Can Genetic Algorithms Be Used As a Practical Design Tool in Architectural Acoustics?

Abstract

In this project, a parametric ceiling design was created for an auditorium due for refurbishment in order to keep the acoustics the same before and after. Initial reverberation time measurements were taken in the auditorium, and a 3D model of the space was constructed from architectural drawings. Materials were assigned to the surfaces in the model with absorption coefficients obtained from literature. The reverberation time in the model matched the measured reverberation time of the room. Although details of the proposed refurbishment were not available, a modified 3D model was created for the new room. A parametric ceiling design was created for the new room in Grasshopper, a generative design tool associated with the 3D modelling package Rhino. The ceiling in the new room was then optimised using a multi objective evolutionary solver to keep the Reverberation Time, Early Decay Time, Strength, and Clarity as similar as possible between the two rooms. In all three solutions presented, the difference between all room parameters in the new and old rooms is below the "Just Noticeable Difference", indicating that the acoustics would be almost identical and that genetic algorithms can successfully generate complex designs which match acoustic requirements. Uncertainty in the results come from the absorption and scattering coefficients used, since no real materials could be tested. There is also uncertainty in predicting acoustics using ray tracing. Genetic algorithms could be used at an early stage in the design process to create better acoustic spaces, and, since it is now possible to "listen" to spaces using auralisation, communicating the benefits of the strategy is made easier.

Section 0: Introduction

In conjunction with a qualified acoustic engineer, reverberation time measurements were taken by the author inside an auditorium due for refurbishment. The brief was to design a new ceiling so that the acoustics would remain the same after the refurbishment. In this project, a tool for acoustic design optimisation using genetic algorithms is presented. Genetic algorithms offer a way to systematically test the performance of many different designs in a way which works towards an optimal solution. This reduces the need for trial and error and can create designs which could not have been conceived through conventional techniques.

In order to have anything to optimise, a design must first be constructed whose geometry can be manipulated through the alteration of a relatively small number of variables. This is known as parametric design. The algorithm then tests hundreds of different combinations of these parameters and, in a process which mimics the process of evolution, the quality, or “fitness” of the designs gradually increases the longer the algorithm is left to run. When the algorithm is stopped, a selection of designs with a high fitness is available for selection.

Section 1: Literature Review

1.1: Physical Models vs Computer Models

Prediction and modelling have long been a part of the design of auditoria. The first acoustic scale model was made by Spandock in the 1930s. Physical models are still used today for large, high profile projects. However, computer modelling of auditoria has become more popular in recent years due to its increasing speed and accuracy (Barron, 1997). In a physical scale model, the smaller model size means that a higher frequency range needs to be considered in the analysis. Therefore, materials need to be found with the required absorption at the scaled frequency, which can be problematic. Also, in a scale model, the absorptive and diffusive characteristics of a material cannot be altered independently. In a computer model, this can be easily achieved by setting absorption and scattering coefficients at each frequency (James, 2006).

If a scale model is built to a high level of accuracy, then diffusion and diffraction effects from complex surfaces can be reproduced with great accuracy, since real sound is being measured and ray tracing approximations do not have to be made. However, with the correct choice of scattering coefficients, computer modelling can produce equally accurate results far more quickly, especially when calibrated against a real auditorium (James, 2006).

1.2: Design Optimisation

An optimisation problem consists of: a vector of input data which describes every possible design in the system, a set of one or more “objective functions” that describe the goals of the system, and an optional set of constraint functions which determine the feasibility of any design. The aim is to either maximise or minimise the objective function. The optimisation process finds combinations of input data which best satisfy the objective functions while working within the limits of the constraints (Nagy, 2017). A problem with more than one objective function is a *multi-objective* optimisation. The goals may compete with one another, so it is unlikely that a single best solution will be found. Instead, a set of “Pareto Optimal” solutions is produced, describing different trade-offs.

In Genetic Algorithms (GA), the value of each variable is represented in binary as a string of 0s and 1s. Each individual 1 or 0 is referred to as an “allele”, each variable string is referred to as a “gene” and the long string of genes, representing a design, is referred to as a “chromosome”. A “population” is a group of individuals (chromosomes) that interact (breed) together (Querin, et al., 2018).

$$\text{Allele}$$

$$Chromosome = [\overbrace{101010011}^{Gene\ 1}\quad \overbrace{001111001\boxed{0}}^{Gene\ 2}\ \ \ldots\ \ \overbrace{0\boxed{1}00100101}^{Gene\ n}]$$

$$Population = \begin{bmatrix} 101010011 & 0011110010 & \ldots & 0100100101 \\ 001001001 & 1110001010 & \ldots & 1010100001 \\ 111110010 & 0010101110 & \ldots & 0010011001 \end{bmatrix}$$

Figure 1.3.1: GA naming convention

A population of, say, 50 individuals (chromosomes) is generated at random. The population is then manipulated and combined using a series of processes which simulate Darwin’s theory of evolution. A single iteration of the algorithm creates a new generation. First, the “fitness” of each individual is evaluated. The fitness function is a measure of how well each individual satisfies the objective function(s). Fitness function values are always positive, with higher values being better. Next, the bottom 10-20% worst performing designs are exterminated and the top 10% are carried forward to the next generation. This ensures that good genetic material is carried forwards and that the solution quality does not decrease from one generation to the next. Two individuals from the remaining population (all individuals which have not been exterminated) are then selected for reproduction. The most common selection method is Proportional Selection, which is biased towards fit individuals. Here, each individual can be imagined as a space on a Roulette wheel proportional in size to its fitness. When the wheel is spun, the individual on which the ball lands is selected. Selected individuals are paired into couples. Each couple creates two “offspring”, so the number of couples chosen for reproduction needs to be enough so that the size of the next generation is equal to the size of the current generation. When an individual is selected for reproduction, they remain in the population for further selection, ensuring that the average fitness increases from generation to generation.

The two chromosomes selected for reproduction are subjected to a crossover operation to create two “offspring”. The simplest example of this is “Single Point Crossover”. Here, a crossover position, i, between 1 and the length of the string is randomly selected. Assume for example, that the position i = 14 is selected for the parent designs shown in Figure 1.3.2. In the resulting “offspring”, every allele after this position is swapped between the two parents.

$$i = 14$$

$$Parent1 = 10101100101100\boxed{001010100010110100010011}$$
$$Parent2 = 00101001010101\boxed{010001010101010010111100}$$

$$Offspring1 = 10101100101100\boxed{010001010101010010111100}$$
$$Offspring2 = 00101001010101\boxed{001010100010110100010011}$$

Figure 1.3.2: Single point crossover

The final stage of the algorithm is “mutation”. This stage acts as a safety net to recover good genetic material which may have been lost through selection and crossover. A single allele is randomly selected from the population and modified from 0 to 1 or vice versa. The fitness of every individual in the new population is then evaluated and the process repeats. The algorithm either runs for a set number of generations or until the fitness function converges and stops increasing (Querin, et al., 2018).

