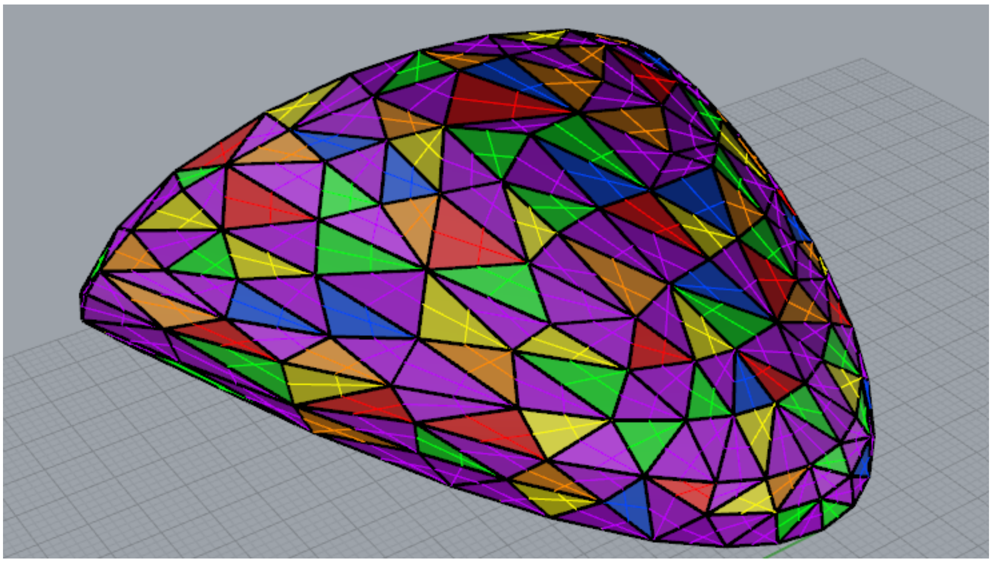


Simplified Architectural Models and Affected Acoustic Parameters

Creation of a method to simplify architectural models and the effects of the simplified models on various room acoustic parameters

Master's thesis in Master Program Sound and Vibration

SPENCER MASON

Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Master's Thesis ACEX30
Gothenburg, Sweden 2020

Master's Thesis ACEX30

Simplified Architectural Models and Affected Acoustic Parameters

Creation of a method to simplify architectural models and the effects of the simplified models on various room acoustic parameters

SPENCER MASON

Department of Architecture and Civil Engineering
Division of Applied Acoustics
Chalmers University of Technology
Gothenburg, Sweden 2020

Simplified Architectural Models and Affected Acoustic Parameters
Creation of a method to simplify architectural models and the effects of the simplified models on various room acoustic parameters

SPENCER MASON

Supervisor: Ben Burgess, Buro Happold
Examiner: Professor Jens Ahrens, Department of Architecture and Civil Engineering

Department of Architecture and Civil Engineering
Division of Applied Acoustics
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Reduced model with different coloured mesh faces representing different acoustic materials.

Department of Architecture and Civil Engineering
Gothenburg, Sweden 2020

Simplified Architectural Models and Affected Acoustic Parameters
Creation of a method to simplify architectural models and the effects of the simplified models on various room acoustic parameters

Spencer Mason
Division of Applied Acoustics
Department of Architecture & Civil Engineering
Chalmers University of Technology

Abstract

For acousticians to create accurate acoustic models in CATT the models must be of a simplified form, with minor details excluded from the implementation. The models used in CATT are either made from scratch or by taking the existing architectural model and simplifying it by hand. By creating a program in Grasshopper, models in Rhino can be automatically simplified to a desired number of faces, saving on time and manpower. Further, the program can be extended to include the application of acoustic materials to each face and the export of the files from Grasshopper straight to CATT without other intermediary steps.

The program was successfully created, and now can take an existing model and reduce it down to even just a small number of faces. But at what point does this simplification take a toll on the acoustic results? This was explored further with emphasis on the following acoustic parameters: Clarity (C_{80}), Strength (G), Sound Pressure Level (SPL), Speech Transmission Index (STI), and Reverberation Time (T_{30}). The extent to which these parameters are affected by the reduction of a mesh is explored in both the source to receiver calculations and the audience maps for three differently shaped venues. Three different levels of simplification were tested: 50%, 80%, and 95%. These were compared to the original model and also an unsimplified, 0%, model that was altered (but not reduced) by the Mesh Reduce component.

All the five parameters for the 50% reduction deviated only slightly from the unsimplified models. As the simplification increased to 80% most of the parameters were still within a reasonable range with little deviation, except for the reverberation time. From the results it was found that the upper limit of reduction would be about 80%, and falling somewhere between that and 50% would be a useful range for simplification. The results also showed a great amount of time saved for these simplified models, particularly in the audience map results. Ultimately, the program can be used effectively to reduce meshes for acoustic modelling with little detriment to the final results.

