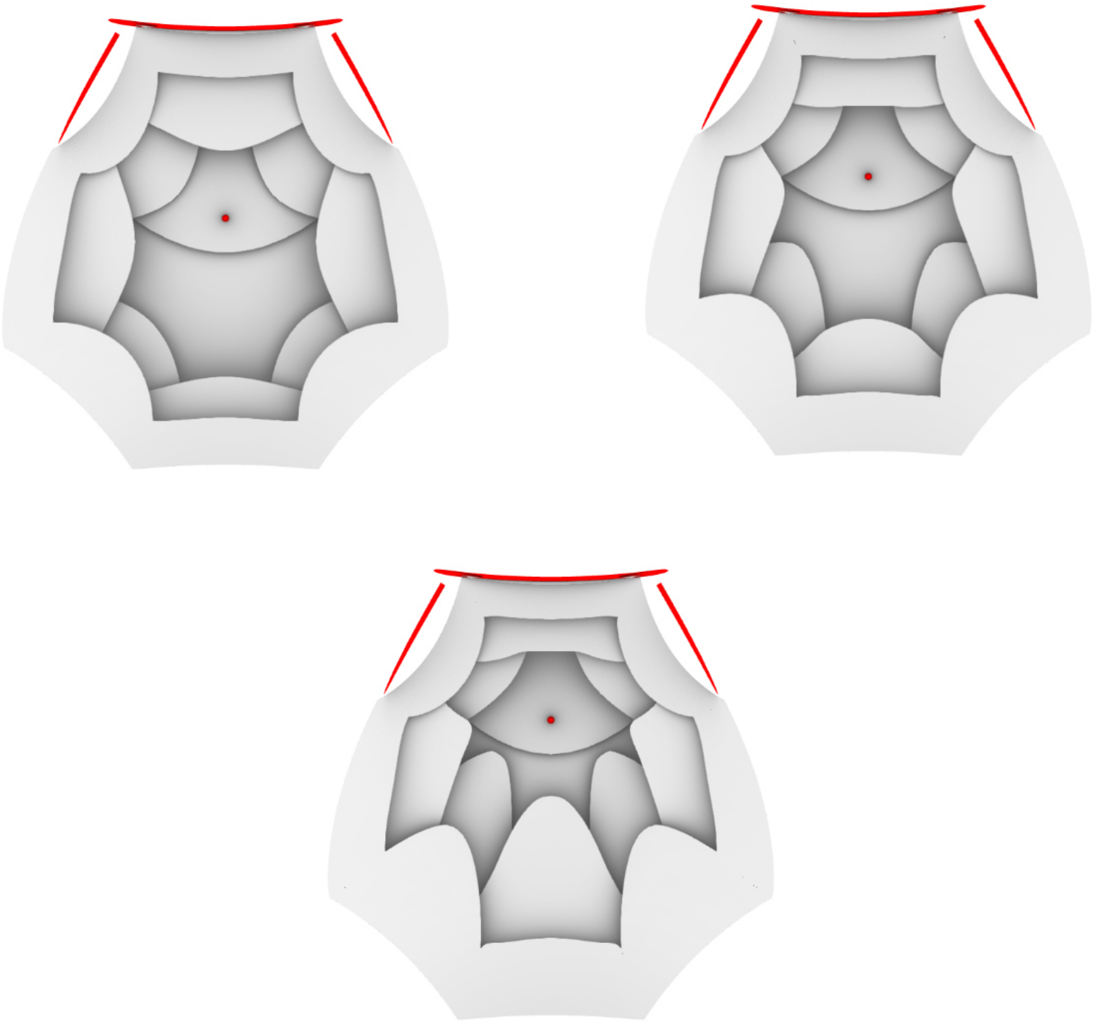


Figure 40, The seating surfaces can vary due to different field strengths.

For the seating areas themselves, there is a need to adjust the slope towards the stage, both due to the acoustics as well as visibility. The seating areas are divided into three different general levels. Each audience surface within each level has its own unique slope. The height difference between each level can also be adjusted.

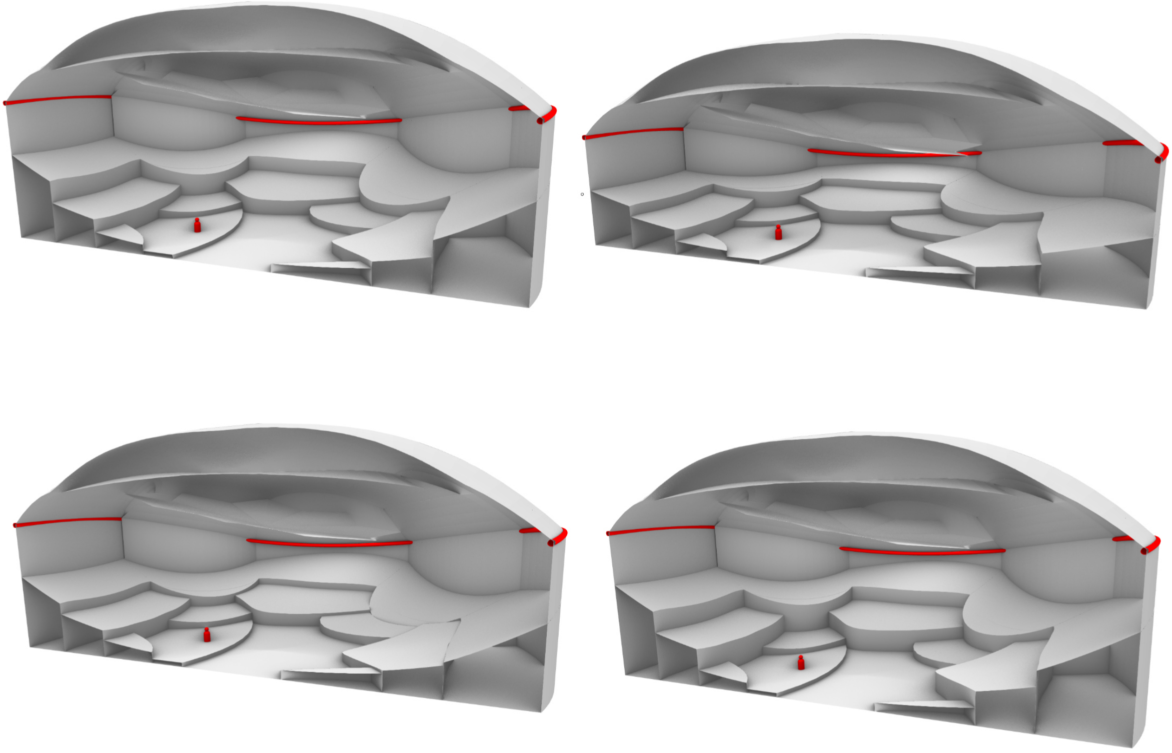


Figure 41, The angle and the height difference between the seating surfaces can vary.

The project did at this stage contain two different types of components and two ways to go forward. On one hand there was the shoebox auditorium which focused on the design of a shoebox-type auditorium with the sole input of an approximate stage. This component was a black box of sorts as next to no design work was necessary or even possible for the final output. The benefits of this solution was instead that it provided an acoustical optimized auditorium without any extra work. This auditorium could although be improved structurally and aesthetically afterwards, but then with a smaller impact on the overall shape. This component did however optimize the entire room, from the seating to the roof, and might therefore provide better acoustical properties.

The other type of component was the vineyard auditorium, which had a bigger focus on initial design. This component worked towards an optimization of the roof structure as well as parts of the seating to an already partly designed auditorium, which brought more control to the designer over the finalized shape. However, as the component mostly optimized the roof structure, and not in the most versatile way, the acoustical properties of the room might not be as good as the shoebox. This component did however have a bigger focus on shell structures, and could bring a deeper investigation of the impact of a single shell on the acoustical properties of an auditorium.

As both solutions worked and were based on the same original theory but towards different goals, it was found interesting to continue working on both. However, since the different components had different goals in mind, they needed to follow different processes before being finalized. This project first aimed to finalize both solutions simultaneously, as each of their outcomes are of high interest. Several problems and issues was however found while finalizing the shoebox, which resulted in the vineyard being put on hold. As these issues were brought into light, it affected the way the vineyard was finalized, as well as its final outcome.

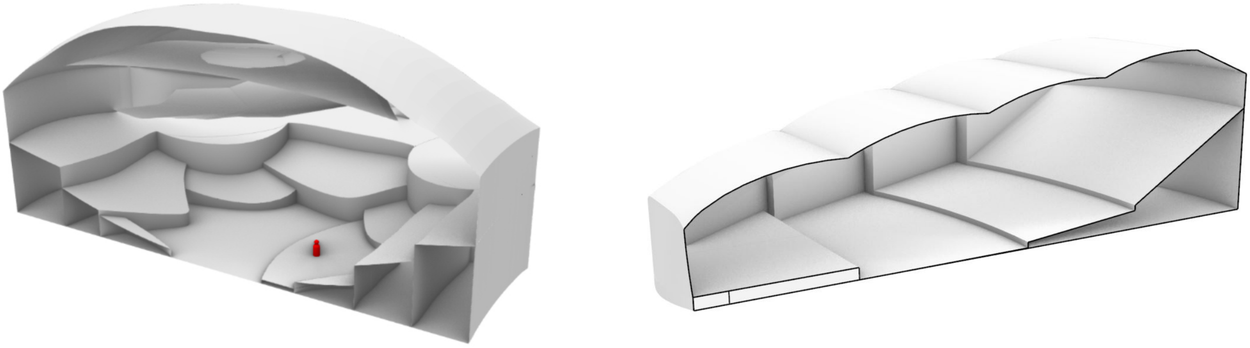
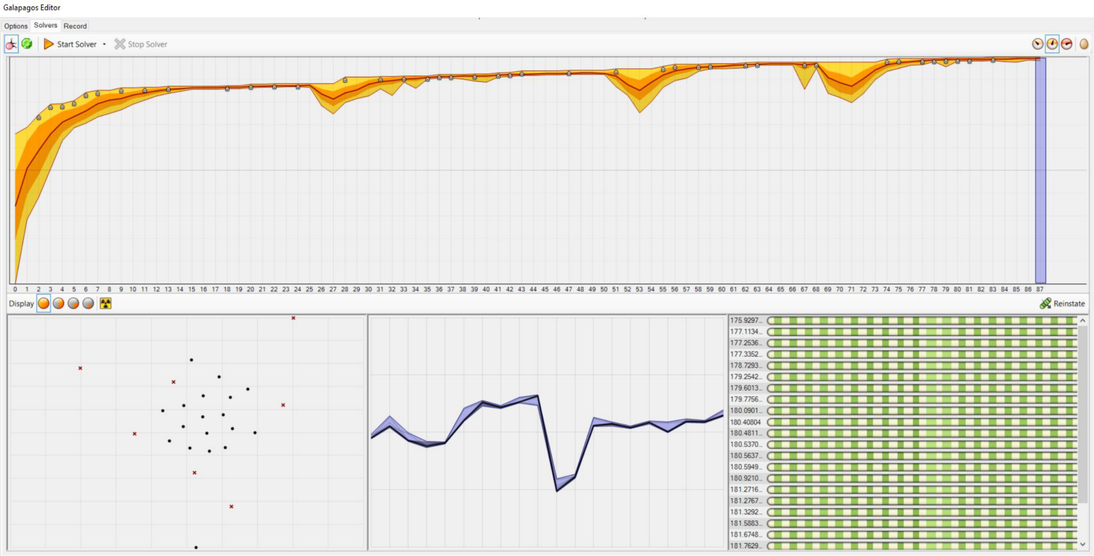


Figure 42, The two auditorium types

The Evolutionary Algorithmic Iterations were performed following the theory above, however an iteration operator was not created in this project. Instead a plug-in for Grasshopper called Galapagos was used. Galapagos iterates evolutionary following a fitness function with a goal value connected to the input parameters controlling the shape of the geometry. As such it can iterate the geometry while searching for goal values from the acoustical analysis performed on each new geometry by the ray-tracing method.

In this project, the initial iteration with Galapagos was performed with goal values of the acoustical properties. Looking at this process with the theory of Evolutionary Algorithmic Iterations in mind would help increase the understanding of the process. The gene pool in this iteration is the input data parameters in the grasshopper script, for the shoebox script that would be the 14 parameters controlling the entire shape of the geometry. The fitness function would be the acoustical analysis performed by the ray-tracing component, and its goal values the optimal values of the different acoustical properties mentioned in Phase 1. As such, Galapagos is connected to the input parameters, and to the goal values from the ray-tracing component, before iteration starts.



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175.9297...
177.1134...
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177.3352...
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180.0901...
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180.5949...
180.9210...
181.2716...
181.2767...
181.3292...
181.5883...
181.6748...
181.7629...
```

Figure 43, The Galapagos solver working in generations on the X-axis and fitness of the function on the Y-axis in the top diagram. Each white dot represents a new best iteration and the thickening of the yellow area is due to mutations being added.

The iterative method described on the previous page was at first tested in two dimensions. This was done to be able to test both Galapagos as an iterative component but also the way to balance the different goal values compared to eachother in a simpler environment and therefore a faster script and a quicker process. The testing was also done as a proof of concept, that the theories could work together and that the shape of the ceiling actually had a big impact on the acoustical properties. The tests were performed with the acoustical properties of Sound Pressure Level and Clarity (C50, C80) on a ceiling that could move in the Z-direction in a certain number of points. It was found that the results differed massively depending on the balancing of the goal values, something that is necessary to note and discuss before the final iterative process is begun.