1.3: Measurement Parameters for Auditorium Acoustics

The most commonly used parameter for reverberance in building acoustics is Reverberation Time (RT). RT is a measure of how long an impulse response takes to decay by 60dB. In practice, it is often difficult to fill a room with enough sound to create a 60dB drop, so the time interval between -5dB and -25dB is used, and then multiplied by three, giving a reverberation time parameter known as T20. (Bolstadtunet, 2008) gives several other subjective parameters which control the acoustics of a concert hall, including: Early Decay Time (EDT), Sound Strength(G) and Clarity (C_{80}).

Early decay time (EDT) is another measure of a room's reverberance. It can be calculated as the time it takes for an impulse response to drop from 0dB to -10dB, multiplied by six (akuTEK, 2019). The reason for the different methods of calculation is that the decay of sound is rarely a perfectly sloping straight line. This would only occur in a perfectly diffuse sound field. In rooms where absorption is concentrated in a few places, such as on the ceiling, the sound field will be less diffuse, and the first few decibels of sound decay will be significantly steeper than the rest of the decay curve (Acoustic Bulletin, 2018). Working with both parameters gives a more detailed description of a room's reverberance. RT describing the later portion and EDT describing the early portion. Figure 1.4.1 shows the difference between T20 and EDT.

Sound Strength (G)is a measure of the loudness of a room. It is defined as the difference between the sound pressure level in the room and the sound pressure level that would be experienced in free field conditions (an anechoic chamber). Clarity (C_{80}) is an objective measure of the intelligibility of speech. Reflections arriving after 80ms are unfavourable for speech because they cause syllables to merge with one another. Clarity is the ratio between the sound energy that arrives before 80ms and the sound energy that arrives after 80ms. It is calculated as shown in equation 1.4

$$C_{80} = 10 * \log\left(\frac{Energy(0-80ms)}{Energy(50-end)}\right) dB \qquad \text{(Acoustic Bulletin, 2018)} \qquad (1.4)$$

Clarity and reverberation conflict with one another. A high clarity will not accompany a high reverberation, since the more reverberant the room, the less clear speech will become. (akuTEK, 2019) give "Just Noticeable Differences" (JND) for each room parameter. If the difference at a given receiver between two rooms is below the JND for all parameters, then the acoustics of the rooms will be almost identical.

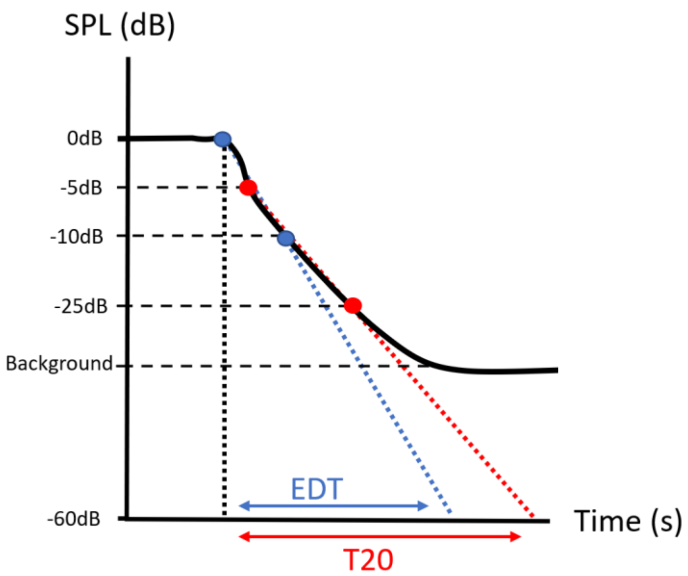
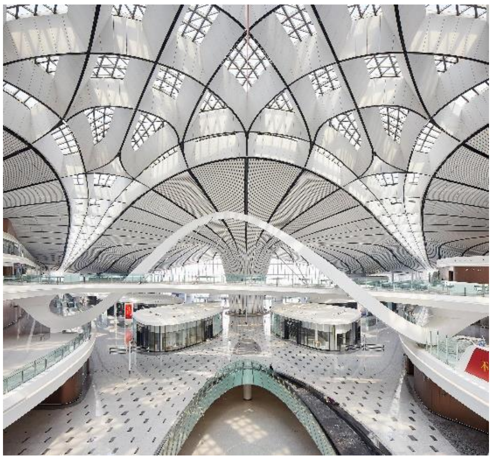


Figure 1.4.1 Early Decay Time vs T20

1.4: Why Use Genetic Algorithms?

The acoustics of a space have a crucial effect on how it is perceived. In recent years, auralisation techniques have allowed architects and acousticians to "listen" to a space together before it is built, allowing a more integrated approach to be taken, and good acoustic design to be built in from the early stages (Patel, 2020).

When the first diffusors first introduced, they were in keeping with the architectural trends of the time. In recent years, architecture has been greatly influenced by advances in engineering to allow previously unimaginable shapes to be constructed. For example, Zaha Hadid Architects, a key proponent of the Parametricism movement, use parametric models to build large spaces with curved forms and complex geometry (Architonic, 2019). In spaces such as these, Schroeder diffusors and absorptive rafts may not match the style required (Cox, 2006).




Parametric Architecture: From Left: Bejiing Daxang international airport by Zaha Hadid (Architonic, 2019)*, and Stack by the Mirage in Las Vegas* (Mirage, n.d.)

A huge variety of shapes and geometries can be constructed (or reconstructed) parametrically, and these can be optimised for their acoustic performance using evolutionary solvers. This would be especially useful in complex scenarios, where it becomes difficult to predict the overall acoustic effect of a given change. In parametric design, any changes to individual parameters can be immediately visualised, allowing appropriate constraints to be defined. Optimisation makes it easier to create architectural features which perform well acoustically, and allows diffusors to be designed which have harmony with the architectural style of a building. With auralisation, communicating the benefits of the process is made easier, since the improvement can be heard, rather than shown through a number. Additionally, there is readily available RT, EDT, C_{80} and G data for many different concert halls considered to have excellent acoustics (akuTEK, 2019). This data could act as a benchmark for optimisation algorithms to work towards, allowing the acoustics of a given hall to be emulated in a different space.