Keywords: Room Acoustics, Architecture, Rhino, Grasshopper, Reduce Mesh, Simplify, Automation, CATT

Acknowledgements

I want to thank Ben Burgess, Harry Rees, and the rest of the team at Buro Happold for providing support and resources to take on this thesis. As well as, providing me the opportunity to work as an intern in the summer of 2019, which led to the idea for the thesis. I would also like to thank Jens Ahrens who provide support and feedback throughout the process, and more broadly thank the faculty and staff at the Division of Applied Acoustics for the wealth of knowledge I gained over the last two years as a student in the Sound and Vibration master's program at Chalmers. Thank you to my classmates and friends that have been great partners to work and laugh with. And, finally I'd like to thank my parents for the years of support in getting me to this position.

Spencer Mason, Gothenburg, August 2020

Contents

List of Figures

List of Tables

1

Introduction

1.1 Anecdote

During my summer as an acoustic intern at Buro Happold I worked with the room acoustics of a football stadium and how parameters were altered due to the introduction of an ethylene tetrafluoroethylene (ETFE) roof. As with most of these types of roofs the structure was made of a mesh containing numerous smaller components. The model, originally provided in Revit format, was successfully migrated to Rhino with some simplifications in the roof geometry, particularly the cushion style pattern turned to planar faces. However, this mesh was still complex in terms of the number of faces that existed in the mesh.

I thought that, in order to increase the processing speed and simplify the manual labour of "adding material" to each face, it would be useful to simplify the mesh. Simplifying a mesh involved deleting multiple lines (edges) and reconnecting points (vertices) in the mesh to create new, larger faces. This was successful, but also time consuming. The exposure to Grasshopper and working with this model led to the idea for this thesis came from, using parametric design software to quickly and simply reduce the complexity of meshes in architectural models.

1.2 Background

The use of parametric design software is increasingly being used by architects to design buildings, allowing for easier and faster methods to design complex structures. For example, large curved roofs made of glass and ETFE are becoming commonplace, as seen in Figure 1.1. In order to construct such roofs small panes of the material are used creating a mesh, which is a discretization of the rounded surface; the smaller the faces in a mesh the more round the object appears. This can lead to models consisting of thousands of planes. These models are then sent to engineers for analysis and further modelling.

Figure 1.1: Picture of the tesselated roof covering the Queen Elizabeth II Great Court at The British Museum in London. Taken by Spencer Mason.

The acoustic modelling performed on buildings is typically preformed with the help of software such as CATT-Acoustic to perform calculations through ray tracing and image source modelling. Since each ray is interacting with multiple planes, each additional plane increases the calculation time, which can create processing times up to ten to twelve hours for a highly detailed, high resolution calculation. To reduce the processing time acousticians will simplify the models down to as few planes as possible while still preserving the shape and the necessary design elements.

In the past companies such as Buro Happold have used SketchUp to either alter the provided models or as a reference to create a new, simplified model. This is a tasking process, and with advances in design software such as Rhino and Grasshopper, Buro Happold is looking for a more streamlined method for simplifying and converting architectural models. This is to be done with Rhino's plug-in Grasshopper, a tool that is widely used throughout the company for parametric design. The two main goals of this research are:

1. Reduce the number of planes in the model.
2. Create the CATT files through Grasshopper

Furthermore, the consequences of reduced models are researched and analyzed using CATT-Acoustic. The computation times recorded to compare how the simplified models save time. And, the following parameters are calculated and compared to unsimplified models:

- Sound Pressure Level (SPL)
- Reverberation Time (T_{30})
- Clarity (C_{80})
- Strength (G)
- Speech Transmission Index (STI)

1.3 Limitations

This thesis is limited to analyzing only the results from Grasshopper and CATT, as they are the main tools that are available at Buro Happold. There are, however, many methods to reducing architectural models and many methods to analysing room acoustics. The thesis is focused on Grasshopper because it has become a leading force in the industry for automation, computational analysis, and parametric design.

The models are limited to testing changes in geometry; the different types of materials and resulting absorption coefficients are not considered. This is impart due to ensure that even distribution of materials is achieved, which is best for acquiring the most accurate results from CATT.[2]

2

Theory

2.1 Purpose of Research

The topic of room acoustic software has been investigated through the years to test the efficacy of the programs and to compare different methods. This thesis will work to build on the past research and to develop a faster method for acousticians to obtain credible results. With the intent to create a program that reduces a model provided by an architect into a simpler model that can be easily handled by an acoustician, it is necessary to look further at how the simplified model compares to a more detailed model. Further looking at multiple iterations of simplification is important.

By quickly providing a simplified model using a program that exists in frequently used software, acousticians can save time on simplifying models and computation time, thereby allowing them to focus on the analysis of results.

2.2 Terminology

Vertex This term is used when referring to points in space in Rhino and Grasshopper. The points define the shape of the object, and are where two or more lines meet. They are defined by coordinates in the Cartesian coordinate system.

Corner The term for vertices in CATT-Acoustic. When vertex coordinates are transferred from the Rhino/Grasshopper domain to the CATT domain, they are then referred to as corners. Furthermore, each corner has an associated ID number.

Face The surface created when a two-dimensional space is enclosed by three or more lines, i.e. triangles, rectangles, pentagons, etc. In Rhino and Grasshopper these can be either planar or not. And, in Rhino/Grasshopper, a face is acquired when using a deconstruct component on either a BREP or a mesh.