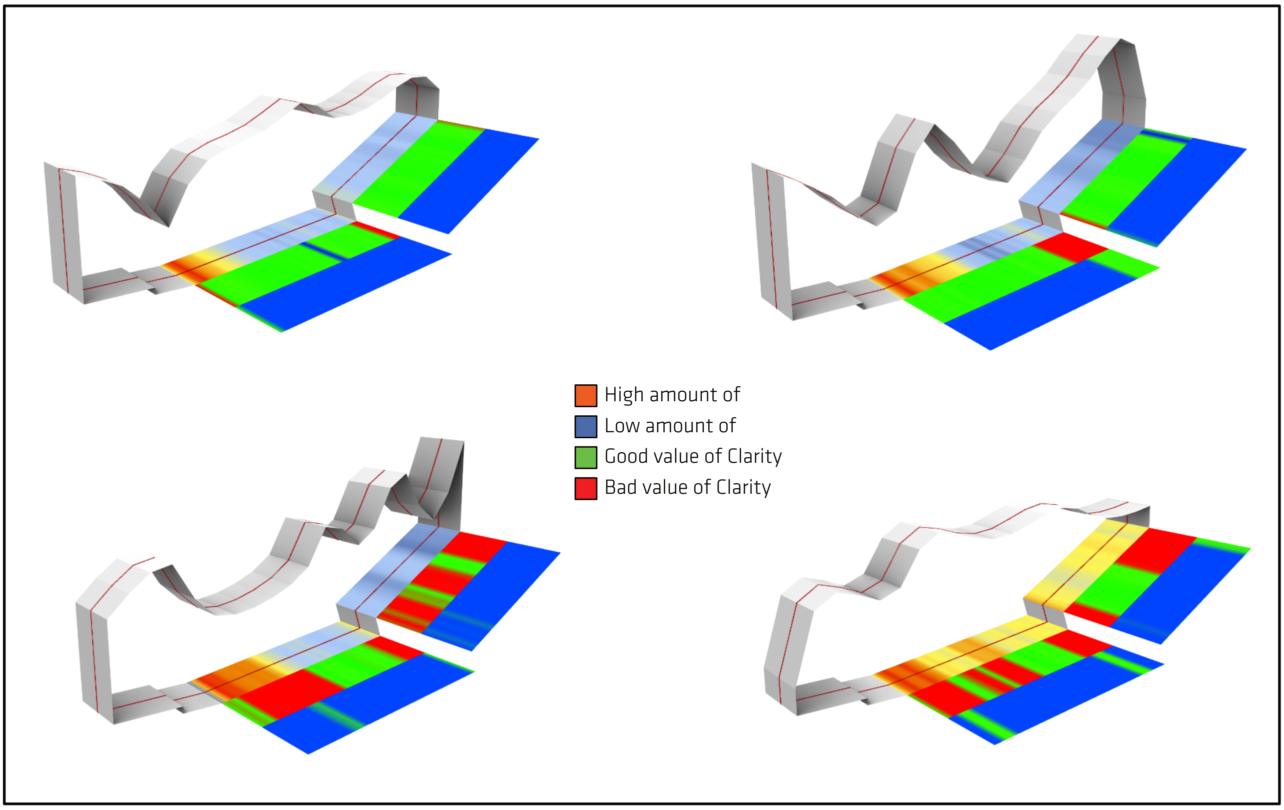

Figure 44, 2D testing of the iterative process. The colored surfaces represent SPL, C80 and C50 respectively, however, their values are in this stage of little importance.

As mentioned on the previous page the evaluation criteria is of the highest importance to discuss before starting the iterative process. Not only which parameters to look at and which goal values of each parameter, but also the balancing inbetween them. As many different criteria will try and affect the geometry of the auditorium it is important to value these compared to eachother. Which criteria are hard criteria and cannot be compromized, and which can be slightly outside of their goal values if necessary.

The initial iterative process with Galapagos will as mentioned have the focus on the acoustical properties, i.e. RT60, C50, C80, BR, ST1, STI, and their respective goal values presented in Phase 1. These properties are of different importance due to the performance of the auditorium. The STI is for example very important for speech, such as theatre or lectures, but not as much for music. The same goes for C50 and C80 where one is important for music and the other for speech. Therefore, specific goal values should be sought depending on the performance.

For a speech performance, the algorithm should look for a value of RT60 between 0.7-1.0s, a C50 of more than -2dB, a Bass Ratio of 0.9-1.0 and a STI as high as possible.

While a symphonic performance should look for a RT60 between 1.4-2.2s, a C80 of between -3 to 8dB, a Bass Ratio of 1.0-1.3 and a ST1 between -15 and -12dB.

In both cases the algorithm should however try for an as evenly distributed SPL as possible throughout the auditorium.

Since it is next to impossible to know how the different properties will affect the total shape of the geometry, the appropriate balance between these properties is something that needs to be found through testing. From checking the values after an iterative process is finalized, it should be quick to note which properties go well together, and which will need to have their impact on the end result strengthened.

As the initial iteration focuses on the acoustical optimization, the next iteration will focus on the structure of the geometry, and of the optimization of its structural properties. Here the evaluation criteria will be the structural response of the shell structure that is being analyzed.

The final iteration will focus on the acoustics again, with a special look into the segment plates and their scattering, absorption and possible rotation. Here the evaluation criteria will be the same as in the initial iteration.

There will however occur an additional evaluation somewhere along the process. This evaluation will not be automatized like the others but instead be performed manually on several different solutions. The evaluation will focus on criteria that are not numerically measurable, but that have a big impact on the final design. These criteria will focus on such properties as effect, aesthetics and materiality, and are of highest importance before choosing a final geometry to continue with for Phase 3.

The different iterations of the shoebox were visualized together with their respective acoustical values and properties, in the shape of a few diagrams. These diagrams show the iterations value for SPL, Clarity, RT60 and Bass Ratio, as well as their respective fitness value and also the iterations total fitness value. As can be seen from Figure 45 the program finds a generally good solution quite quickly and then spends a large amount of time finding the best solution in the original solutions "family", as expected.

Figure 45, Different solutions from the same iteration process, with each solutions respective fitness value in the top numbers, and acoustical diagrams describing its properties. The program looks for highest possible fitness value.

When finding the optimal solution for the shoebox several iteration attempts where made, to increase the numbers of solutions while being kinder to the program as well as to the computer. The best solutions of the different iterations where then compared and a winner was selected due to both its acoustical properties as well as its general geometric design.

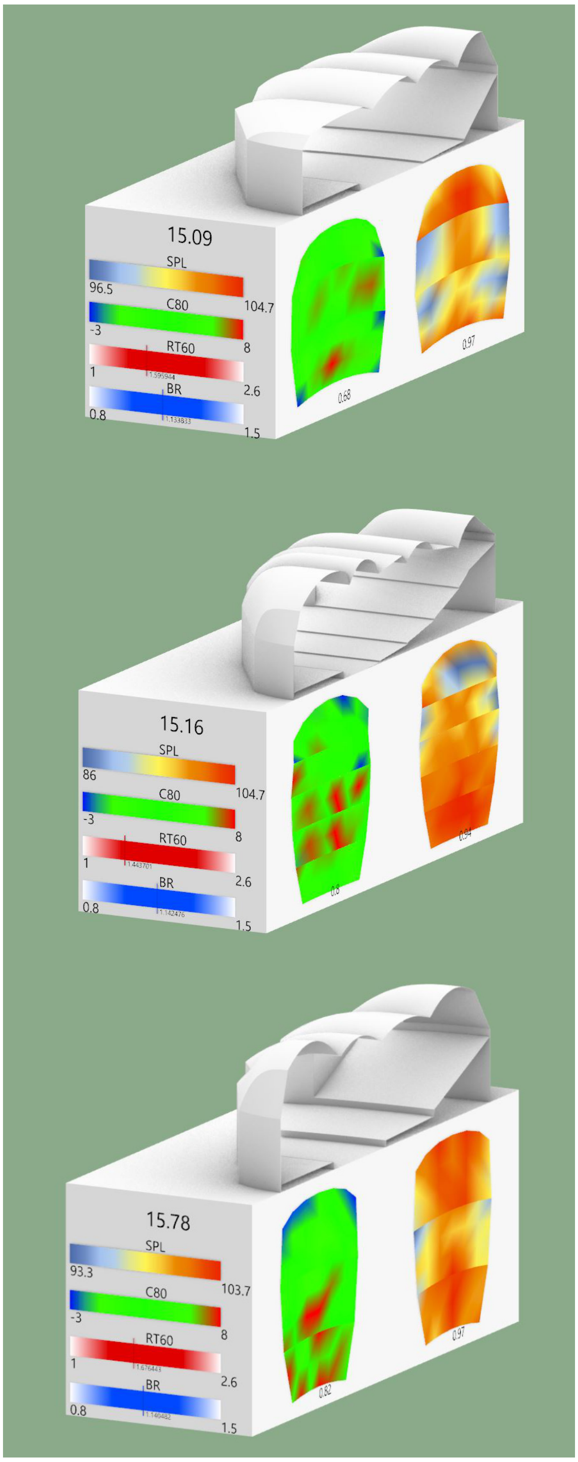

Figure 46, Some of the winners from different iteration attempts.

The winner from the selection was a geometry divided into four different sections, one for the stage and three for the audience, with an increase in both ceiling height and "roundness" in the front and the back section. The seating was in general very flat in the two front sections and quite steep in the section in the back. Its acoustical properties were all inside the target range, with an especially evenly ditributed sound pressure level.

As such, this geometry was then chosen as the base geometry for the following design project.

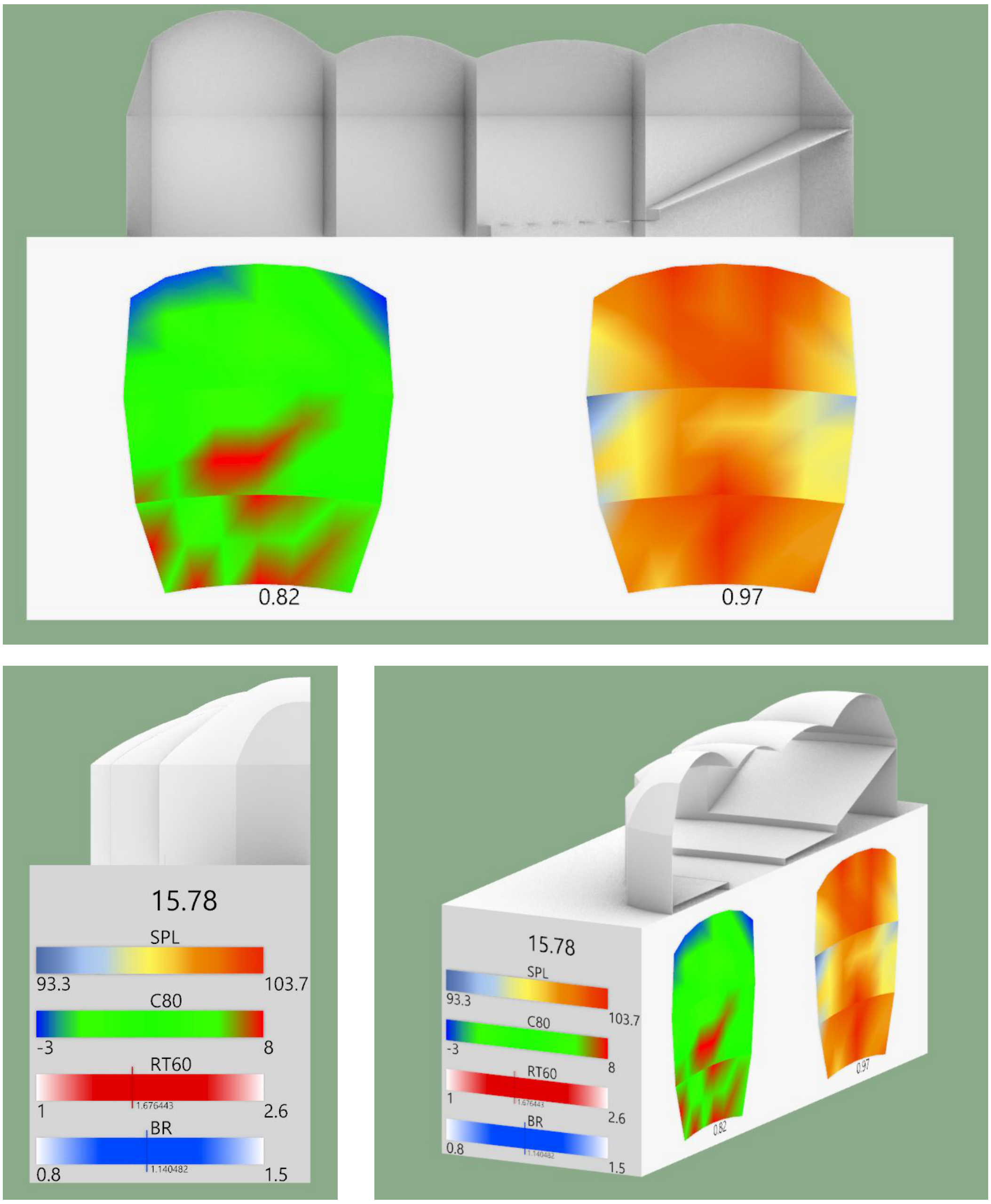

Figure 47, The winning geometry from the shoebox iterations.

After optimizing the geometry acoustically an optimization was sought for the structure. For the shoebox two different methods were found to achieve this.

Method one would be to use the walls of the geometry found in the acoustical analysis as a boundary and optimize only the ceiling as a cassette based shell structure. The issue with this solution would be that it disregards the general intention of the project to a higher degree. It would also be difficult to guarantee the structural capabilities of the walls as a boundary. With this method however, it would be quite easy to find an optimized cassette based geometry thats very similar to the acoustically optimized geometry.

Method two would be to optimize the entire geometry as a cassette based shell structure. The issue with this solution would be that an optimized shell structure would be lower and flatter than the acoustically optimized structure, as it wouldn't have vertical walls. This could however be solved by making the final design an interpolation between the acoustically optimized structure and the structurally, which should result in a geometry with acceptable structural and acoustical values.

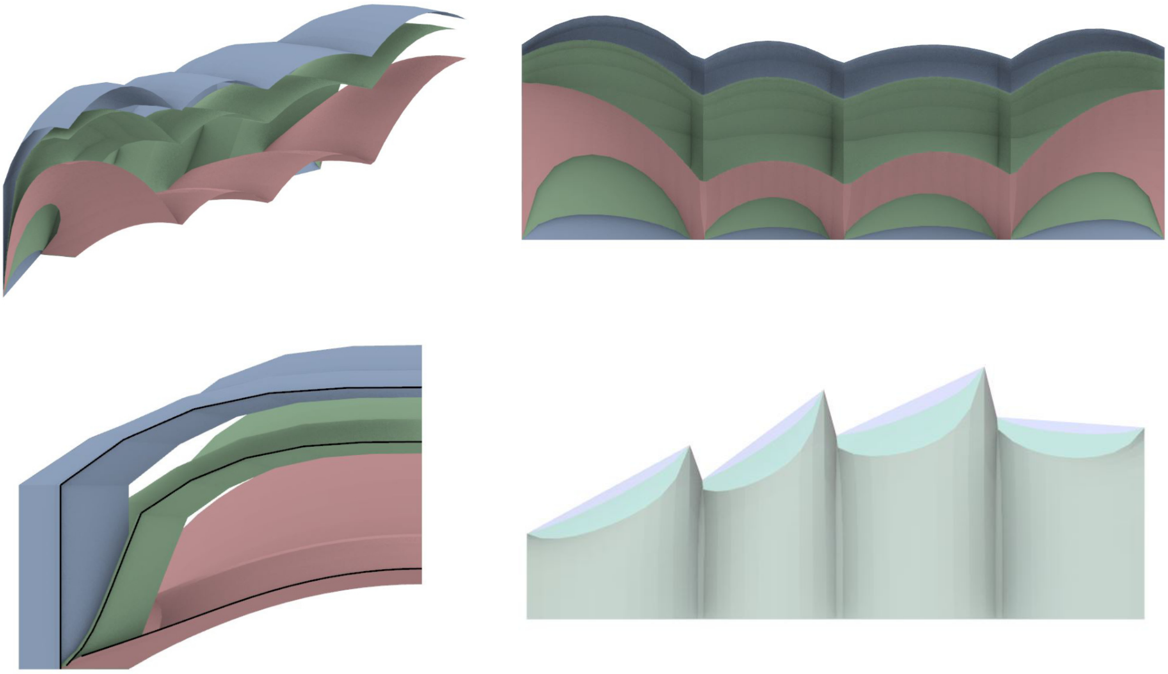

Figure 48, Conceptual images of how an interpolation between a structurally optimized and an acoustically optimized geometry could be made, with the acoustically optimized geometry in blue, the structurally optimized geometry in red and the interpolation in green.