1.5: Recent Work in Field

For the ceiling of the recital room at the University of Iowa School of Music, a parametric model was developed in Grasshopper by LMN architects and JHA Acoustics. The tool was used to iteratively refine the shape of the reflector to concentrate the sound towards the audience and upper areas of the side walls (LMN Architects, 2020).

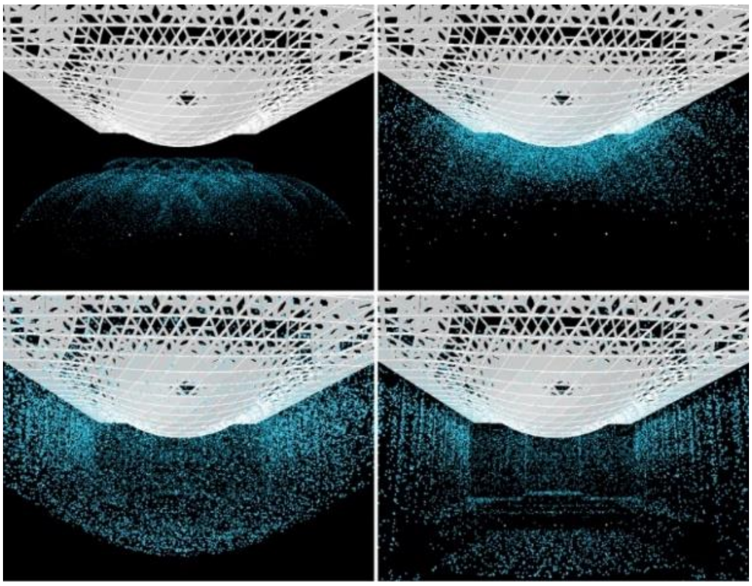


Figure 1.6.1: Visualisation of sound propagation within University of Iowa Recital Room (LMN Architects, 2020)

(Echenagucia, et al., 2014) used multi objective genetic algorithms to design a curved concrete shell ceiling for a concert hall. Instead of optimising specific parameters such as strength or reverberation time, the impulse response was split into three time windows: early, medium and late. The shape of the ceiling was optimised so that an equal amount of sound ray reflections reached each receiver in each time window, ensuring there are no sound concentrations or shadowed areas in the audience area.

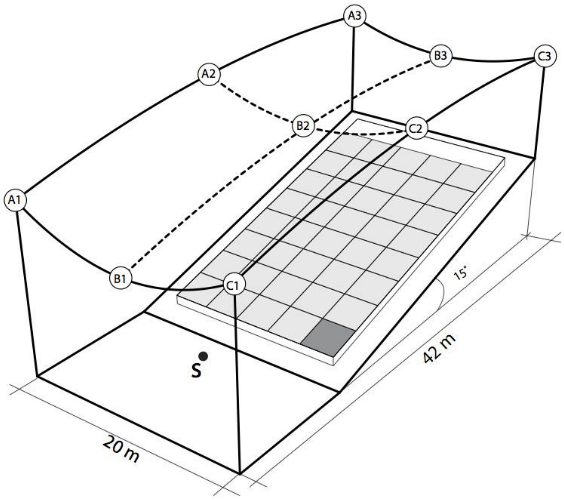


Figure 1.6.2: Concrete shell ceiling from (Echenagucia, et al., 2014)

Section 2: Design Process

2.0 Introduction

The basic design process for the project, once the initial measurements were taken, was as follows:

1. Build model in Sketchup from drawings
2. Import to Rhino
3. Split into layers and assign material properties in Pachyderm
4. Simulate acoustics in the model and check against measured reverb time
5. Calibrate model to the measured values
6. Create a new hall model – post refurb
7. Create a parametric ceiling design in Grasshopper
8. Feed parameters into evolutionary solver
9. Select a pareto optimal design

2.1 Initial Measurements

Reverberation time measurements were taken using a starter pistol at three source positions and eleven receiver positions, as shown in Figure 2.1. From analysis of reverberation data, the mid frequency reverberation time, Tmf, was found to be approximately 1.1s, with very little deviation between receiver positions. See Appendix 1 for full data.

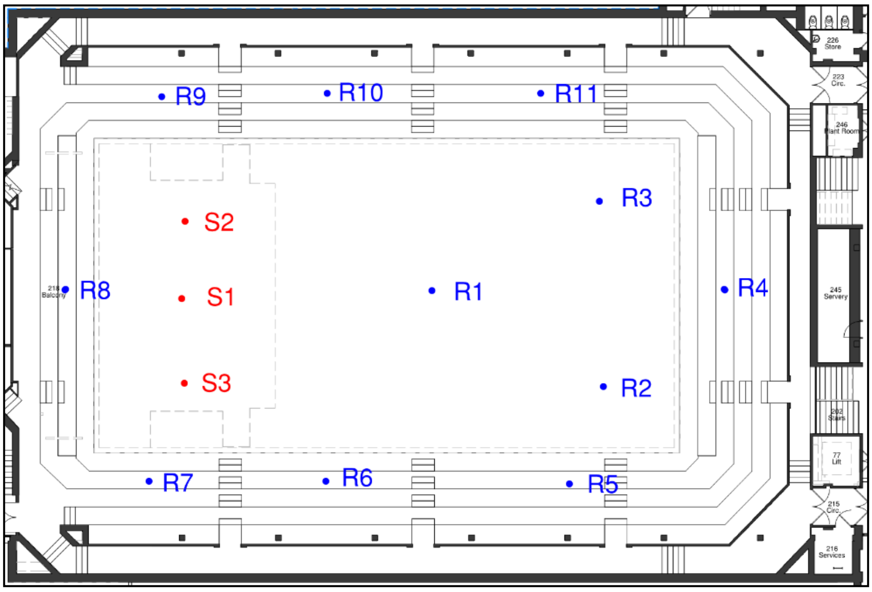


Figure 2.1: Source and receiver positions inside the auditorium ((Confidential), 2019)

2.2: Software Choice

2.2.1: Wave Based vs Ray Tracing

The original plan was to use a wave-based computational fluid dynamics engine such as COMSOL or openFOAM. Wave-based modelling has been shown to yield more accurate results than ray tracing, since diffraction effects and standing waves are more accurately portrayed (James, 2006) However, COMSOL is prohibitively expensive, costing around £3000 for the full version. openFOAM is free but it has no graphical user interface and no clear documentation, making it very difficult to work with. Although less accurate than wave based models, several acoustic prediction engines based on ray tracing, such as ODEON and CATT, are regularly used in industry.