Plane The term for faces in CATT-Acoustic. The planes are created by combining the vertices in a specific order. For each plane the corner IDs are listed in a line of code in the order the corners should be connected. Depending on syntax of the code the corners can be connected clockwise or counterclockwise. Each plane also has an associated ID number. In CATT-Acoustic planes must be coplanar.

Coplanar All vertices of a surface lie in the same plane. Thus creating a non-twisted surface.

Double-sided Planes that are specified with absorption/scattering properties on both sides of said plane, this is mostly important for CATT. Any plane in CATT that has material on one side will only affect rays impinging from that side, if rays come from the other side (where there is no material) then the rays will travel through. If there are planes within the model, such as reflectors or partitions, that can reflect or absorb from either side then they must be defined as double-sided.

Mesh A mesh is surface that has been created from a collection of faces to create a shape. Each face consists of vertices, and in Rhino each face is either triangular (three vertices) or quadrangular (four vertices). The higher the number of faces in a mesh the better the approximation of the shape that is being formed. A sphere that is created of a mesh with six faces will appear as a square box. As the number increases, higher order polyhedral shapes are created then approximating a sphere.[14][18]

BREP An abbreviation for Boundary Representation, a BREP is a surface created from faces and vertices (like a mesh) but also uses the edge information represented by mathematical formulae.[25]

Ray Tracing To simulate sound propagation in geometrical acoustic analysis, the sound source can be modelled with a finite number of rays, each ray representing a portion of energy. The rays then radiate out from the source in a direction, which is based on the directivity of the source, interacting with the room. As they meet planes in the model the rays' values and travel paths are changed based on the angle of the plane (according to Snell's Law), the absorption coefficients, scattering coefficients, and diffraction properties of the material the ray meets.[9]

Image Source From the source to the receiver each ray takes a different path, the rays at the receiver that lie in that path then add up to the observed sound. While in reality the source is one location with multiple rays reflecting off planes, the sound observed can be modelled by a collection of other sources that exist outside the model. Each source outside the model forms a straight line from the mirror "image source" to the receiver.[9]

Leaks When sound rays escape from the model due to an opening, which is caused by either missing or twisted/warped planes. Since CATT works best with closed models, the leaks can be detrimental to the final calculated results in the simulation. Leaks can be seen in Figure 2.1, where some of the rays have exited the model, even though to the user it would look like the model used is closed, since the two faces meet and no holes are visible.

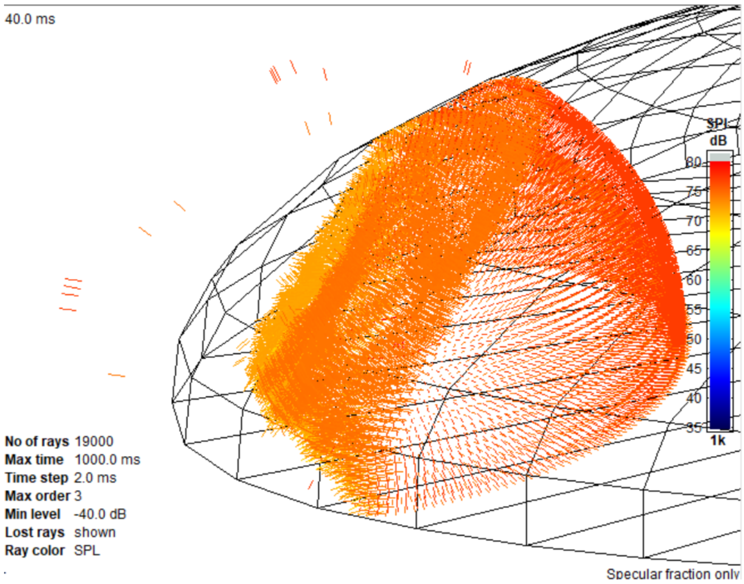


Figure 2.1: Sound rays leaking from the model simulation in CATT, making use of the Ray Trace feature.

Sound Pressure Level The sound pressure level (SPL) is used to quantify the pressure that is heard/measured by a receiver. This value is calculated to a reference value (p_0), which in most cases is 20 μPa. This reference value is chosen as it is the threshold of hearing for humans at 1000 Hz. The sound pressure level is given in decibels and the equation for conversion can be found below.[10]

$$SPL = 20\log_{10}\left(\frac{p_{\text{rms}}}{p_0}\right)\text{dB} \tag{2.1}$$

Reverberation Time The time it takes for the sound pressure level of an impulse in a room to decrease by a specified decibel level, typically either 30 dB (T_{30}) or 60 dB (T_{60}). There are many methods for calculating and measuring reverberation time. Sabine's formula, Equation 2.2 and Eyring's formula, Equation 2.3, can be used to calculate the reverberation time based on the equivalent absorption area and the volume. Sabine's formula is used when the absorption is less than 30%, when the absorption is evenly distributed around the room, and the geometry is not extreme.[9]

$$T \approx 0.161\frac{V}{S\alpha}\text{ s} \tag{2.2}$$

$$T = \frac{24\ln(10)}{c}\frac{V}{4mV - S\ln(1-\alpha)}\text{ s} \tag{2.3}$$

The equations for reverberation time calculate a single value for the room and the value does not change in different places in the room as stated in Kuttruff's *Room Acoustics*.[10] In measurements, when following standards such as ISO 3382-2:2008[27], measurements are taken in six locations in a room and then averaged to the calculate the reverberation time in said room.