For the final shoebox geometry the second method from the previous page was chosen. The bottom outline of the walls from the acoustically optimized geometry where chosen as a boundary for the structural optimization in Kangaroo. From this boundary shape a flat mesh was created with the same amount and distribution of faces as the acoustically optimized geometry. To be able to further control the shape of the geometry different material with different strength and weight were assigned to different parts of the base mesh. One light and relatively weak material, and one heavy and strong.

When running the optimization program the result became a mesh structure that was mimicing the acoustically optimized geometry, but was both clearly lower and flatter. From these two geometries a geometrical interpolation was made to find the mesh that lied in between them, creating a geometry relatively optimized both structurally and acoustically.

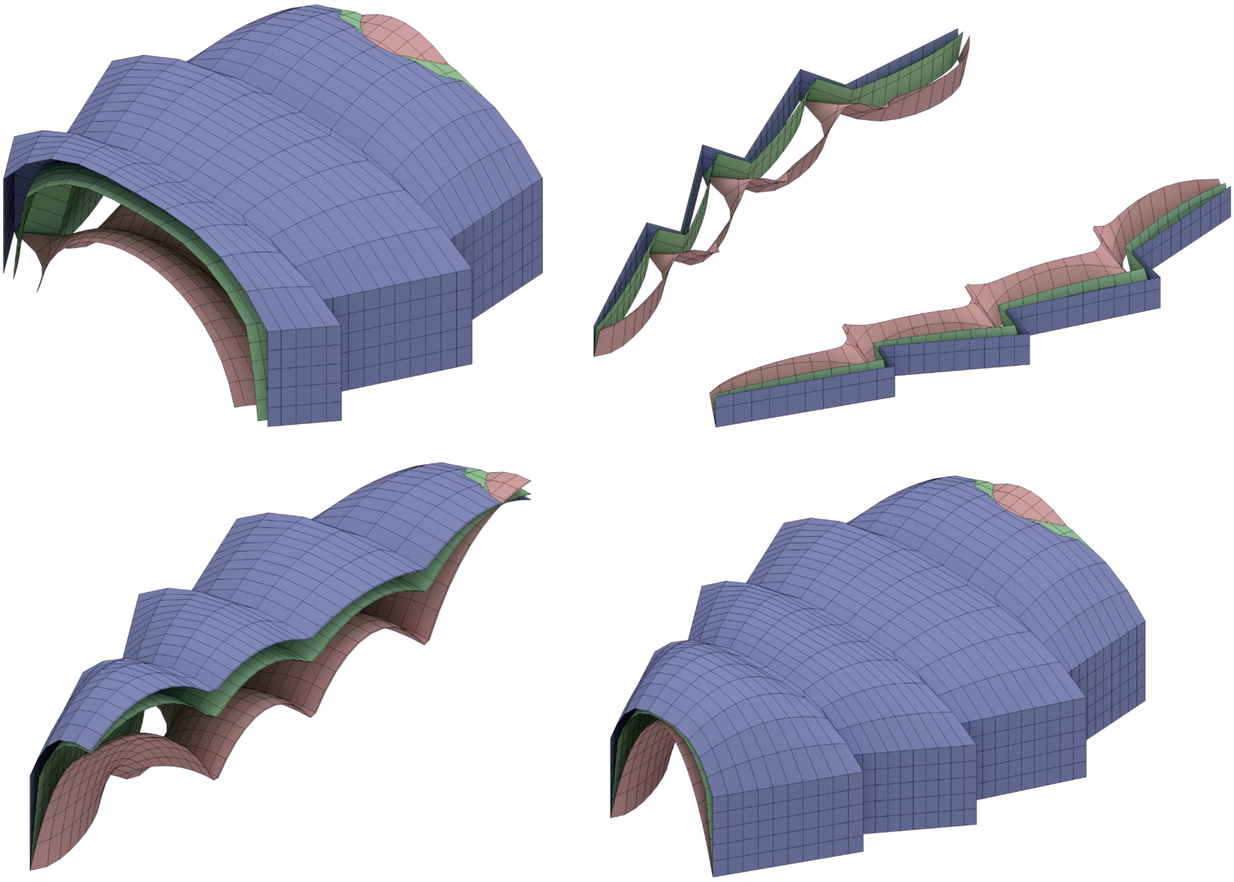

Figure 49, Interpolation between the acoustically optimized mesh (blue) and the structurally optimized mesh (red) resulting in the final mesh (green).

When iterating the vineyard it was found that a problem that could arise was that the stage was not at all times visible from all seating positions. As this had never been an issue for the one directioned shoebox, the solution was not already in the component. Therefore a fitness function was added that looked into this behavior to be able to find a solution where all seating positions could see the stage.

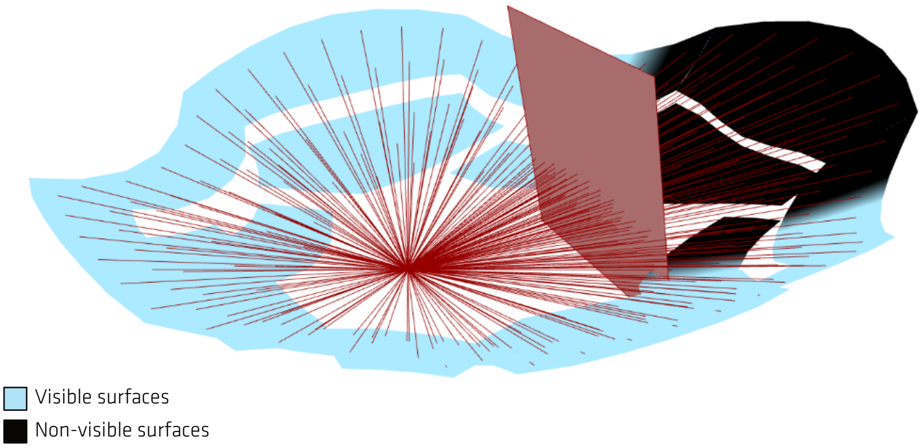

Figure 50, Testing the visualisation function.

The different iterations of the vineyard were, as with the shoebox, visualized together with their respective acoustical values and properties, in the shape of a few diagrams. These diagrams show the iterations value for SPL, Clarity, RT60 and Bass Ratio, as well as their respective fitness value and also the iterations total fitness value.

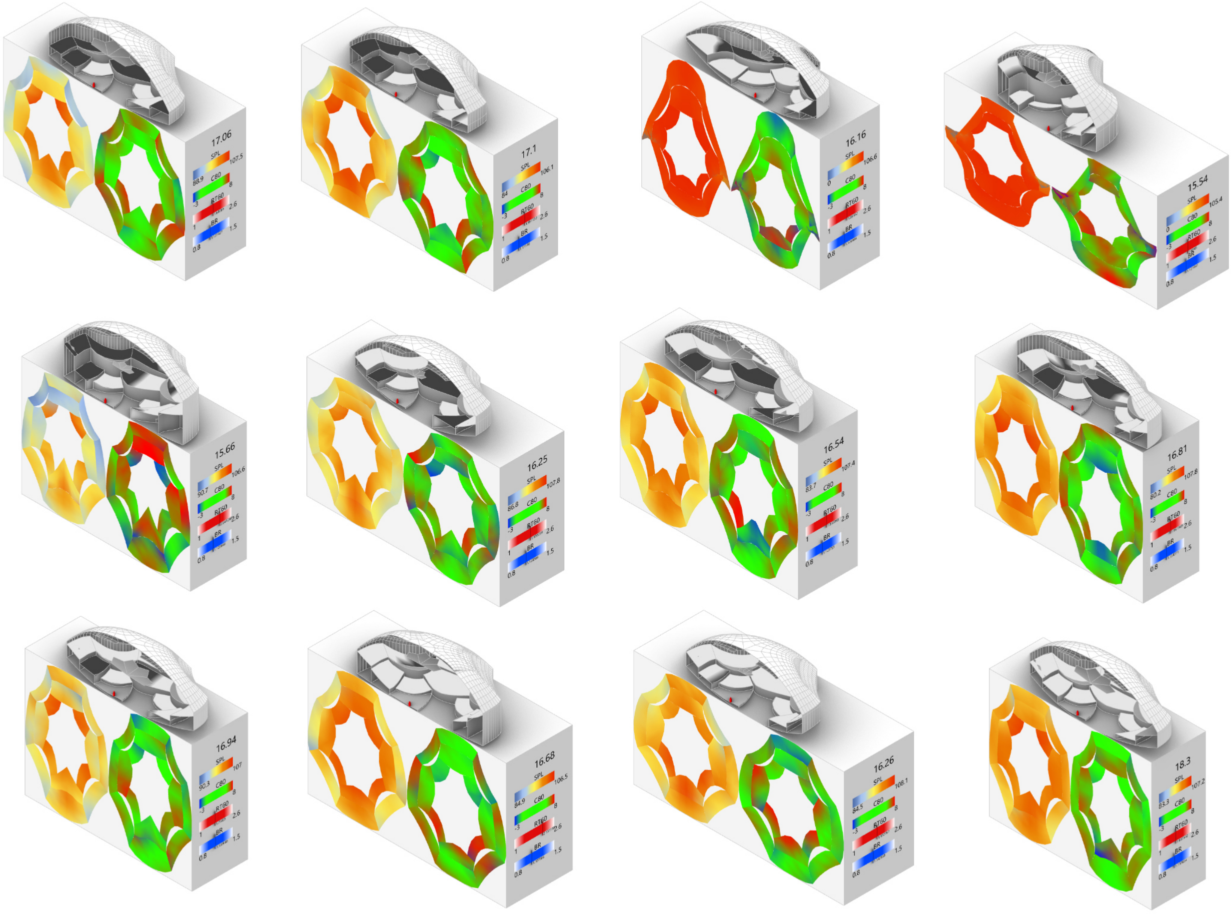

Figure 51, Different solutions from the same iteration process, with each solutions respective fitness value in the top numbers, and acoustical diagrams describing its properties. The program looks for highest possible fitness value.

The winner from the vineyard iterations was a geometry that does not stand out very much in any particular way, but is rather average in most of its parameters. There are, however, a few conclusions that can be made about it. The inclination of the seating areas vary through the hall, with steep inclination behind the stage and less steep inclination for the areas on the lowest level. The stage is located slightly to one side of the hall, but relatively close to the middle. The height difference between the seating levels is evenly distributed, with no extreme differences throughout the hall. A few parameters that stands out are however the ceiling height, which is relatively high, and the direction of the reflector hanging from the ceiling, which points directly towards the stage.

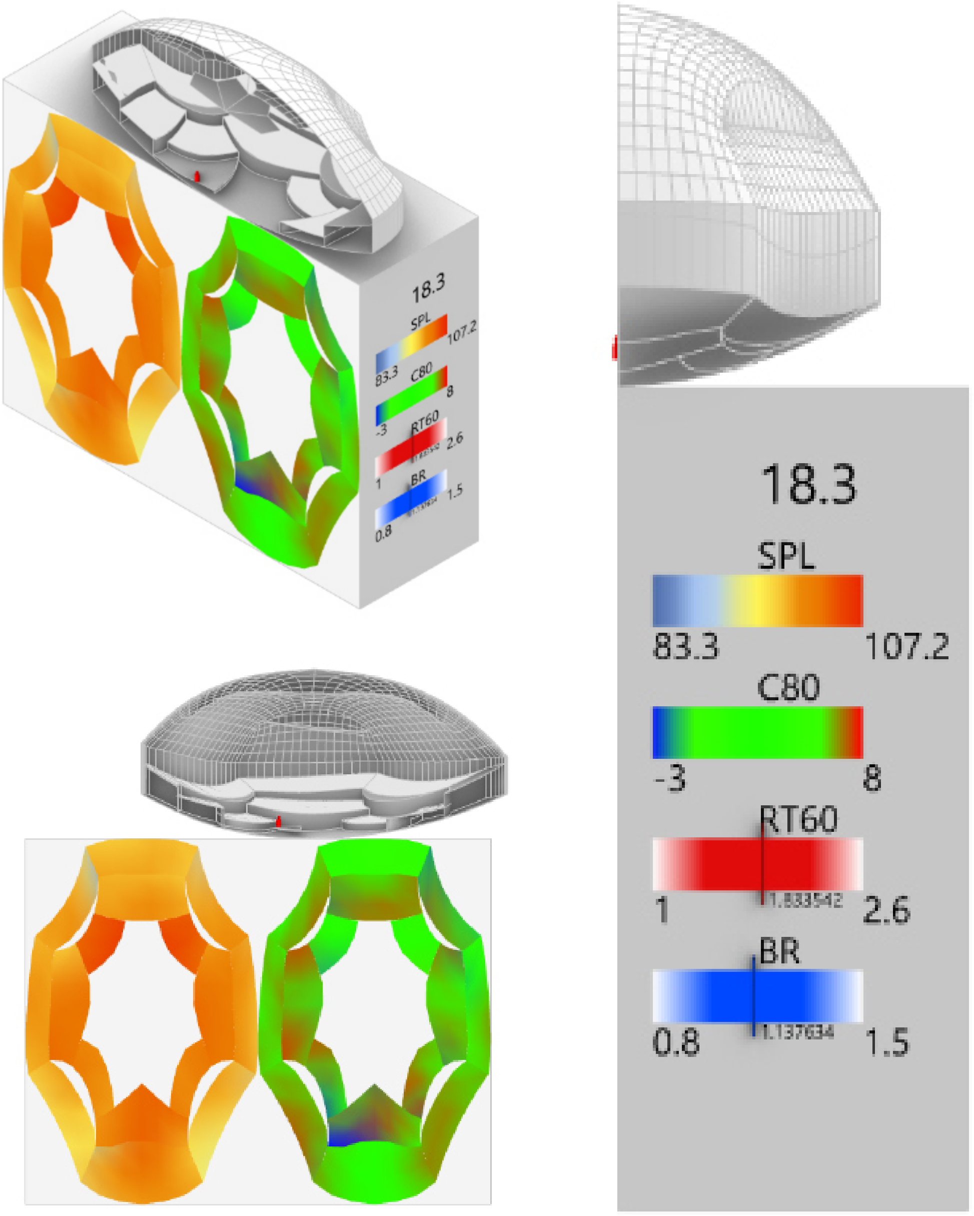

Figure 52, The winning geometry from the vineyard iterations.