2.2.2: Rhino 3D

Rhino is a 3D modelling tool used primarily by architects. Grasshopper is an extension to this which allows geometry created in Rhino to be subjected to mathematical operations which can create new geometry which could not be created in Rhino. Grasshopper is an open source software, which means that new plugins and solvers can be downloaded for free and implemented into the script. Galapagos is one of such solvers and comes as standard with Grasshopper. It is an evolutionary solver which allows a single objective function to be maximised or minimised through the alteration of variables.

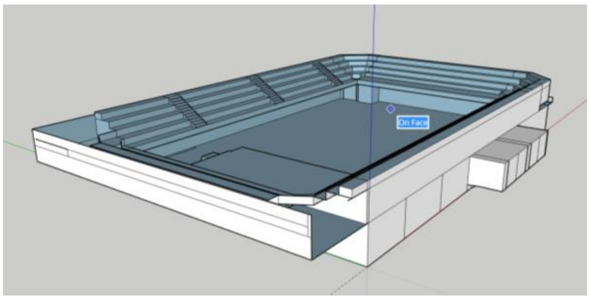
One way forward would have been to minimise the difference between the reverberation time in the pre refurbishment model and the new model. However, in auditoria, the subjective impression of a room is governed by more than just the reverberation time. As discussed in Section 1.3, the strength of the sound, the clarity of the sound and the early decay time are also important parameters for the acoustics of a performance space. In optimising just one parameter, another parameter may be left by the wayside, so a multi-objective approach should be taken.

Octopus is a third party plugin which allows multiple competing objective functions to be optimised at once. Even if there is no point at which every function is optimised, a “Pareto Optimal Front” can be found. This is a series of solutions for which no objective function can be improved without worsening another. In effect, the best trade-off possible is found.

Pachyderm Acoustic is a plugin for Rhino and Grasshopper created by Arthur Van Der Harten, which allows the acoustics of a space to be evaluated through a ray tracing algorithm. (Wright, et al., 2016) tested the ability of Pachyderm to accurately predict the acoustics of a café and generate designs based on acoustic criteria. When tested against measured data, it was found that Pachyderm was able to accurately simulate the reverberation time of a café to within 0.02s of the measured result. Several design solutions were generated with superior acoustics, proving Grasshopper is capable of creating architectural form from acoustic requirements. However, only a limited number of variables were tested. Although not as accurate as wave based models, Pachyderm’s speed and seamless integration with Grasshopper made it a more appropriate choice.

2.3: Building a 3D Model of Auditorium

Scale drawings obtained from the architect were used to construct a 3D model in Sketchup. This model was then imported into Rhino, and split into layers. Material coefficients were assigned to each layer. Because of the disruption caused by Covid-19, material data compiled from available literature (HM Government, 2015) (Department for Education and Skills, 2003; British Standards, 2002) was used instead of physical testing of material samples. The audience was represented by a solid volume suspended over the seating area. Figures 2.3.1 and 2.3.2 show the evolution of the model.



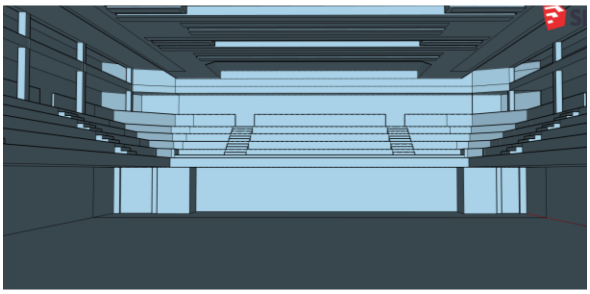


Figure 2.3.1: Initial build in Sketchup (Left), Finished build in Sketchup (Right)

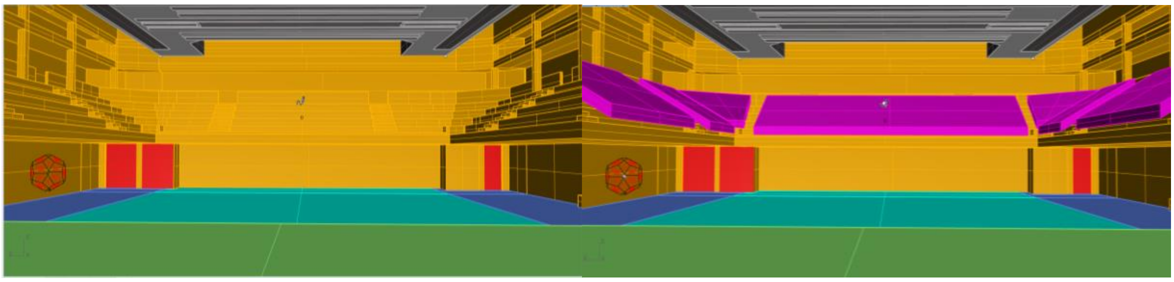


Figure 2.3.2: Materials applied in Rhino (Left), seating applied in Rhino (Right)

2.4: Calibrating 3D Model Against Measured Data

Initially, simulation times were far too high, exceeding 20 hours, making it impossible to gain any information on the model's accuracy. This issue was eventually solved by contacting Arthur Van Der Harten, the creator of Pachyderm. It was noted that, due to gaps in the absorption data available from literature, some materials in the model had absorption coefficients of 0 assigned to them at the highest and lowest frequencies of 63Hz and 8kHz. This meant that the ray tracing algorithm got stuck at these frequencies. Since Pachyderm's ray tracing algorithm only stops when the energy of the rays is negligible, if absorption is set to 0, then the algorithm runs indefinitely. To fix this, values at 63Hz and 8kHz were estimated by extrapolating the available data. Once this issue was solved, simulations could be run in around 3 minutes, meaning the model could be calibrated to the measured data. The exact materials of the ceiling were unknown, but in order to get close to the measured reverberation time of 1.1s, a Class A (very absorptive) (British Standards, 2002) porous absorber had to be assigned as the material for the suspended acoustic ceiling and the ceiling in the corridors. The seating material was obtained from analysis by (Beranek, 2006).

Sources and receivers were placed in the model at the same locations as the on site reverberation tests (See Figure 2.1). The simulation was run with 3 sources and 11 receivers. Using 3 sources meant that the ray tracing had to be run 3 times. As shown in Table 2.4.1, the spread of the average mid frequency reverberation times was small, with approximately 4% maximum deviation from the mean. It was therefore considered that in the optimisation stage, it would be appropriate to only use 1 source, since many simulations would need to be run and the increase in speed would be worth the small decrease in precision.