This measure is considered one of the most important parameters for objectively characterising the room acoustics a space, such as a concert hall. It is also the basis for other parameters used to describe and characterise a space.

Clarity Using the decay of an impulse in a room, clarity is defined as the proportion of early energy to late energy, which can be seen in Equation 2.4.[10] For concert halls, the first 80 ms is declared the "early energy" and the tail that follows is the "late energy", and the greater the ratio of early to late energy, the higher the clarity. In the equation $g(t)$ is the impulse response under consideration. The parameter C_{50} is typically used in rooms used for speech, as the reverberation is less desired in speech thereby using a more strict time of 50 ms. Clarity is one of the important parameters that most designers will include when designing a space.

$$C_{80} = 10 \log_{10} \frac{\int_0^{80\text{ms}} [g(t)]^2 dt}{\int_{80\text{ms}}^{\infty} [g(t)]^2 dt} \text{ dB} \tag{2.4}$$

The typical and target values for clarity in a concert hall are -4 dB to +1 dB, so a suitable range would be about 3 dB, i.e. half the range.[4] This then could be considered the acceptable range for clarity to vary within with little detriment to the results.

Strength In an enclosed space where the acoustic field is not perfectly diffuse, the reflections from surfaces will have a larger affect on the sound pressure level and the perceived sound of the listener. The strength takes into account how much the room contributes to the sound pressure level, where $g(t)$ again is the impulse response under consideration in the room. And, $g_A(t)$ is the impulse response when the same sound source is used in an anechoic chamber and measured at a distance of 10 m.[10]

$$G = 10 \log_{10} \frac{\int_0^{\infty} [g(t)]^2 dt}{\int_0^{\infty} [g_A(t)]^2 dt} \tag{2.5}$$

Typical values for strength in mid-range frequencies (500 Hz and 1000 Hz) for concert halls is 5 dB with a range of 2 dB.[11]

Speech Transmission Index Closely related to speech intelligibility, the speech transmission index (STI) is measured on a scale from 0.0 to 1.0. The STI is calculated with regard to modulation frequencies, reverberation, background noise, and masking in the human auditory frequency bands.[10] The scale then is broken down into five levels of speech transmission[1]:

- Excellent >0.75
- Good 0.60-0.75
- Fair 0.45-0.60
- Poor 0.30-0.45
- Bad <0.30

2.3 Why Simplify?

As stated in the CATT-Acoustic manual it is better to use a simplified model, with less detail. As well, it states that it is better to affect the high frequencies through the scattering coefficients rather than extraneous detail.[2] The documentation for CATT-Acoustic continually makes a point to say that the detailed visual model is not always accurate for an acoustic model, "but has to be simplified to work with [Geometrical Acoustics] and the model must also be made according to certain rules".[3] So then the next step is to determine what is extraneous and what is necessary. As well, find a way to make changes as needed.

An architectural model can be highly detailed. This includes the acoustically significant details such as reflectors hung at precise locations, or walls that are specifically designed to create a diffuse space using changing curvatures. However, too much detail such as modelling an organ with every pipe and button is gratuitous for the acoustic modelling software.

In order to reach a certain level of simplifications acousticians will either alter the given model by hand. This is useful most of the time as it is easy to see which edges of a model can be deleted. However, when a roof is composed of a complex mesh it can be time consuming deleting hundreds of lines while preserving the proper shape. Another way is to make a completely new model using the known dimensions. This is useful when you want the shell of the building and do not have to be too concerned with the acoustically important details such as balconies. Both of these can be very time consuming, and take away from the actual time it takes to analyze the results from the modelling. So it stands to reason that creating a program that reduces the complexity of models with a few button clicks can improve efficiency for the acousticians working with models.

Further to reducing complexity is the transfer of models between programs. Exporting Rhino files to SketchUp has commonly led to the issue of "hidden geometries" created which consist of many more planes than one might realize. This issue is counterproductive to the need to reduce the number of planes in the model. So it is also important to create a way of ensuring models are created without unnecessary complexity, for example having 20 planes represent one flat wall. Reducing the number of planes reduces the processing time of the acoustic modelling software, thus reducing the time spent working with model and providing more time for analysis.

The next few subsections will discuss what can be found in models that cause increased number of planes and how to handle these design features.

2.3.1 Rounded Surfaces

A rounded surface is known for its focusing properties. In sound this creates hot spots of higher sound pressure levels, so it is important in room acoustic analysis that if a rounded surface creates focal points, then these should appear in the modelling analysis.

A surface created from curves, rather than straight lines, will create rounded surfaces, which in both architecture and acoustics can be desired and necessary. These surfaces, however, are challenging when working with modelling software and typically are considered warped or twisted leading to leaks. Thus it is necessary to move from the analog, continuous world to the digital, discrete world and discretize these round surfaces into many flat surfaces.