Segment Plates Demands

When turning the mesh into three-dimensional segment plates, or cassettes, there are certain demands that should be fullfilled for each cassette. Firstly, the cassettes should be buildable for any shape of the mesh, no matter the curvature. There should be a method for assemblying the cassettes both individually from the different elements of each cassette and the assemblying of several cassettes into the entire structure. Each cassette should also be structurally believable from the relative dimensions of its elements, although no calculations will be done. Each cassette should also contain as few elements as possible to simplify the construction.

They should also contain at least two layers. One layer with sound absorption material, with different sizes in openings which should make it possible to change the absorption of different frequencies. And one layer containing an air pocket, which should be continous between the cassettes and somehow decoupled from them.

Finally, the cassettes should also have the possibility to change the angle of their bottom plate. The rotation of the bottom plate gives the opportunity to one last time improve the acoustical properties of the shell structure. This rotation could be achieved with an equal rotation of all cassettes or different rotation values on different cassettes in different locations of the structure following some sort of attractor point.

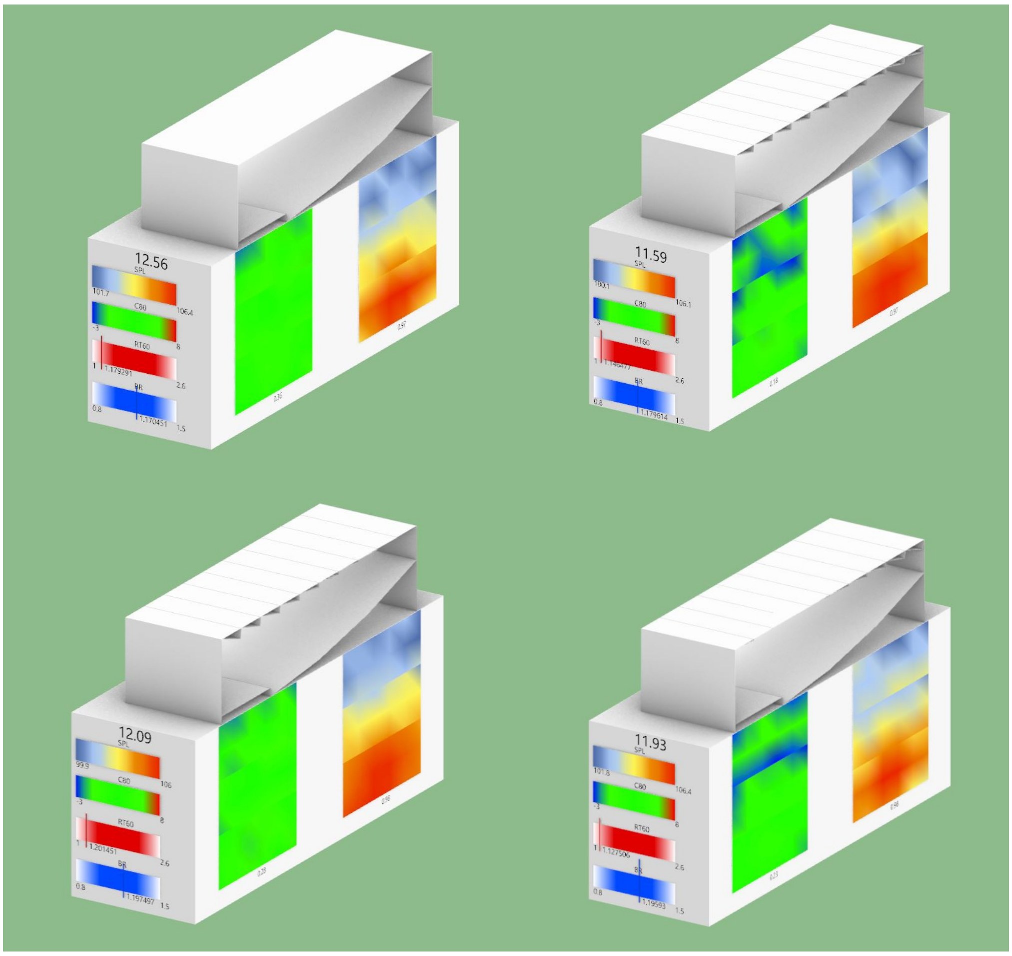

Figure 53, Results from a generic test of rotating the cassettes, no rotation (up left), rotating all (up right), rotation by attractor point in the front (down left), rotation by attractor point in the back (down right).

Following the demands on the cassettes from the previous page a design as well as a construction and assembly method was developed. Due to certain acoustical demands on the cassettes, they consist of 5 parts. Firstly there are 4 structural parts, in the form of two beams and two plates that carries the structure. Inbetween the plates there is a layer with sound absorption material. In the bottom of the cassette there is a third, thinner, plate that exist only due to acoustical reasons. This panel is rotatable and bendable to a certain degree, providing extra control over acoustical reflections. Inbetween this panel and the bottom structural plate there is a layer with a decoupled air pocket, which is continous over all cassettes.

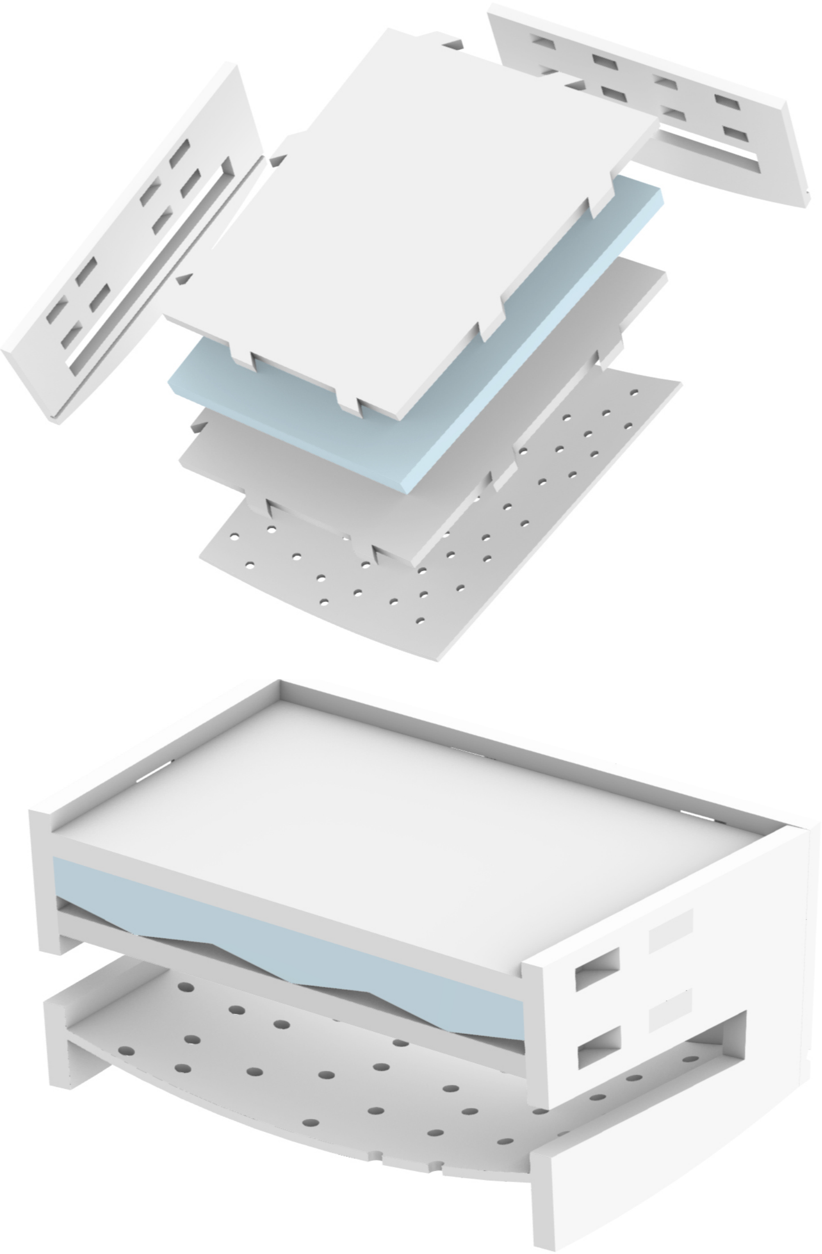

Figure 54, The five different parts of the cassettes.

The cassettes are constructed to be easily buildable in clear steps. First the structural parts are put together, in order, and lastly the bottom panel is slid into place. This process is performed in the same way for all cassettes, forming an L-shaped structure obeying all demands put on it.

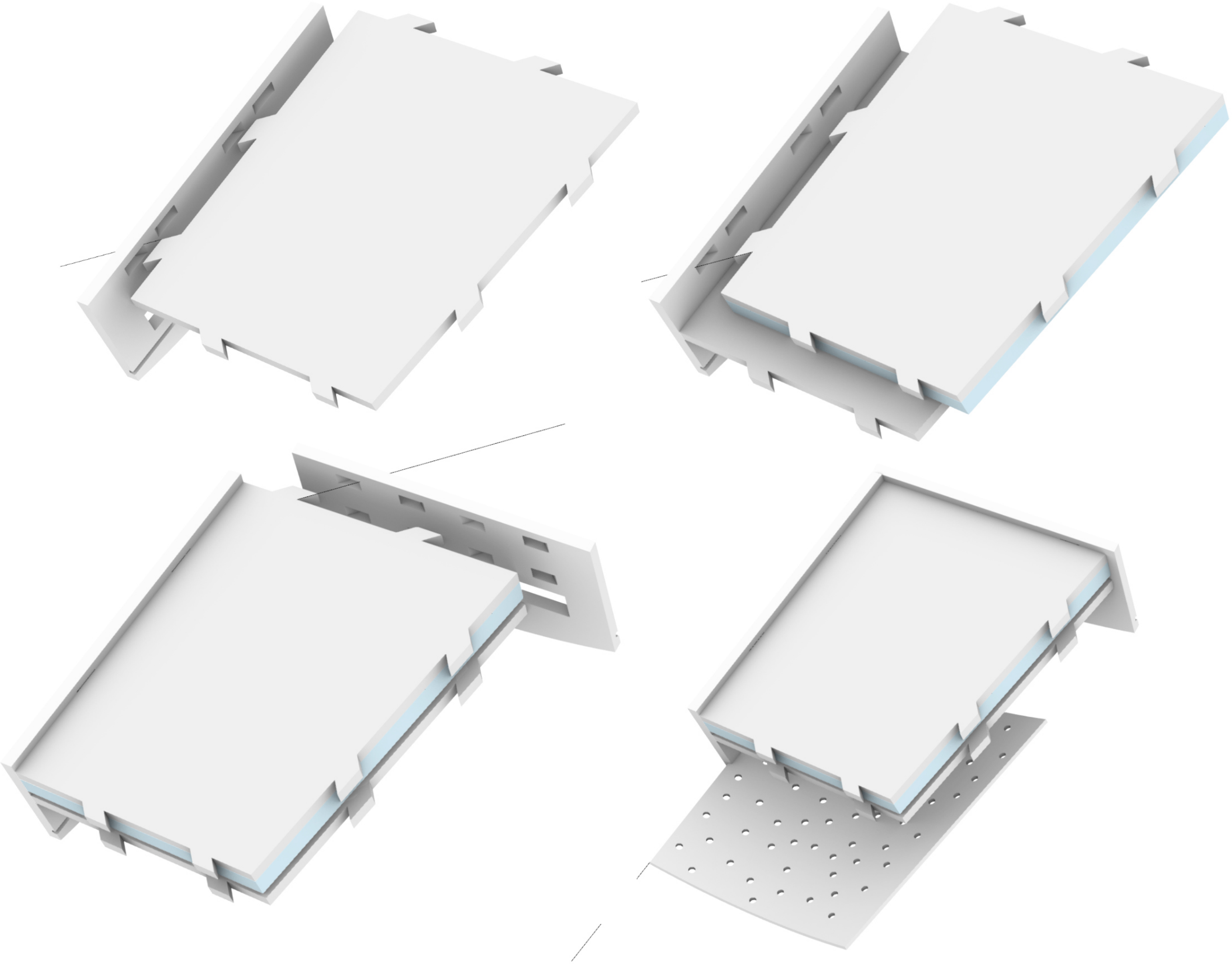

Figure 55, Assemblying a cassette from its five different parts. With sound absorption material in light blue.

The cassettes can then be assembled together into the double curved structure. The order of the cassettes in the assembly is very important as they can only be assembled in one way. When joined together each cassette locks the two cassettes it’s connected to, which renders is impossible for any cassette in the entire structure to move, besides one.

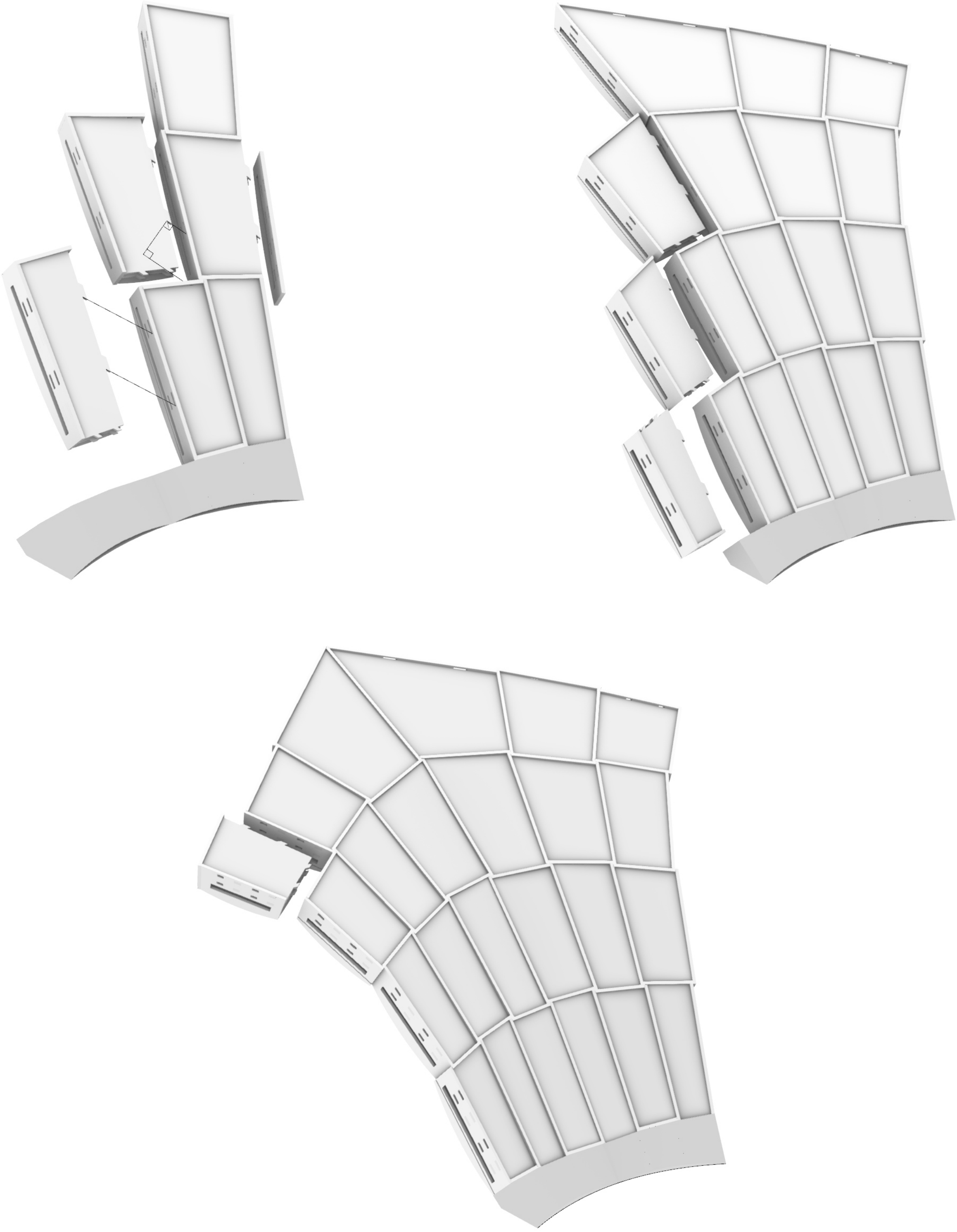

Figure 56, The process of assemblying the cassettes into a double curved structure.