Table 2.4.1: Average reverberation times for each source position

RT (Source 1) (s)	RT (Source 2) (s)	RT (Source 3) (s)
1.23	1.18	1.21

As seen in Table 2.4.1, an average reverberation time of 1.2s was obtained from the simulation. When compared with the reverberation time of 1.1s from the initial site tests, a difference of 0.1s (or 9%) was considered to be small enough to give reasonable confidence in the accuracy of the model and of future models. Although strength, clarity and early decay time were not measured in the site tests, since the reverb time was similar and the 3D model was built from architectural drawings to match the real room, it was assumed that, should they have been measured, the other parameters would have been comparable too. Single figure values for Reverberation Time, Early Decay Time, Strength and Clarity are shown in Table 2.4.2

Table 2.4.2: Average RT, EDT, G and C_{80} values for each receiver position

Receiver Position	RT (s)	EDT (s)	Strength (G) (dB)	Clarity (C_{80})
R0	1.01	0.78	6.16	7.42
R1	1.15	1.02	1.93	6.83
R2	1.21	1.25	-2.13	6.03
R3	1.29	1.17	-1.83	5.08
R4	1.24	0.90	3.32	6.31
R5	1.04	0.82	6.56	6.66
R6	1.01	0.69	8.06	8.63
R7	1.45	1.19	-5.46	3.30
R8	1.18	1.04	1.78	2.49
R9	1.36	1.16	-0.93	0.84
R10	1.33	1.15	-0.47	1.02

2.5: Creating a New "Post Refurbishment" Model

In the absence of information on the details of the proposed refurbishment, an imagined "Post Refurbishment" model was created, so that the effectiveness of the method could be gauged. In the new model, the corridors around the perimeter of the room were removed, and the seating was extended. This increased the overall absorption in the room, and increased the volume of the reverberant space. Figure 2.5 shows the room before and after refurbishment.

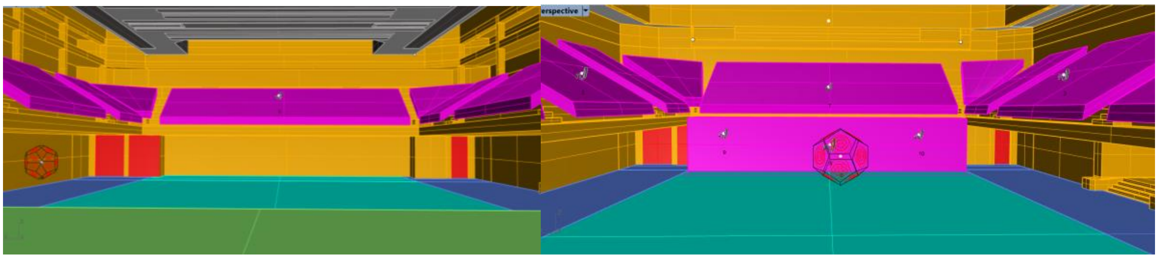


Figure 2.5: Auditorium before and after refurbishment

2.6: Creating a Parametric Ceiling Design

To make the acoustics in the new model match that of the first, a ceiling design for the new model was created in Grasshopper. It was decided that the design should be symmetrical in form and should allow for a mixture of materials to be used. Using more than one material allowed for greater alteration of acoustic properties, and symmetry allowed the sound distribution to be more uniform across the room. Using a curved geometry allowed the ceiling to provide diffusion as well as absorption. The workings of the Grasshopper script for the design can be split into five stages:

1. The first stage generates a grid of points surrounded by a rectangle covering half of the area of the previously existing ceiling.

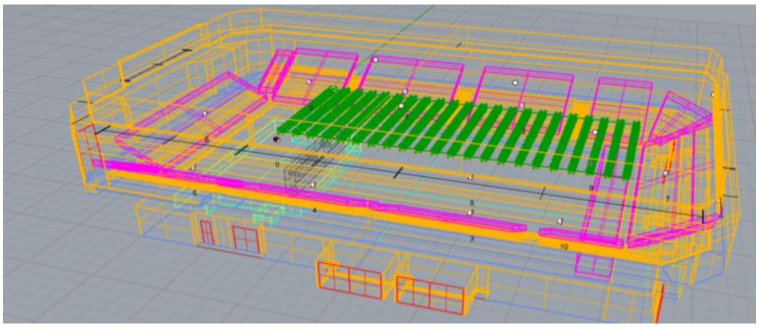


Figure 2.6.1: Stage 1 – grid of points

2. The second stage populates the rectangle with additional “control” points and mirrors them, along with the grid of points generated in stage 1. Control points are so called because they are used to control the geometry of the design.

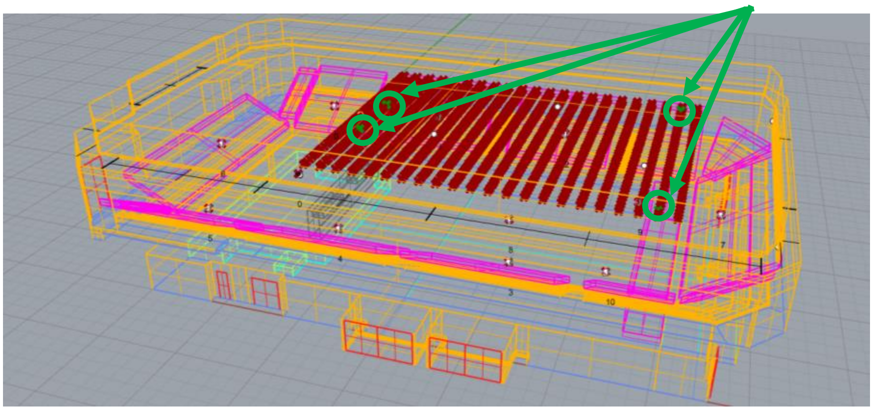


Figure 2.6.2: Stage 2 – Mirrored grid of points(red) and control points (green)

3. The third stage assesses which grid points are closest to the control points. All grid points are then shifted in the Z axis according to their proximity to the control points. The grid points are then joined together to create a surface