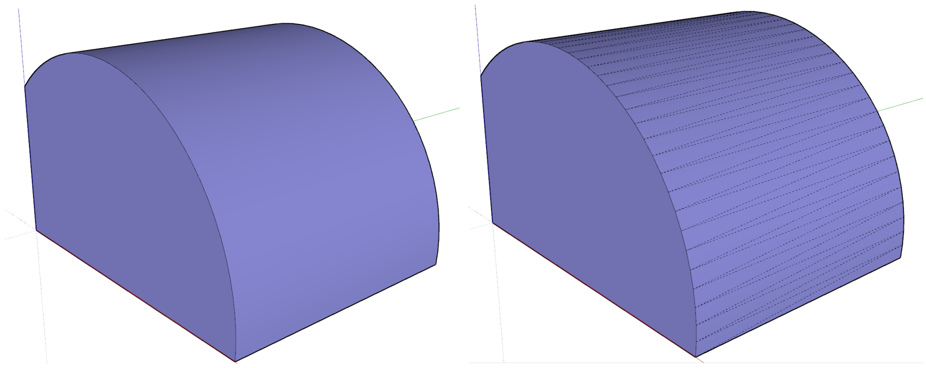
2.3.2 Meshed Surfaces

A mesh is typically used to discretize a rounded surface using a set number of polygons to approximate the rounded surface. The higher the number of polygons the better the approximation, visually. Typically the mesh is created from quadrangular or triangular faces. It is possible though that quadrangular faces are also twisted, which again in acoustic modelling software can lead to leaks.

Meshes can also be a design feature for architects because the materials are the limiting design feature. So, their models are created with meshes, which again could contain faces that are twisted or warped. And, if they are trying to achieve rounded surfaces, these meshes could contain up to thousands of small faces.

2.3.3 Conversion

For a program like SketchUp to handle the complexity of a twisted or warped face is to create “hidden geometries”, whereby the user does not necessarily know these extra planes exist. However, once then converted to the acoustic modelling software these hidden geometries appear adding to the number of planes in the model. A screenshot from SketchUp shows the hidden geometries that exist in a model can be found in Figure 2.2.



(a) Normal **(b)** Hidden Geometry

Figure 2.2: A model in SketchUp showing both the typical view and the hidden geometries, which are seen with the dotted lines.

2.4 Past Research

"[T]he architect's three dimensional model is typically useless, and in most cases it is better to build a new model from the beginning than to start cutting, trimming and stitching the surfaces. On the contrary, Odeon is more permissive, architect's model can be imported more easily, and calculations run immediately. The question is if this freedom was dangerous, e.g. do extra surfaces slow down simulations, or do the indolence of the architect result in an acoustically incorrect model." An excerpt from a paper on the comparison of room acoustic modelling software, called *Room Acoustical Modelling Differences and Their Consequences.*[16] This leads to the need to research and test how different iterations of simplification and reduction of a model affect the results of a simulation. And, indeed, the topic has been explored before.

From the mid-1990s to the mid-2000s a series of round robin tests were undertaken by Ingolf Bork to test the efficacy of room acoustic computer simulators. A group of international organizations, including Chalmers University of Technology, tested various pieces of software, including CATT-Acoustic and Odeon. In the second round robin test they found that the most important factor when simulating a space was the acoustician's knowledge of determining the absorption and diffusion coefficients for the materials in the space, rather than the number of planes used.[8]

These round robin tests have also influenced further research into specific software and the effects of simplification, such as research performed in 2008 using Odeon. The research utilized both an in-built reduction program in Odeon, as well as an algorithm created to iteratively reduce the model to simplified versions. With their method they achieved fast calculation times as the model was reduced, but are wary of the results for some parameters for highly reduced models, particularly when looking at their standard deviation.[24]

As stated in the conclusion of *A Comparison of Room Simulation Software - The 2nd Round Robin on Room Acoustical Computer Simulation* it stated that "a good program cannot replace the skill of a good acoustician, but also the usability plays an important part for the rating of the quality of room simulation software."[8] This sentiment is continually reiterated, where the knowledge of the user is of the utmost importance. However, a question posed by this thesis is even if the structure is kept similar and the users are capable to use the acoustic software correctly, then to what degree will simplification affect the results? In other words, what is the range of values that certain parameters including sound pressure level, reverberation time, clarity, strength, and speech transmission index will vary by?

In both studies on the simplification of models, the computation times were recorded and both, generally, found that the reduced models improved the computation time with little detriment to the results. Though both also warned the users of software to take care when reducing and use good judgement to ensure the models hold their geometrical and acoustic meaning.

As we see in all the past research and documentation a highly-detailed model is less desired due to both the results and computation time. Subsequently we want to find a way to simplify the model in a way that saves time for the acoustician, while keeping the important geometry of the space. Many acousticians do not come from an educational background of architecture, and some not even a background of engineering, which means they may have less exposure to 3D modelling software. To learn new software is necessary but time consuming. To ease the work and time taken to learn such software a program that can simplify models may be desired. A program that is created within an existing software, such as Grasshopper in Rhino.