The method presented on the previous page is then implemented on the double curved shape of the shell structure. As long as a mesh can be found that approximizes the geometry in question the method should be appliable to any double curved shape, providing that the angles are not to steep. Every face of the mesh will need to be planar and in the shape of a quadrilateral to be turned into a cassette. These cassettes can then be assembled into the approximate mesh geometry, forming a shell structure.

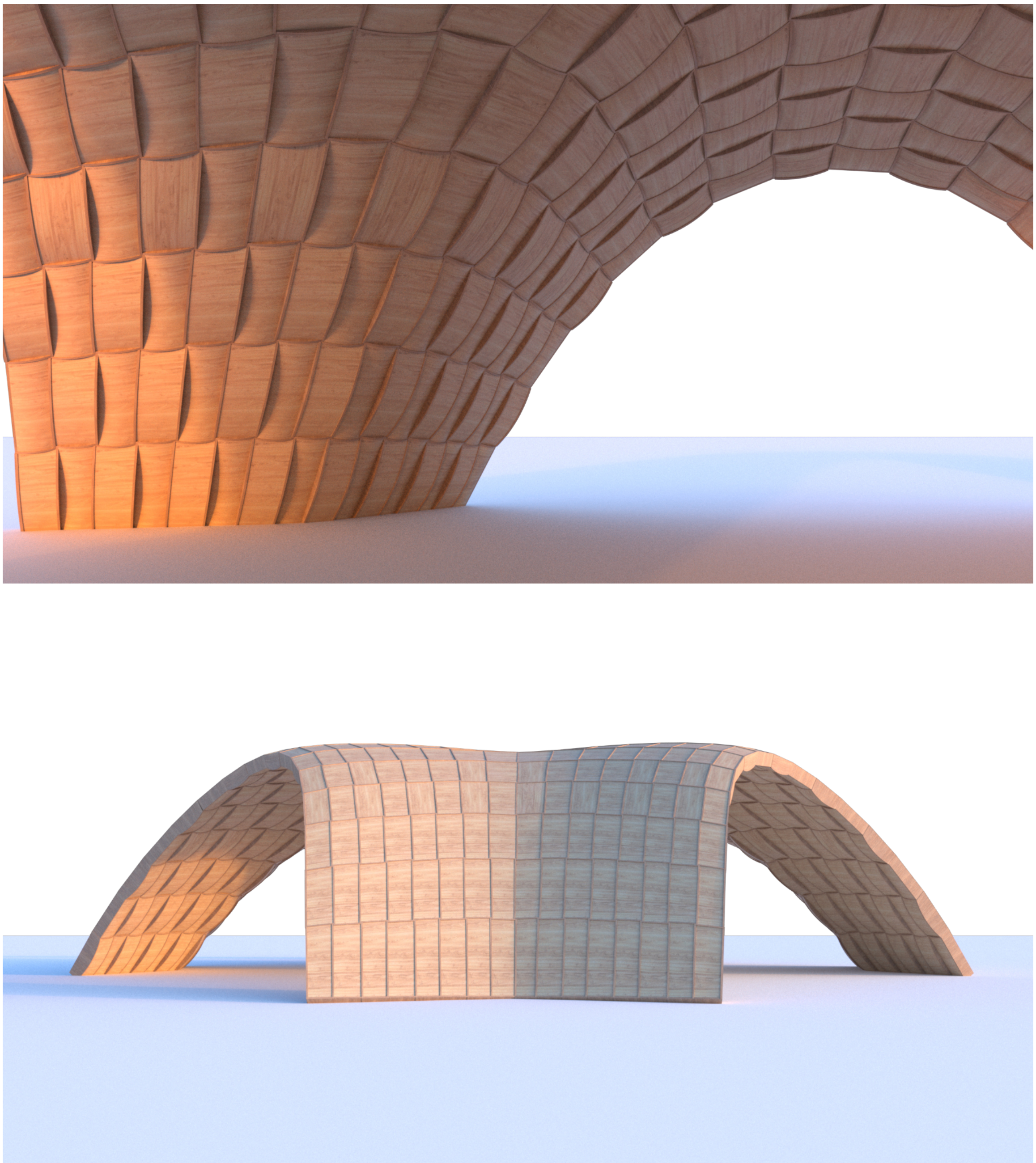

Figure 57, An example of the cassette structure on a generic double-curved shell structure.

When optimizing the mesh before turning it into a cassette structure the faces of the mesh will, as mentioned earlier, have to be planar. Two different approaches on how to planarize the surfaces were tried out. Firstly a local approach that planarize each face independently was tried. This approach did however result in large angles between the neighbouring faces which in our case was very undesirable.

Secondly a global approach was tried, where the faces are planarized in a way where they also take their neighbours into consideration. This resulted in a much better solution where the angles inbetween the faces were very small.

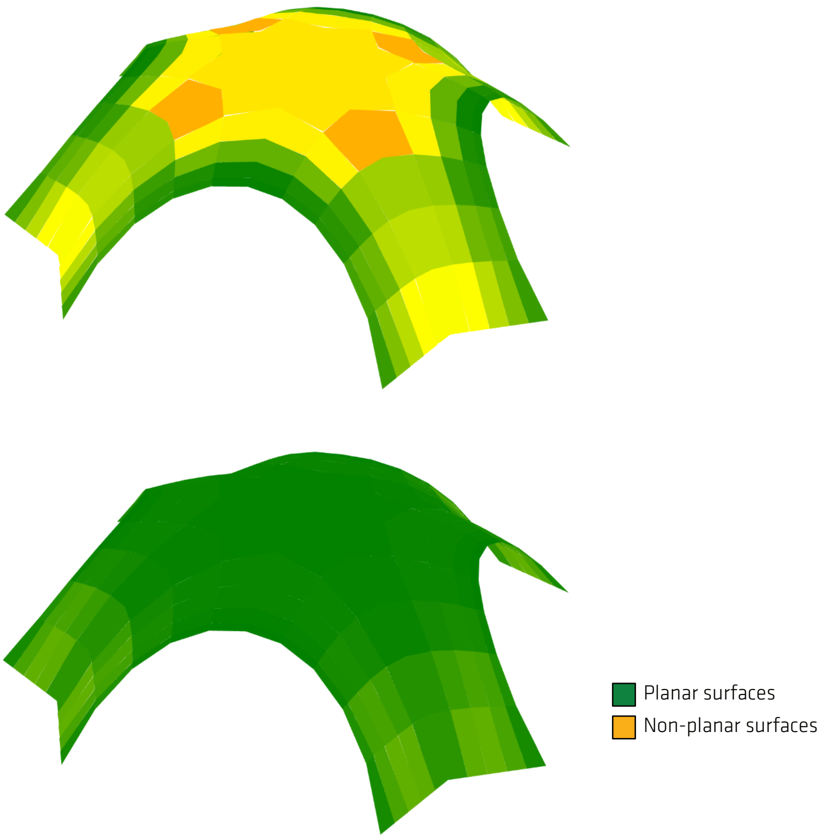

Figure 58, Comparison of a local and global optimization approach applied on the generic shell. The faces are colored according to a maximal angle between the edges of neighbouring faces.

A script was created for the implementation of the cassette structure on the mesh describing the geometry of the structure. This script also had the quality to be able to rotate and bend the lower panels of the cassettes to a certain degree following an attractor point. When testing this script on a generic mesh it was noticed that the acoustical result of this rotation was not as predictable as first thought. There was a theory that directing the panels towards a certain area would result in a higher concentration of sound energy in that area, this was not the case. Hence, it was clear that the evolutionary algorithmic iteration method would have to be used to optimize this step as well, since the method was not straight forward enough to be performed manually.

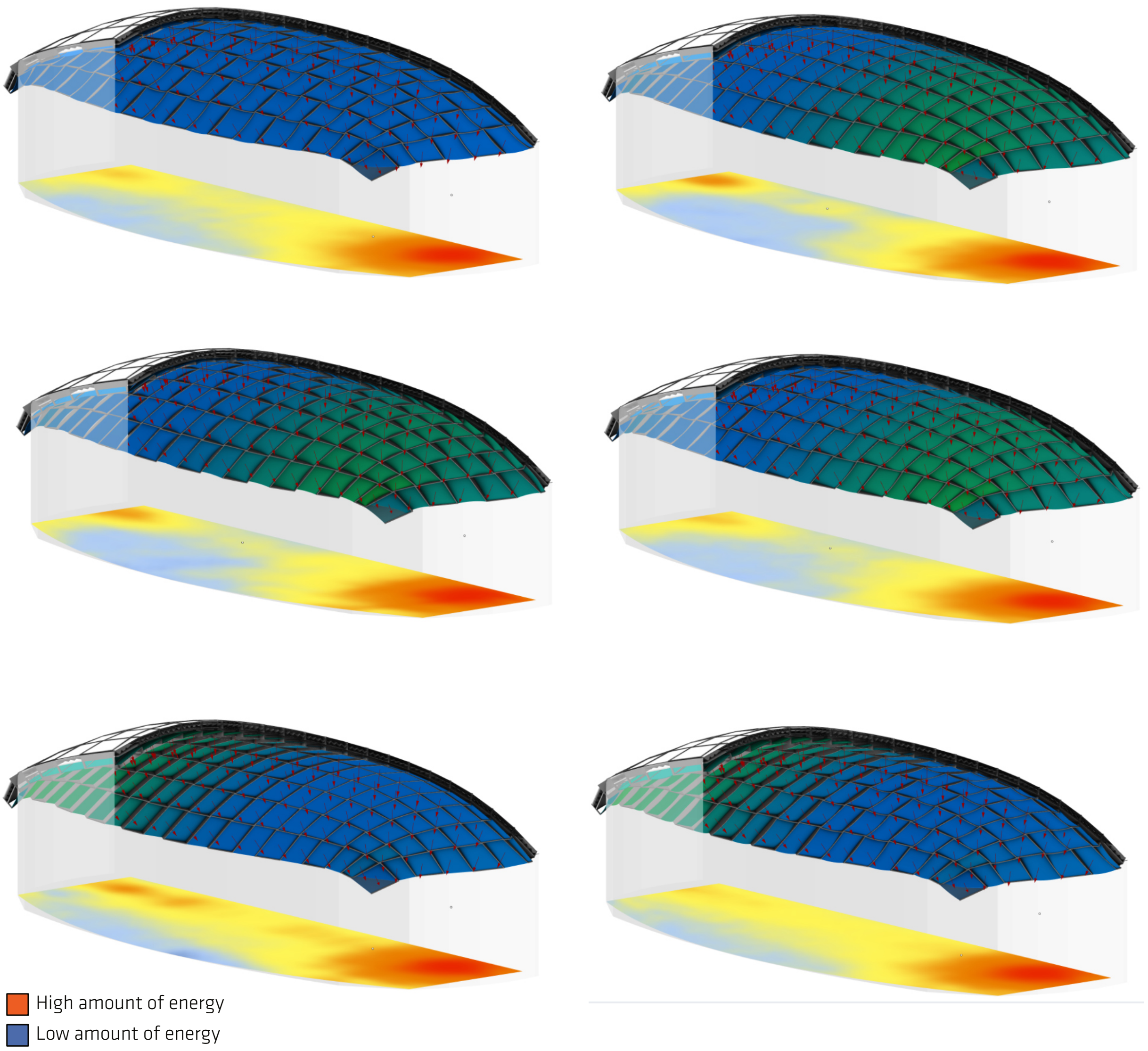

Figure 59, The lower panels of a generic mesh with different values of rotation and bending and the respective sound energy distribution on the surface below.

When implementing the cassette based shell structure on the mesh describing the geometry some decisions had to be made regarding the division of the mesh into faces. As there are many different ways to divide a mesh into faces there are also many different looks for the final design. As the division of its walls and ceiling will highly affect the aesthetics of the interior this decision was of high importance. What was noticed however, was that the more complex shapes and divisions of the mesh had some issues when it came to both approximating the shape of the acoustical analysis and when interpolating between the shapes, which in these cases resulted in unwanted flaws of the structure. In the end the most simple mesh was chosen for post production, a quite defensive decision, but necessary for both simplicity and to save time.