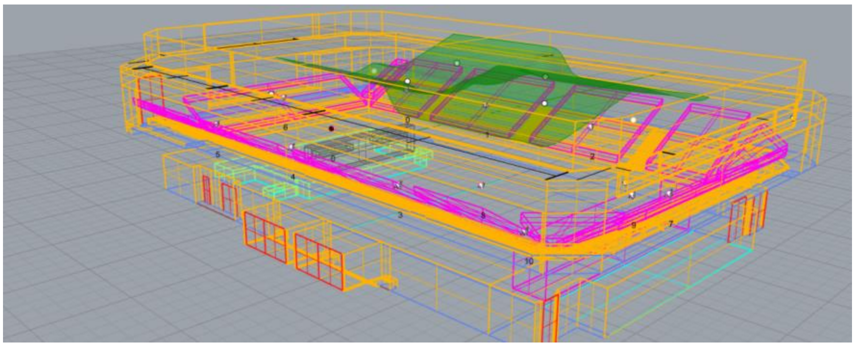


Figure 2.6.3: Stage 3 – Surface generated from connecting the shifted points

4. Next, the surface is split into hexagons, and an “attractor” point is created (The attractor point is just a point within the ceiling area, it is only called an attractor point to differentiate it from the “control” points mentioned in stage 2). The outside frames of the hexagons are made thinner in the area closest to the new attractor point. The centre of the hexagons are later assigned to be “Class A” absorbers and the frames to be “Class C” absorbers. The variation in frame thickness allows for more control over the absorption provided by the ceiling.

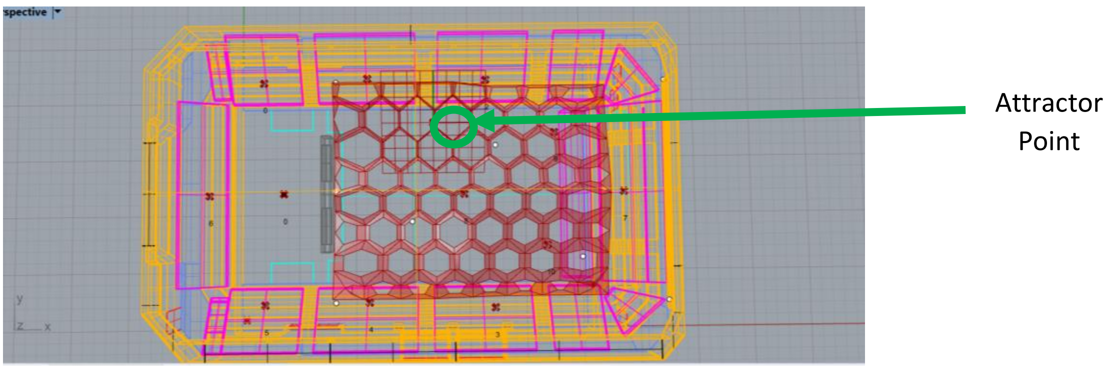


Figure 2.6.4: Stage 4 – Hexagon cells

5. Finally, the whole shape is extruded in the Z direction to create a solid structure. Red areas are Class A absorption and green areas are Class C.

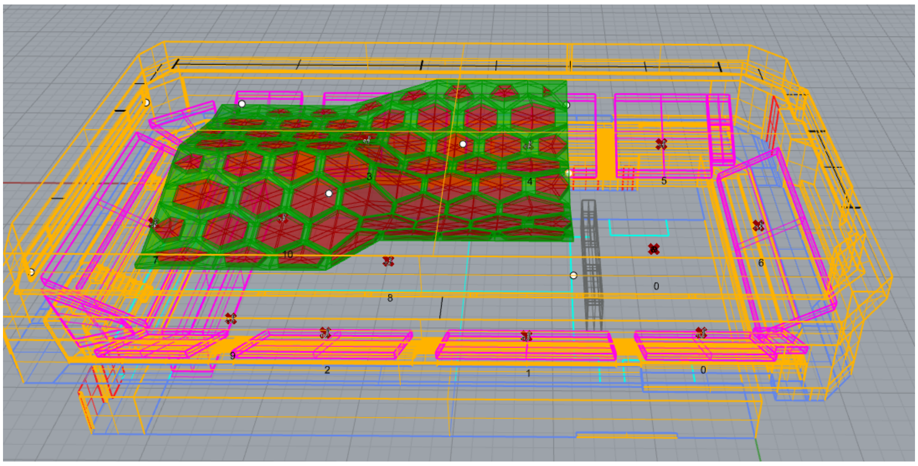


Figure 2.6.5: Stage 5 – Extruded solid shape

The individual stages of the grasshopper script are shown and annotated in Figure 2.6.6

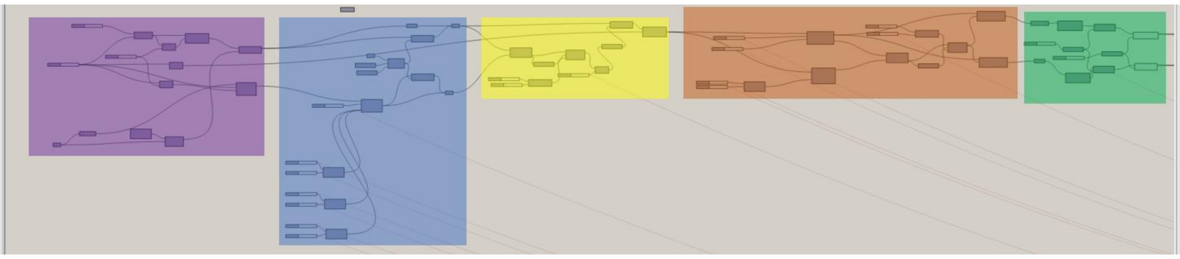


Figure 2.6.6: Grasshopper script for ceiling design: Stage 1-Purple, Stage 2-Blue, Stage 3-Yellow, Stage 4-Orange, Stage 5-Green

In the optimisation process, the variables, or "genes" which were controlled were as follows:

1. X position of control point 1
2. Y position of control point 1
3. X position of control point 2
4. Y position of control point 2
5. X position of control point 3
6. Y position of control point 3
7. Number of control points*
8. Multiplier**
9. X position of attractor point
10. Y position of attractor point
11. Hexagon border thickness
12. Height of ceiling
13. Number of hexagons in X direction
14. Number of hexagons in Y direction

*If >3, additional points are generated computationally based on the positions of points 1,2 and 3

** Determines how much Z deformation the grid points undergo in stage 3

2.7: Optimisation of Ceiling

In one iteration of the algorithm, the Grasshopper script goes through the following stages:

1. First, each surface is assigned to a layer within Rhino, which determines its absorption and scattering coefficients. The hexagon centres are assigned as Class A absorbers and the frames are assigned as Class C.
2. Next, a “Scene” is created, incorporating the Rhino geometry created in section 2.4, the Grasshopper geometry created in section 2.6, and the positions of the source and receivers.
3. The ray tracing algorithm is then initiated, outputting an energy-time curve after approximately 3 minutes.
4. The four parameters of Reverberation Time, Early Decay Time, Clarity and Strength are extracted from the energy-time curve. They are then averaged according to (akuTEK, 2019) to obtain a single figure value for each parameter at each receiver position.
5. For each parameter and receiver position, the absolute difference between the value obtained in stage 4 and the value shown in Table 2.4.2 is calculated. The differences for each receiver position are then summed to obtain a total difference for each parameter.
6. The total differences are fed into the multi objective optimiser, with the goal of minimising them all simultaneously by controlling the 14 variables, or “genes” from Section 2.6 which govern the geometry of the ceiling.