Where does Grasshopper fit into the world of acoustics currently? Buro Happold, with teams covering a range of services in the engineering of the built environment, uses Grasshopper to inform their designs and assist with computational analysis. The acoustics team is beginning to explore the use of Grasshopper as it relates to room acoustic analysis, hence the desire to create a program that can simplify an architectural model. Some firms, such as Marshall Day Acoustics, have gone so far as to perform some acoustic analysis within Grasshopper itself, such as performing the ray tracing. In one project, The Philharmonie de Paris, Grasshopper and ray tracing were used by the acousticians to inform the analysis about how different angling of the reflectors in the concert hall would affect the acoustics in the audience. Further they were able to use the results to inform the architects of the optimal positions for these reflectors. "If architects do not visualise positive improvements to a geometric change, they have no reason to accept the change."[22] By providing this visual feedback with a program that the architects were familiar with, they could more easily communicate with the architects about changes that were necessary to be made. Thus showing there is a place for Grasshopper in the toolbox of acousticians, and how developing programs in Grasshopper can aid in the ease of design, analysis, and communication with clients. Particularly as Grasshopper continually is improved upon and people create more embedded applications, such as Pachyderm[28], Snail[7], and Esquissons[12], (packages used for acoustic analysis within Grasshopper/Rhino) then the use of Grasshopper will continue to grow.

Reading through the past research it is abundantly clear that there is no one solution to room acoustic modelling nor is any tool perfect for any and all analysis. As stated in the conclusion of *Concert Hall Geometry Optimization with Parametric Modeling Tools and Wave-Based Acoustic Simulations*, which was a study on the geometry of concert halls utilizing iterative design methods with the aid of Grasshopper and MATLAB, "Acoustic design will remain a mixture of art and science, but tools such as this can help to inform the art."[20] Therefore it is not the intent to show that a simplified model will provide a better result than the original, but rather to inform the user on how simplification can affect the different results from the computation. As well, to show the difference in time saved from a reduced model, considering the documentation tends to promote a simplified model and the past tests done were many years ago. So the results can provide an updated look as the software has been refined over the years.

2.4.1 Mesh Reduction

All mesh reduction methods are based on the desire to reduce the number of vertices and edges in a model, reducing the number of faces used to portray the model. Some work is based on first eliminating a vertex then filling in the space. Others move a vertex and its edges till the vertex is in the same position as another and then can be merged. Many are created to run iteratively so that the movements occur until a threshold is reached, this threshold usually is the maximum error allowed.

The methods used to achieve the goal of this thesis are covered in the coming chapter, however, there is one important component that has to be discussed first. That being the component used in Grasshopper called Reduce Mesh[19], which is the method used to simplify the architectural models. The component is made using the RhinoCommon API used for developers [13] a blackbox function developed by Robert McNeel & Associates, the creators of Rhino and Grasshopper. It is proprietary algorithms implemented into the software, therefore difficult to know exactly what is occurring. However, due to the extensive research in the field some basics can be deduced.

The component is likely made up of one common algorithm, with secondary smaller algorithms also implemented to further the usability. The inputs of the component used are similar to the method proposed by Hugues Hoppe, and summarized in *A Short Survey of Mesh Simplification Algorithms* by Jerry O. Talton III [26], which is the Edge Contraction method.

The edge contraction method simply moves two vertices together along their shared edge until they meet and can be combined into one vertex. The plane equations from the original faces are adopted from the original vertices and the new vertex is defined by these planes. Any strong deviations are penalized in the iterative process, where the error is high. This method is seen to be an "extremely-efficient contraction algorithm...produces high-fidelity approximations, and requires progressively less memory with each iteration."[26]

Edge contraction it is described as “the most common simplification operation”.[26] The second feature of the method that is similar to the Rhino function is the four metrics that can be altered to change the simplification/reduction. However, only three are close matches. The first in edge contraction is the distance that the vertex should be moved, where as the Rhino function works based on a specified amount of faces for the goal reduction. In the Rhino function the distance moved is likely a function of that specified number and is likely determined iteratively as the basis of the method. The other three metrics are outlined and compared below.

Edge Contraction	Reduce Mesh
Whether sharp edges are kept or not	Distort
Accuracy of scalar attributes	Accuracy
Regularize the minimization	Normalize

Table 2.1: Comparison of the two algorithms, the first the theoretical method proposed by Hugues Hoppe (Edge Contraction) and the implemented algorithm in Rhino.

The method does, however, require triangulated faces and the component used in Grasshopper can create both triangulated and quadranuglated faces, therefore it is likely that some other algorithms also exist in the function to provide more to the user.

3

Methods

3.1 Tools

3.1.1 Rhino

Rhinoceros, typically referred to in the industry as Rhino, is a three-dimensional computer aided design (CAD) software that has grown in popularity for parametric design and architectural geometry. It is frequently used by the engineers at Buro Happold for design and modelling. It is also popular due to the Grasshopper extension that has been developed and refined for programming-based design.

In the creation and use of the model simplification program, Rhino is used as the software to open the architectural model that the acousticians will use to perform the simplification. Though the main portion of the program is contained within Grasshopper.

3.1.2 Grasshopper

Grasshopper uses visual based programming for designers to create and alter their models using logic (true/false), cases (if, while, for), and parameters – hence parametric design. Components are chosen and dropped into the workspace, then connected together in a workflow. Grasshopper also allows users to write components using C# and Python. As well, many others have developed their own components and created libraries that are made available to the public. The main components utilized are listed below, some are native to Grasshopper, while others come from third-party libraries.

3.1.2.1 Important Components

Closest Point The component parses through a list of vertices, considers each on an individual point, and then compares each point to a list of other points to find the closest match. In the program it is used to compare the list of vertices in the model to the vertices of the individual faces in the model to produce the planes definitions for CATT.