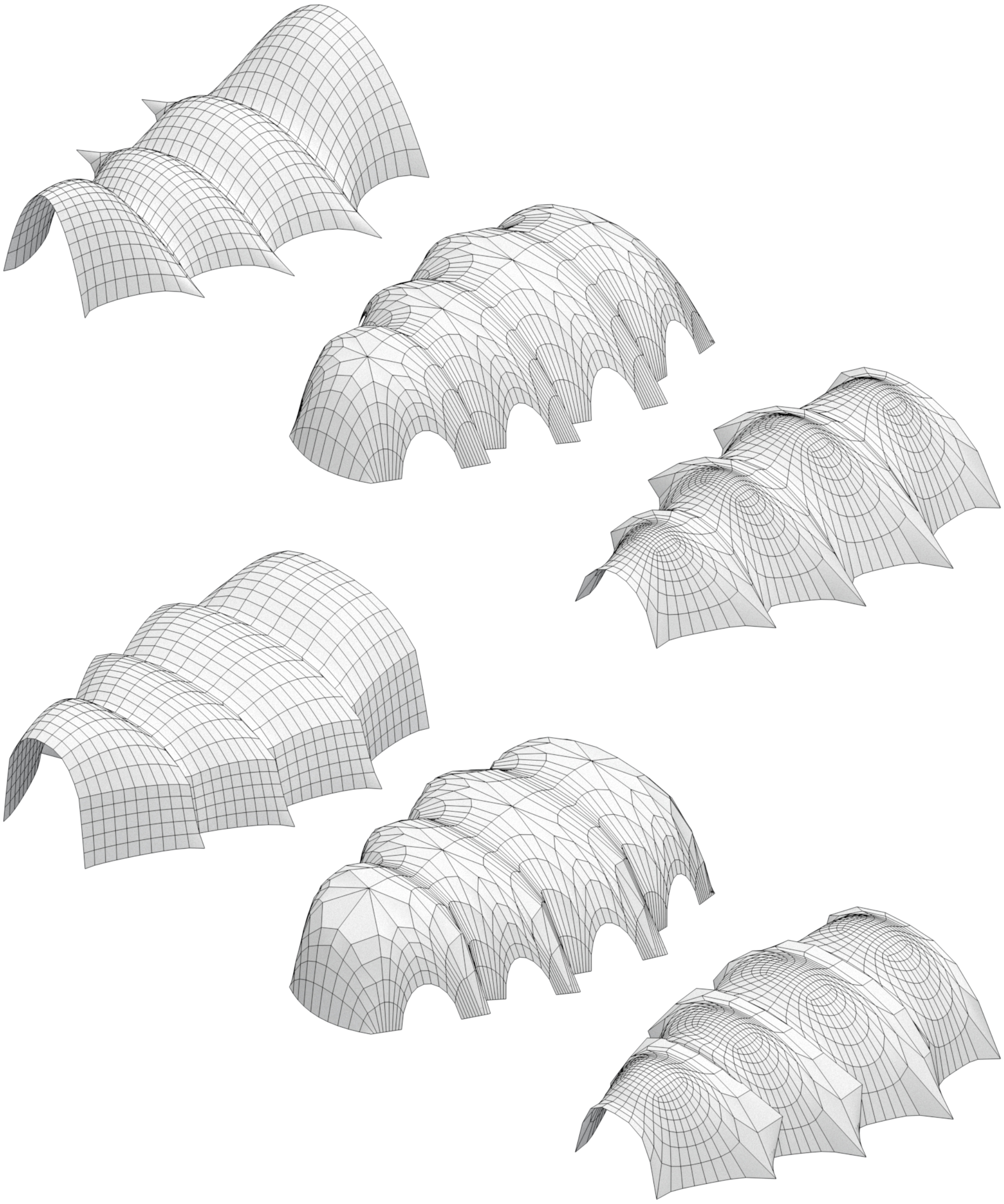

Figure 60, Three different types of division of the mesh, in the top the original structurally optimized mesh and in the bottom the interpolated mesh. As can be seen the more complex types of division has some issues with the interpolation.

The cassette structure was then implemented on the chosen mesh, creating a finalized design. This design did however have worse acoustical properties than its original mesh, as it was changed due to the structural optimization as well as the cassette implementation. Therefore a method of improving the acoustics in this late stage was sought. As has been mentioned earlier this method consisted of rotation of the lower panels, to be able to distribute the sound more evenly.

As a second evolutionary iterative process the geometry was once again exposed to the ray-tracing script in combination with the acoustical analysis. This time to optimize the rotation of the bottom panels of the cassettes as well as their curvature.

The final outcome of the iterations resulted in improved acoustical properties of a final design of the shoebox type auditorium. This final design was then brought into Phase 3.

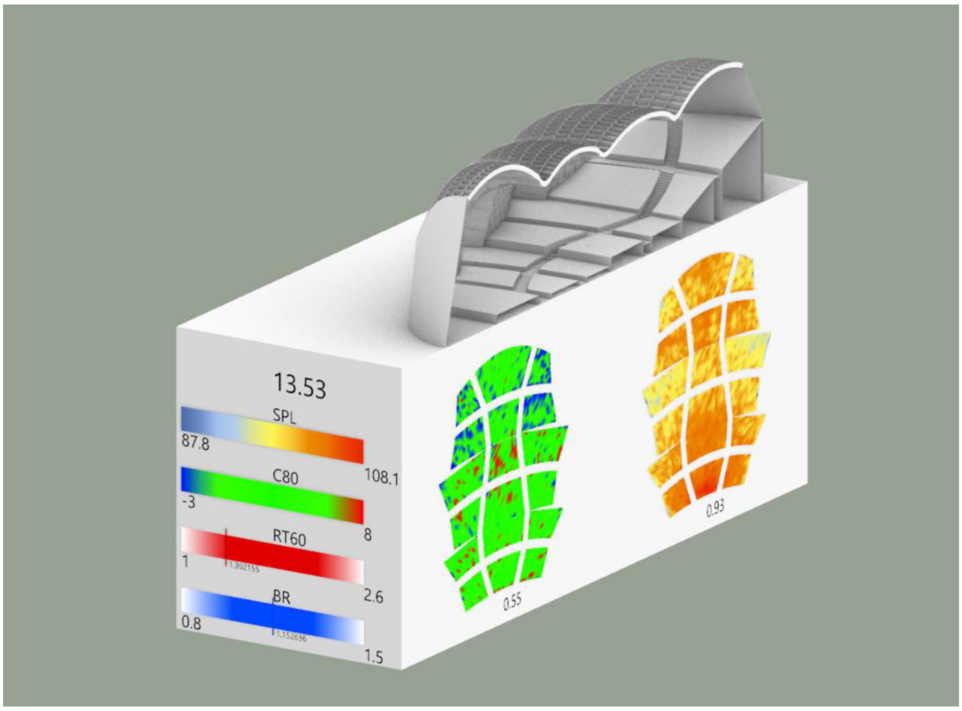

Figure 61, The final iteration of the shoebox-type auditorium.

Due to restrictions needed to apply the cassettes based structure, the mesh was modified such that all edge-beams were coplanar and such that each individual face was very close to coplanar. This slightly changed the form which made it deviate from the optimized mesh. As thickness was also introduced the acoustical properties were also changed. To counteract these modifications a second evolutionary iterative process was implemented in the same way as for the shoebox design. This process may even improve the acoustics over the optimized mesh as it allows the roof to redirect sound in ways not previously possible due to the structural form-finding process that was included in the acoustical iterative process. The resulting design is the final vineyard design brought into Phase 3.

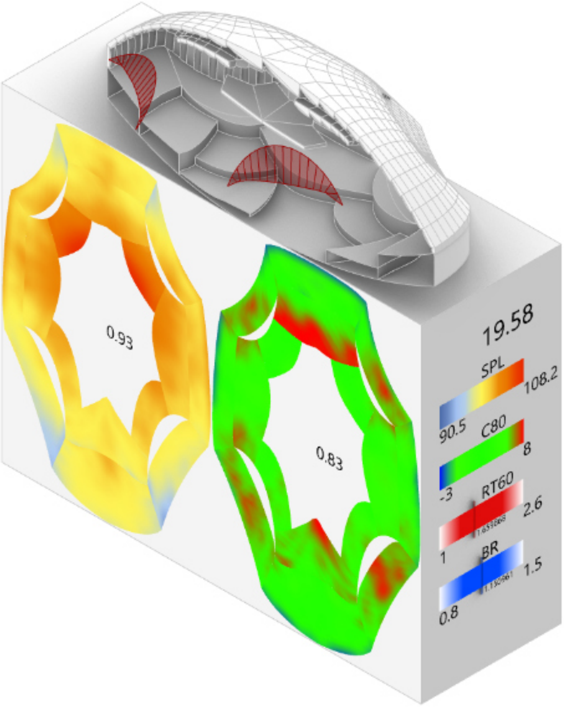

Figure 62, The final iteration of the vineyard-type auditorium.

From Phase 2, two different finalized auditoriums were found. One of the shoebox-type and one of the vineyard. These auditoriums were created from the same theory and similar methods, but does however vary a lot when it comes to overall design, acoustical properties and structural properties. Both types were therefore chosen to continue with into Phase 3.

The focus of Phase 3 is on finalizing the design from an overall geometry into an actual auditorium, by thinking of details, material and aesthetics in general.

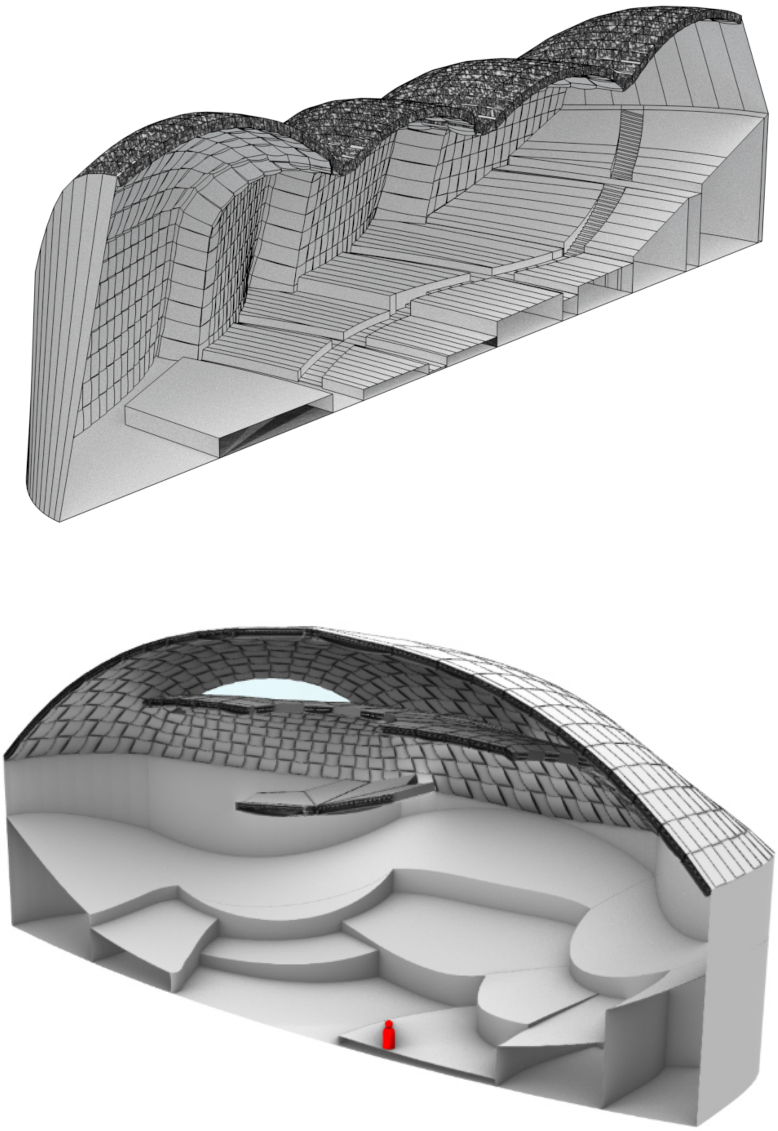

Figure 63, The fully optimized auditorium designs.

Phase 3

Design

The shoebox auditorium takes its basis in the shape of a general shoebox-type auditorum, with its stage in one end of the hall and a clear direction of the room. At the same time it explores new grounds with its massive four shells stretching across the room dividing it into four while still keeping it together as one. Three of these four rooms cover one section each of the seating area, while the fourth covers the stage, giving the hall a sectional view and a feeling of rooms within rooms. In the mighty ceiling the cassettes weave the room together in a powerful way creating a seemless connection between floor and ceiling that encloses the audience. The direction of the cassettes shows the way towards the stage and strengthens the general direction of the hall. Between the shells light finds its way in through the more open walls connecting them.

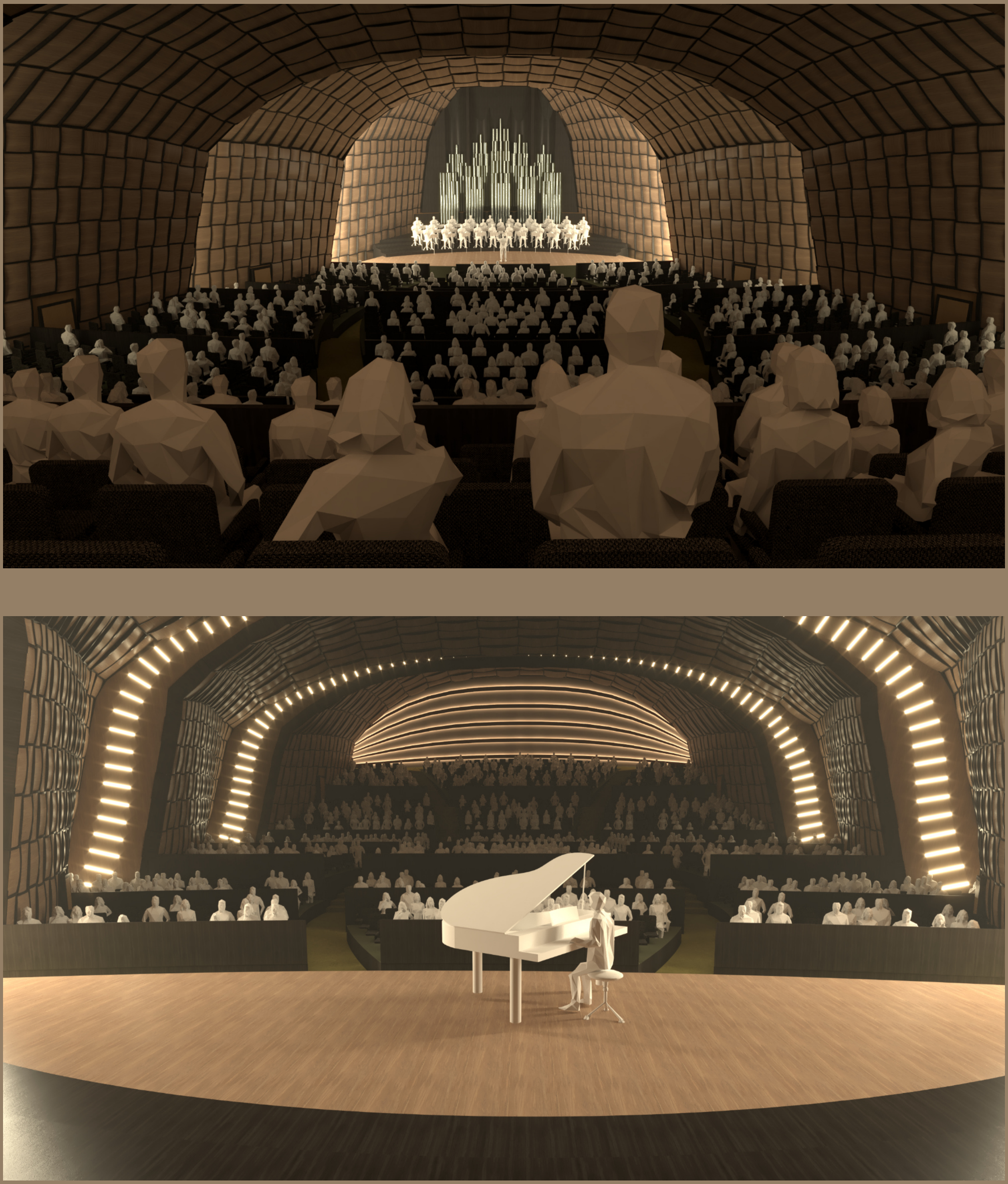

Figure 64, Interior perspectives of the shoebox.