Figure 2.7.1 shows the grasshopper script for optimisation, following directly on from the script shown in Figure 2.6.6.

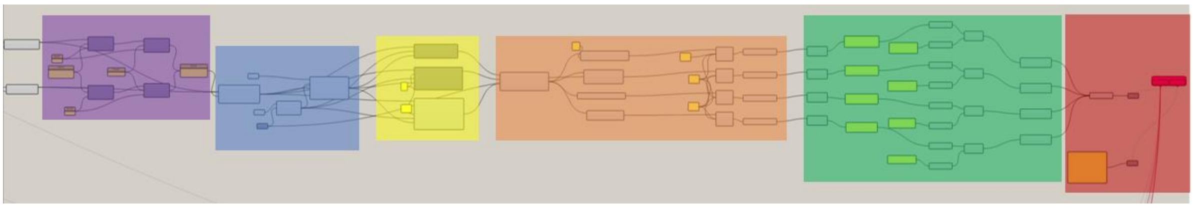


Figure 2.7.1 Grasshopper script for optimisation: Stage 1-Purple, Stage 2-Blue, Stage 3-Yellow, Stage 4-Orange, Stage 5-Green, Stage 6-Red

Section 3: Results

3.1: Optimisation

The optimisation was initiated using the default settings in the Octopus solver with an initial population size of 120. The optimisation ran for 10 generations, plotting each of the 1200 solutions on a 3D plot; the X axis being Reverberation Time, the Y axis being strength, the Z axis being early decay time and colours from green to red representing clarity. Green coloured cubes close to the origin represent good solutions and red cubes further from the origin represent poorer solutions.

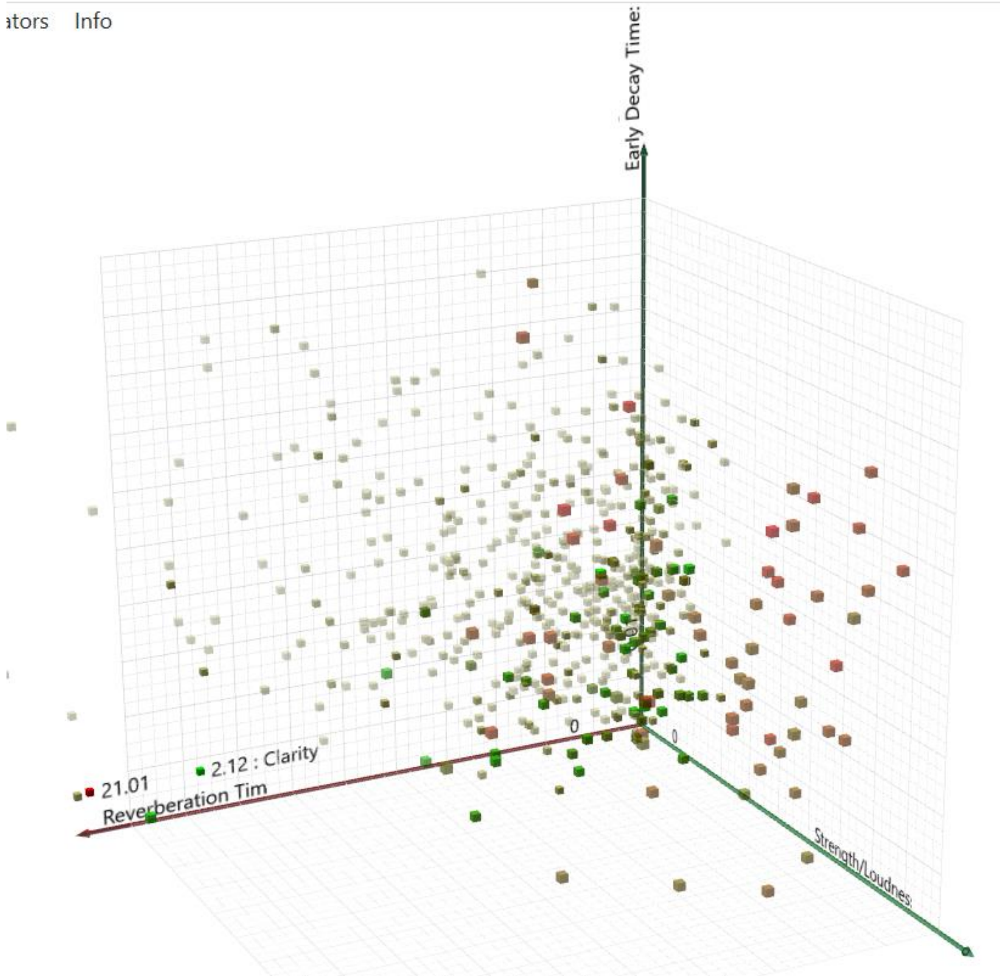


Figure 3.1: The 10th generation of solutions plotted in 3D

The three best solutions are shown in Figure 3.2. The fitness functions for each solution, representing the total difference in reverberation time, early decay time, strength and clarity between all 11 receivers are shown in Table 3.1.

Table 3.1: Fitness functions for Solutions 1-3

	Solution 1	Solution 2	Solution 3
Reverberation Time (T20) (s)	0.14	0.017	0.0023
Early Decay Time (EDT) (s)	0.52	0.5	0.53
Strength (G) (dB)	0.58	0.23	0.023
Clarity (C_{80}) (dB)	4.9	5.1	8.18

To put this into context, Table 3.2 shows the values in Table 3.1 divided by 11, the total number of receivers. This shows , on average, how different each parameter would actually be from the original room at a given receiver. When these are compared with the “Just Noticeable Differences” listed in (akuTEK, 2019), they are all below the noticeable level, meaning that, for all three designs, the acoustics in the new hall would be almost identical to that of the old hall.