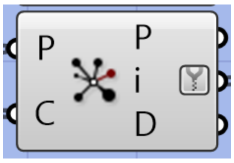


Figure 3.1: Component - Closest Point.

Construct Point Creates a point from given x-, y-, and z-coordinates.

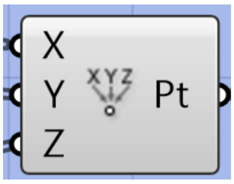


Figure 3.2: Component - Construct Point.

Deconstruct Takes a point and deconstructs it into the x-, y-, and z-coordinates. Necessary to create the corners section of the CATT files.

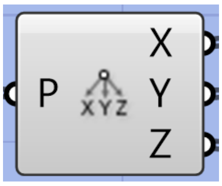


Figure 3.3: Component - Deconstruct.

Deconstruct Brep Takes a BREP and deconstructs it into its defining pieces: faces (F), edges (E), and vertices (V). The main component needed to break down the Rhino model and then reconstructed in the necessary format for CATT.

Figure 3.4: Component - Deconstruct BREP.

End Points Returns the start and end points of a given edge. Necessary to help determine the order that the vertices should be connected in order to create the perimeter of the face.

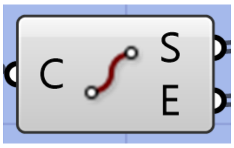


Figure 3.5: Component - End Points.

Merge Used in multiple places to combine multiple lists into a singular larger list. This is performed sequentially, so the list in D1 will be first, followed by D2, D3, etc.

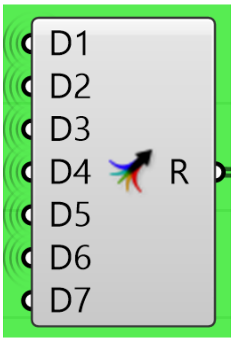


Figure 3.6: Component - Merge.

3.1.2.2 Python

Audience Plane Sorting This component adds the indices that are "audience planes" to a list. When the user marks a face with a material, said material is either marked as an audience plane or not, and if so then the index of that face is added to the list. This list is then later used by the user to set the "Audience Area Mapping" in CATT. If the audience plane is also double-sided then the program is set to take the second of the two indices as the audience plane.

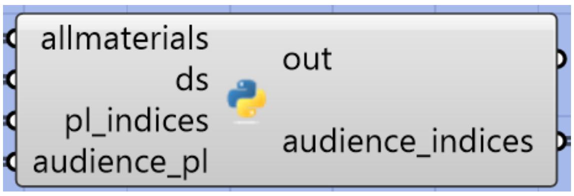


Figure 3.7: Custom Python Component - Sort out the plane indices that are audience planes.

Double-sided Plane Sorting A custom component to sort out the faces that are marked with a double-sided material, which is set by a toggle. In CATT a double-sided plane requires two indices in the planes.geo file, ergo the indexing is altered as soon as a face in Rhino is "painted" with a double-sided material. This component handles the changing indices for the planes.geo file as faces are altered.

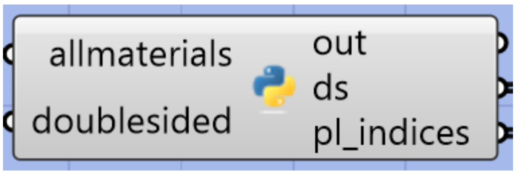


Figure 3.8: Custom Python Component - Sort out the plane indices that are double-sided.

Face Coordinate Index Sorting Custom component created with Python in order to sort the indices of the vertices that create each face. As inputs there are two lists, the start vertices of the edges in the model, and the end vertices of the edges. The end vertex of one edge is the start vertex of the next edge, therefore the end vertices are used as pointers, which are used to find the next starting vertex in the list. The process is continued for each edge of the face. The result is a list of the ordered vertices for each face that can be used to create the planes in CATT.

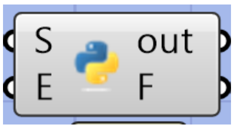


Figure 3.9: Custom Python Component - Sort the indices of the coordinates of a face.

Geometry Type Sorting Custom component created with Python that takes a model from Rhino separates the mesh and BREP portions into separate lists so they can be handled differently at the beginning of the program.

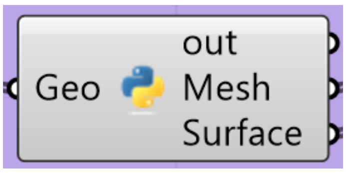


Figure 3.10: Custom Python Component - Sort the type of geometry used in Rhino.

Planes Material List Creates a list of materials (layers) that are applied to the model in Rhino. If “Default” exists on at least one of the faces in the model in Rhino, then it is added to the list of materials with default absorption coefficients.

Figure 3.11: Custom Python Component - Create list of absorption definitions for CATT.

3.1.2.3 Human

Using Human by Andrew Heumann for some functions in Grasshopper.[6]

Bake Geometry Creates a malleable geometry in Rhino. A button can be attached so that the “bake” action can be executed at the user’s desired time.

Figure 3.12: Component - Bake Geometry.