The shape and distribution of the seating areas of the shoebox takes its basis in the shape of the outer walls, mimicing the gentle curve of te shells in combination with the sharp edges at their corners. This creates a collection of sharp edged islands in the hall, becoming more and more steep the further from the stage they move. Inbetween them stretches winding paths and stairs carrying the audience through the hall. The hall itself is in a way divided into four rooms under the four shells of the structure, with a slight difference in both height and angle between the rooms. The room in the front contains the stage, as well as the backstage and all the necessary equipment of an auditorium.

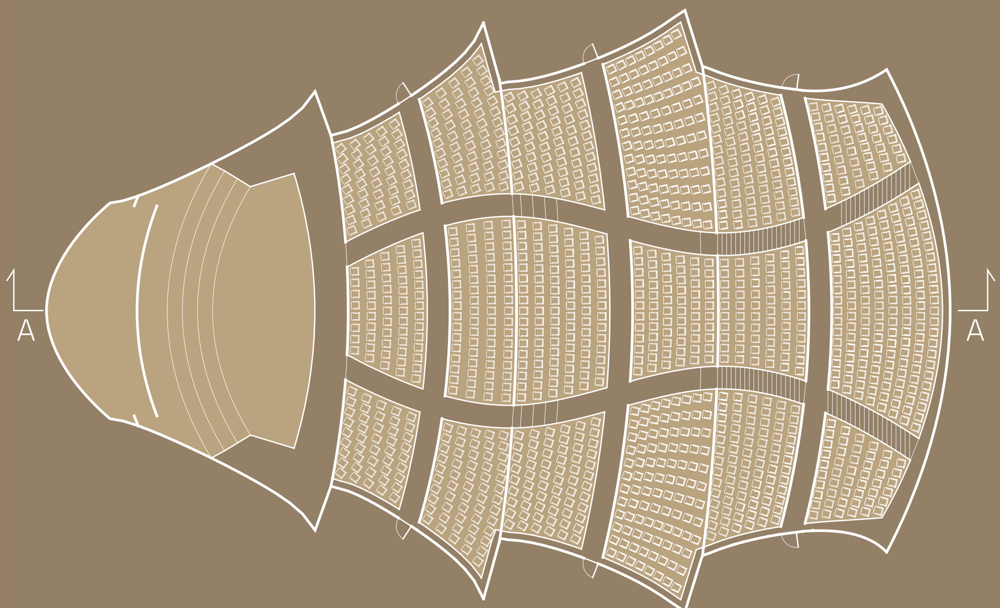

Figure 65, Plan view, 1:500

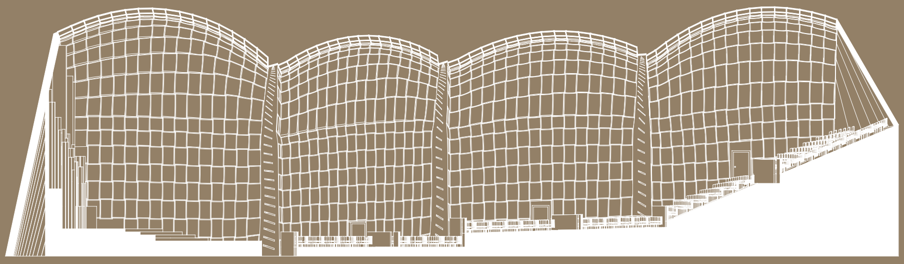

Figure 66, Section A-A, 1:500

The acoustical properties of the shoebox are as expected relatively good and very evenely spread over all the seating surfaces. As the surfaces in the back have a higher inclination, even they receive direct sound from the source at the stage. The sound pressure level is evenly distributed through the hall, and while it differs a little between the different seating areas the level is relatively high in all positions. The Clarity is well within the bounds in most positions and the Reverberation Time is on average at about 1.4 dB which is within the bounds for both symphonic performances and opera. The hall is, however, not very suitable for theatre with these values. The Bass Ratio is at about 1.15 which is as well suitable for music, although not for speaking performances.

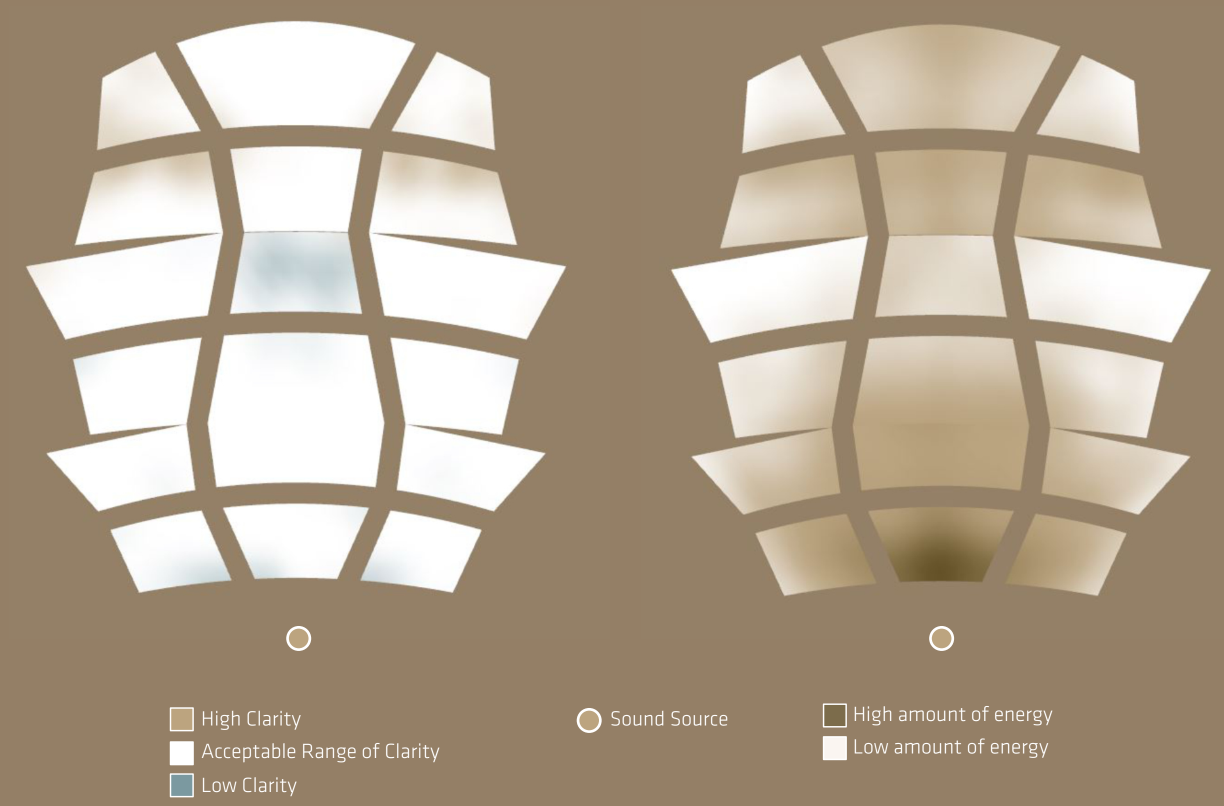

Figure 67, Acoustical diagrams over the shoebox seating area

Structural Properties

The shoebox consist of four separate shells that are individually constructed following the cassette based method. The cassettes of each shape follow the simple topology from the mesh in Phase 2, which is ordered in rows and columns. All shells are double curved and takes support in their short side edges as well as in the long sides of the edge shells, as they are connected to the ground with additional elements. The shells are also interconnected with eachother with additional elements and are structurally working together as a joint structure.

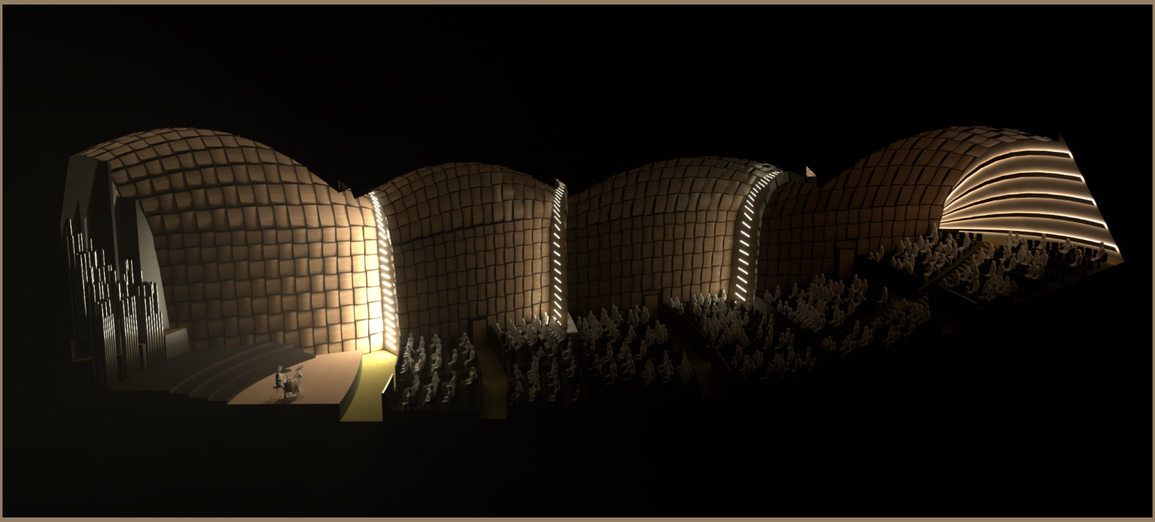

Figure 68, A cut through the structure of the shoebox.

This vineyard design brings the audience closer to the performer, creating a more intimate space while providing great visibility to the stage area from all angles. The shell structure is used to not only help with acoustics, but also provide a unique experience for the audience. The great flower(hanging structure) provides early reflections to the audience but also to the performers, helping them perform to the best of their abilities. This venue is set to use the shell to create an atmosphere where any musician's performance would create even stronger memories in their audiences minds.

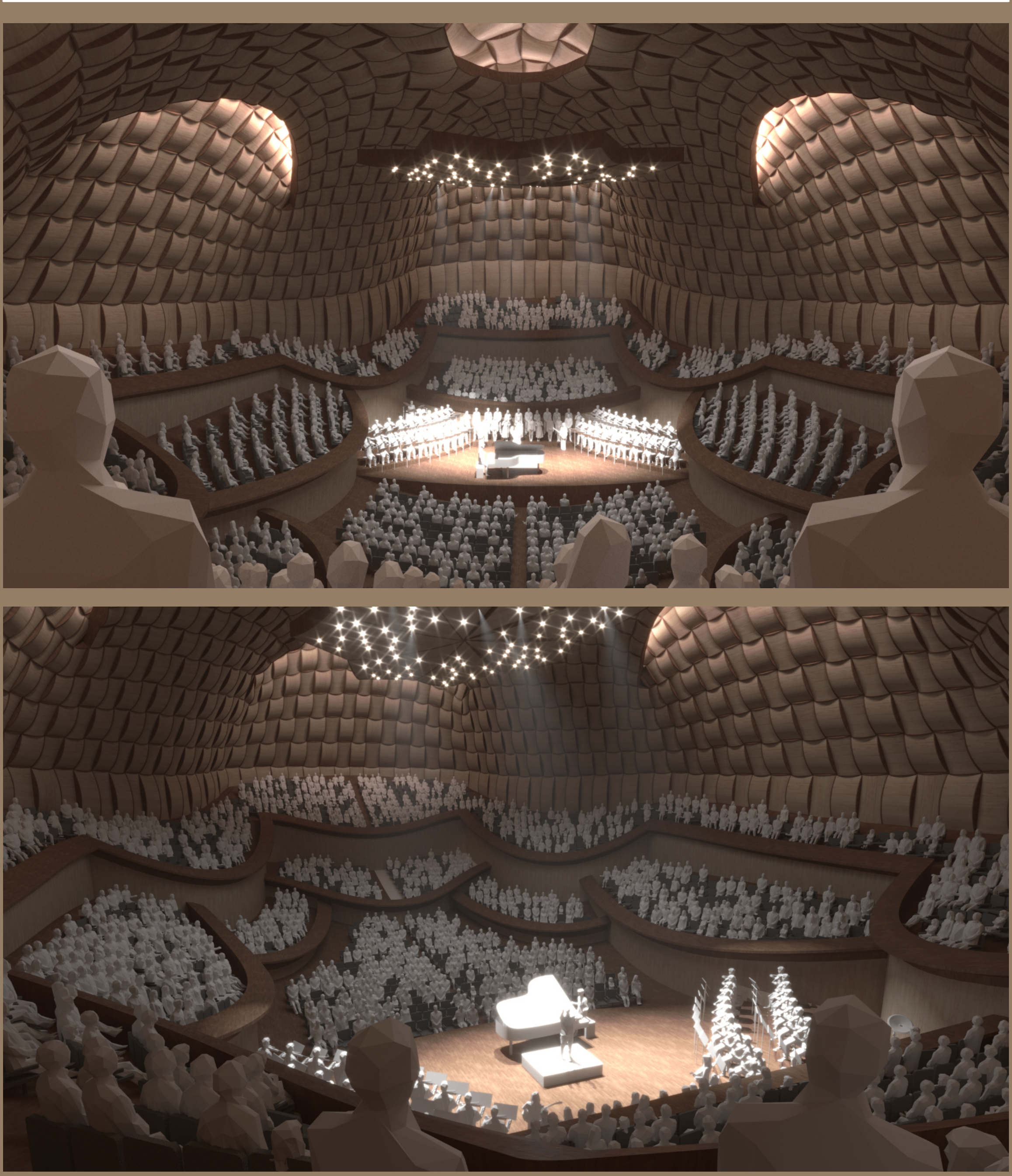

Figure 69, Interior perspectives of the vineyard.

The seating is arranged around the center stage, which is displaced a distance to one side. The seating areas closest to the stage and behind it have a relatively steep inclination while the seating areas furthest down are relatively flat. The ceiling consist of two shells, one outer and one inner, who differs in inclination and are separated by several meters in the middle. In the center of the room there is a hanging reflector following the shape of the cassettes.