Table 3.2: Average differences for a given receiver

	Solution 1	**Solution 2**	**Solution 3**	**JND** (akuTEK, 2019)
Reverberation Time (T20) (s)	0.013	0.0016	0.00021	5% or 0.06s
Early Decay Time (EDT) (s)	0.047	0.045	0.048	5% or 0.05s
Strength (G) (dB)	0.053	0.021	0.0021	1.0
Clarity (C_{80}) (dB)	0.45	0.46	0.74	1.0

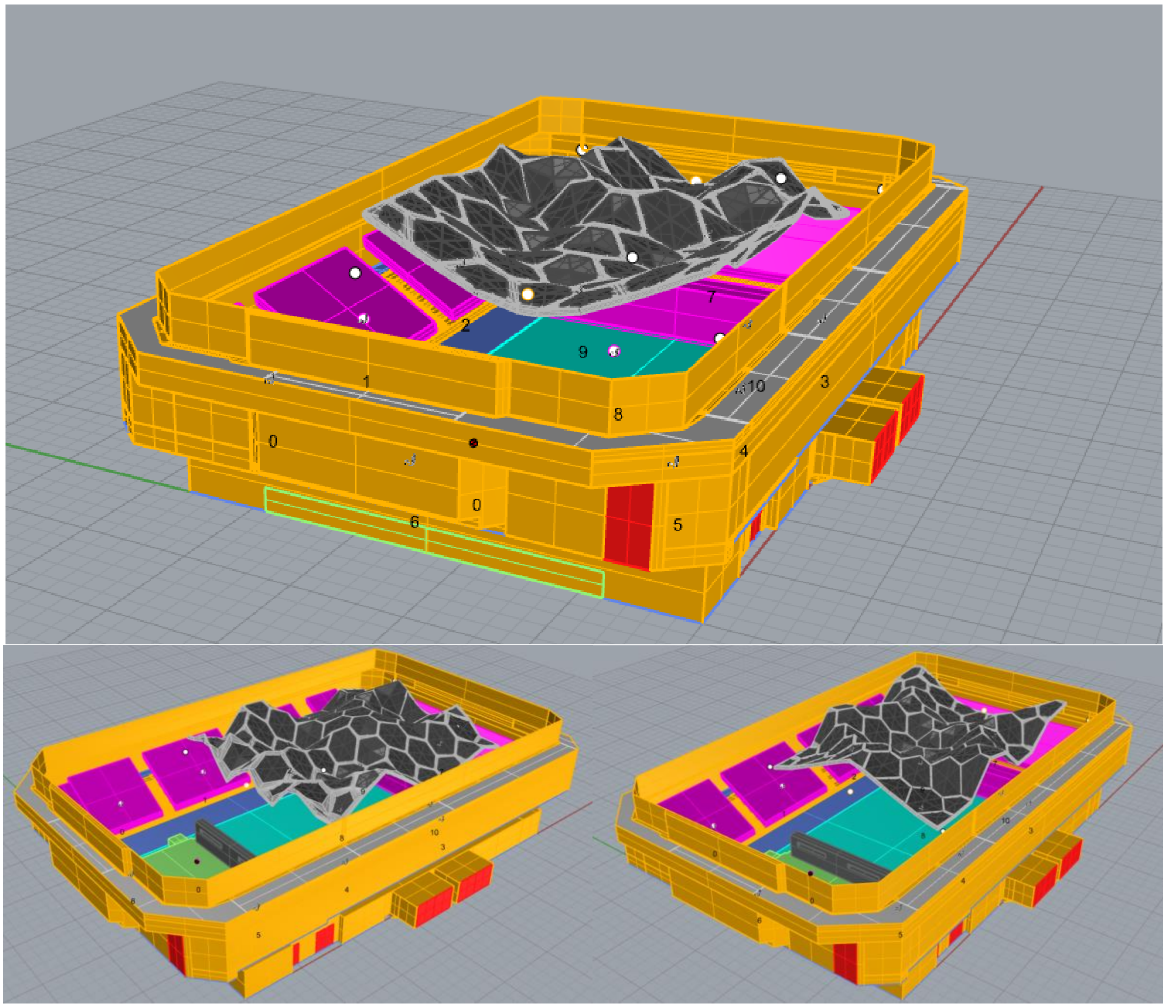


Figure 3.2: Solutions 1, 2 and 3: Clockwise from top

3.2: Discussion

Section 3.1 demonstrates that genetic algorithms can be used to generate solutions which match very well with acoustic criteria. The population size and number of generations could be increased to create a greater number of designs with an even greater fitness. It should be noted, however, that the inaccuracies inherent in ray tracing mean that there will always be some uncertainty in the predictions, so further searches for even better fits may not be worth the computational energy. Even if the simulations were to run indefinitely, it is impossible to know what the perfect design would be, since it is a multi objective problem, and a range of solutions will always be given.

In a real project, the extent to which an architectural feature can be modified by an acoustician depends on the priority given to acoustics within the design process. It also depends on whether traditional acoustic treatment such as rafts and diffusors can be used to achieve the same effect. In some buildings, these treatments would not be appropriate. If used at the conceptual design phase, hand drawings could be recreated in Grasshopper and then optimised for acoustics, reducing the need for acoustic treatment at later stages. This will be easier if there is a clear benchmark to work towards, such as in a refurbishment, or where the room parameters from (akuTEK, 2019) can be used.

Section 4: Conclusions

- The average difference of each room parameter between the three best solutions and the original hall is lower than at the just noticeable differences given in (akuTEK, 2019). Therefore, the acoustics of these designs will be almost identical to that of the original hall
- Inaccuracies in ray tracing mean there will come a point at which the uncertainty will outweigh the benefits from running more simulations
- If integrated into the design process at an early stage, genetic algorithms can be a useful tool in the design of acoustic spaces.

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Appendix 1: Full data from initial auditorium measurements

Receiver Position	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
R0	1.28	1.53	1.13	1.14	1.12	1.01	0.94
R1	1.32	1.47	1.19	1.04	1.10	1.05	0.93
R2	1.35	1.23	1.14	1.02	1.12	1.07	0.96
R3	1.50	1.01	1.12	1.16	1.15	1.08	0.95
R4	1.38	1.06	1.09	1.03	1.07	1.08	0.97
R5	1.21	1.29	1.22	1.02	1.07	1.12	0.98
R6	1.63	0.83	1.15	1.17	1.10	1.16	0.99
R7	1.15	1.01	1.14	1.00	1.13	1.14	0.98
R8	1.58	1.02	1.17	1.06	1.09	0.99	0.91
R9	1.18	1.15	1.18	1.06	1.14	1.08	1.03
R10	1.52	1.25	1.07	1.04	1.02	1.04	0.88