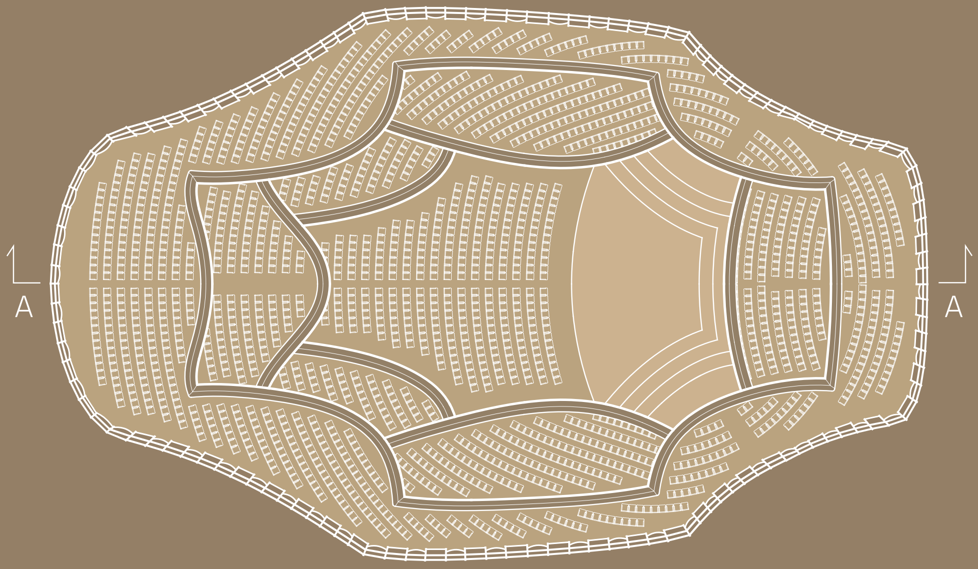

Figure 70, Plan view, 1:500

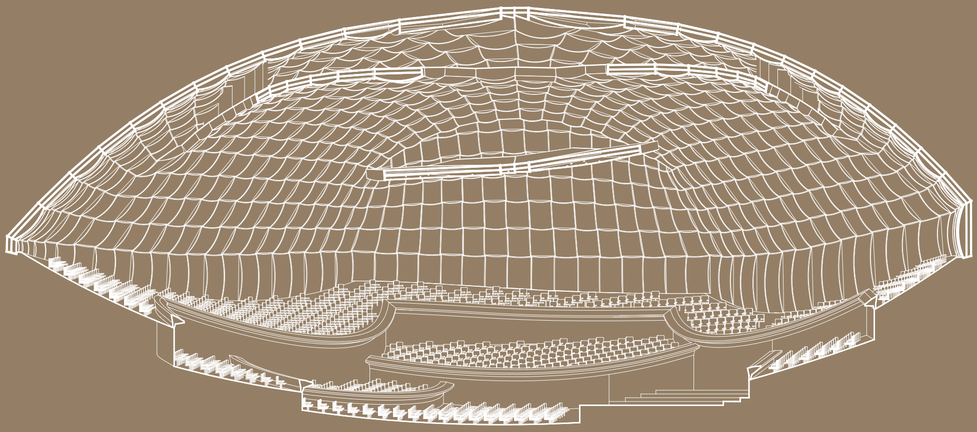

Figure 71, Section A-A, 1:500

Acoustical Properties

The acoustical properties of the vineyard auditorium are not as evenly distributed as the properties of the shoebox. They are although good results, but they vary in a more clear way throughout the hall. The sound pressure level does however have a rather good distribution, although the Clarity differs a lot for different seating surfaces. These differences does however provide different acoustical experiences for different seats in the hall, which is one of the advantages of a vineyard-type auditorium. The Reverberation Time is on average about 1.85 which is good for a symphonic performance and just at the borderline for opera, the Bass Ratio lies at about 1.14, which is well within the bounds for musical performances. For speaking performances, such as the theatre, the acoustical properties are not suitable.

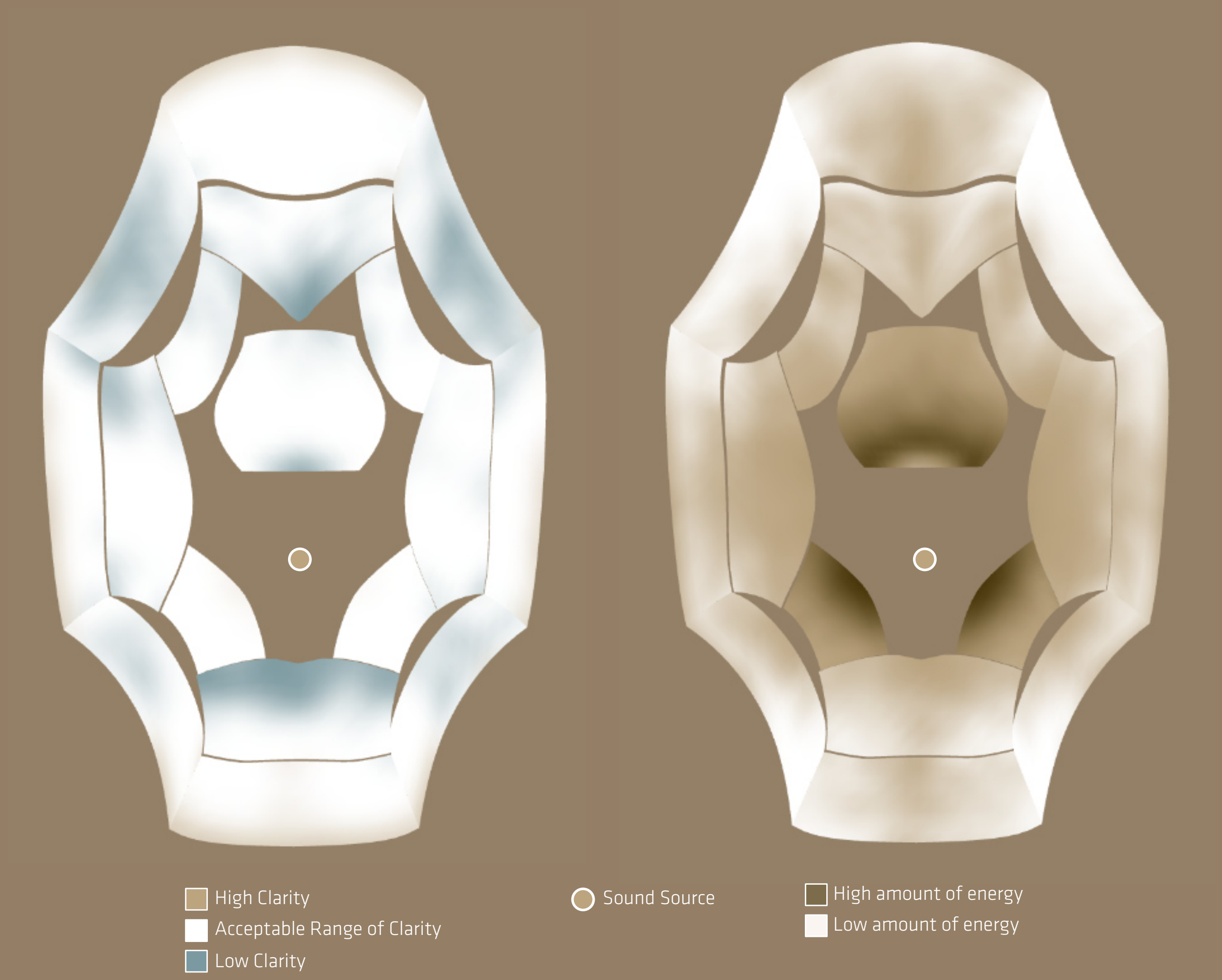

Figure 72, Acoustical diagrams over the vineyard seating area

Structural Properties

Through the use of two overlapping shells sound is allowed to build harmonics between them, while being very structurally efficient resulting in a dynamic space to be in. The directions that can be seen within the roof follows the general force patterns, allowing visitors to see the natural forms of the timber structure.

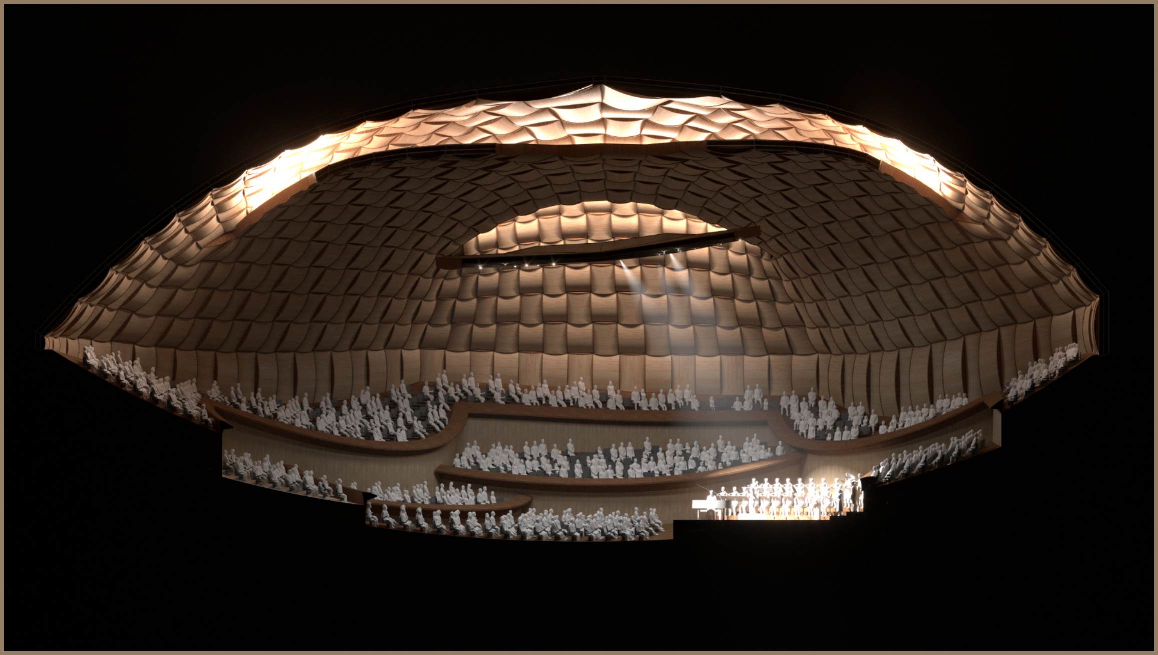

Figure 73, A cut through the structure of the vineyard

Discussion

Looking back at the project there are some things that could have been done differently which would to the greatest probability have improved the results. As the shoebox was created alongside the process of the method several, lessons were learnt along the way.

One thing that could have been simplified would be the iteration process. Instead of dividing into the steps of acoustical and structural optimization, these could have been performed together (as with the vineyard). This would have simplified the whole method and would probably have given a better result as it would have eliminated the need for interpolation. This method would, however, probably have resulted in a less versatile shape, which would have brought other issues.

Some parts of the project felt quite stressed through due to the limitation of time and that there was a certain goal of the project that felt necessary to acheive within the time frame.

One part where more time to find a better solution would have been great was the investigation of different types of mesh division and how to work with interpolation and implementation with these. More time to find an interesting type of mesh division that could actually work with the rest of the method could have resulted in a much more interesting shell structure, and in the end in a better and more aesthetically pleasing auditorium.

Another thing that felt stressed through was working with different materials, both in an aesthetic way, but also for the acoustical analysis. By investing more time on materials the project could have been brought even further, both architecturally and acoustically.

While working with the materials of the cassettes it would also have been an improvement to work more with their general acoustical properties due to cavities, holes and sound absorption. It could have been interesting to experiment with the cassettes being able to “swallow” different frequencies to affect the acoustics of the room.

Discussion

In general it would have been an improvement to have been able to put more time on the final design project. As there wasn't that much time left when this point of the project was reached, the design became in some ways stressed through and not as well thought through as preferred.

There are unfortunately several acoustical properties mentioned in Phase 1 that are not taken into consideration for the final design. Due to lack of time, it was not possible to implement all of these properties, which is a shame as it would have improved the final result and design.

If this project would have been brought even further there are certain things that would have been interesting to look into. One of those things would have been auralization(allowing the ability to listen to the room acoustics digitally, perhaps integrated in a game-engine such that one can walk around the room and experience it both architecturally and acoustically), where it could have been very interesting to compare the sound from different seats in the two auditoriums, as well as between them.

Another comparison which would have been interesting to investigate if the project was taken further would have been that between the shoebox and a real shoebox type auditorium as well as between the vineyard and a real vineyard-type auditorium, such as Göteborgs Konserthall and Elbphilharmonie in Hamburg. Both with the analysis used in the project as well as with auralization. As the project at the moment is optimized locally, it would have been interesting to see a global comparison, how the final design would stand compared to real buildings.

One of the main limitations experienced was the complexity of building a flexible design and making the right assumptions for acoustical properties. Essentially, this method is a "black box" when acoustical expertise and experience is lacking. In this project many of the results were scrapped due to the results not being close to the design intent, each time leading to a substantial redesign. It is very hard to even remotely predict what the result will look like which makes architectural intent even harder.

Constructing a shell topology can be a tedious process, with many settings that need tweaking, this fact leads to many technical difficulties during the iterative process as unimagined bugs can nullify hours of work.

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Herman Ehrnberg & Simon Wikström

We are two students originally from Chalmers that started our studies in the Architecture and Engineering bachelor. Here we quickly found an interest for both architecture and structural engineering, an interest which has then shaped our education. When we finished our bachelor education we both decided to keep studying both architecture and engineering, which resulted in us studying two Master's Programs, Architecture and Urban Design Msc and Structural Engineering and Building Technology Msc. This twofold interest is also what has led to us writing this thesis, in combination with other interests we have picked up during our studies.

During our time at Chalmers we have had many opportunites to hone our knowledge in several fields that has been highly necessary for this thesis. Such as Parametric Design, Optimization, Shell Structures and Acoustics. In courses such as: Architecture and Optimized Structures, Digital Tools - Parameteric Design, Material and Detail, Geometry in Architecture and Virtual tools in a Material Culture.

And as well in our Bachelor's Thesis where we first came into working with an auditorium where the project was focused on designing an acoustical space for a combination of outdoors and indoors use. While working on this project we were struck by how bad the acoustical analysis tools were for our specific use, and mostly how slow the process was. When the acoustical analysis was done for one design we had often already changed it quite a bit and therefore the analysis was mostly redundant. Here the idea was born for an iterative process that could create the geometry neccessary for optimized acoustical properties. And from this idea came the questions that has led to this thesis.