Create Attributes Takes lists of names, colours, etc., to create attributes for a model in Rhino. In this program, it is used to name each face in Rhino with the corresponding plane index in the planes file for CATT. The name of the face is the corresponding index in the planes.geo file, meaning that the names (and layers) are constantly being updated as the program is running to ensure the names and materials match from Rhino to CATT.

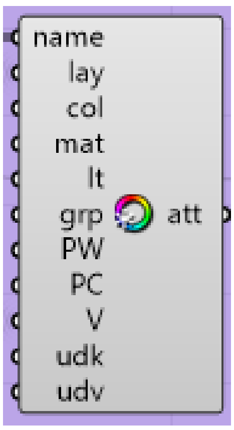


Figure 3.13: Component - Create Attributes.

Object Attributes Takes a model from Rhino and reads the attributes applied to it, then creates a list of each different attribute. Used to retrieve which layers are applied to each face of the model in Rhino.

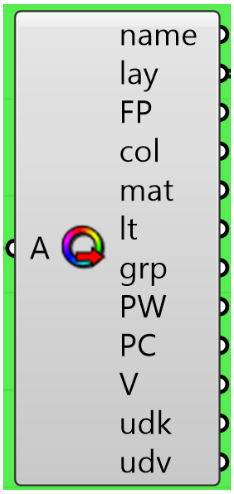


Figure 3.14: Component - Object Attributes.

3.1.2.4 Kangaroo Physics

Using Kangaroo Physics by Daniel Piker for some functions in Grasshopper.[17]

Combine&Clean Combines multiple meshes into one mesh and removes any duplicate vertices.

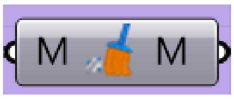


Figure 3.15: Component - Combine&Clean.

3.1.2.5 LunchBox

Using LunchBox by Nathan Miller for some functions in Grasshopper.[15]

Create Layers Takes a list of names and a list of colours, and creates new layers in Rhino. Allows for the user to attach buttons or toggles to choose when the actions are executed; in this instance it is a Boolean toggle. Note that it does not update old layers if information is changed, such as the absorption coefficients or the layer name, instead it creates a new layer. However, if the colour is changed, nothing happens.

Figure 3.16: Component - Create Layers.

3.1.2.6 Pufferfish

Using Pufferfish by Michael Pryor for some functions in Grasshopper.[19]

Are Points Coplanar Calculates if all the points in a list are coplanar and returns true if coplanar, and false if not coplanar. Needed to help determine if there are any non-planar faces in the model, because CATT requires only planar faces otherwise leaks will occur.

Figure 3.17: Component - Are Points Coplanar.

Mesh To Polysurface Creates a polysurface from a mesh, which could either be open or closed based on if the mesh was joined properly earlier in the path. This component also includes an option to merge any coplanar faces. However, there is a tolerance that allows near coplanar surfaces to be merged which creates faces that are not truly planar, which is why the "Are Points Coplanar" component is necessary.

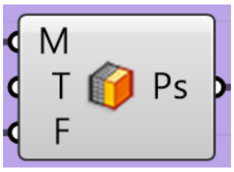


Figure 3.18: Component - Mesh to Polysurface.

Reduce Mesh The most important component of the program, which takes a mesh and reduces it to a simplified mesh with a decreased number of faces. There are a few settings that can be altered depending on the desired simplification.

- **F** - Face Count, which is where the goal number of faces is set.
- **A** - Accuracy, how accurate you wish the new mesh to be on a scale of 1 to 10 (least to most).
- **T** - Face Type, choices being "default", "quadrangulate", or "triangulate". Changes the shape of each face depending on whichever option is chosen.
- **D** - Distort, will change the shape of the model if set to "true".

- **N** - Normalize, will distribute the size of the faces of the mesh to more equal sizes.

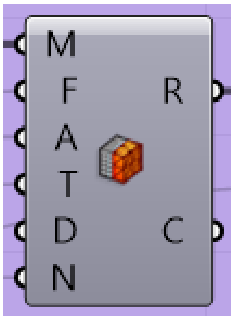


Figure 3.19: Component - Reduce Mesh.

3.1.3 CATT-Acoustic

CATT-Acoustic uses three-dimensional CAD-type models to simulate the acoustics in a closed room utilizing geometrical and statistical acoustics. Implementing ray tracing, image source modelling, and Sabine's and Eyring's formulae to provide results of many acoustical parameters and to auralize the room. Source to receiver calculations and audience mapping are the main tools used to analyze acoustical parameters such as sound pressure level, clarity, strength, speech transmission index, reverberation time, and many more. The source emits rays and the receivers and audience maps record the resulting rays that reach the respective positions. CATT also includes such features as Time Trace to see how the rays travel through the model and Image Source Model to see the path that each ray took to reach the receiver.

The parameter data is presented with two different calculations, the energy echogram appended with "_E", and the impulse response appended with "_h". The energy echogram was introduced first in CATT simulations and analysis, with the impulse response arriving later as auralization was implemented.[3]

3.1.4 MATLAB

MATLAB is used for any of the mathematical post-processing of data. The CATT data is imported into MATLAB to create plots of the five parameters: clarity, strength, sound pressure level, speech transmission index, and reverberation time. The mean of the receiver positions can be taken for each parameter of each model to see the average value over the room in each octave band.

3.2 Program

The program is created in Grasshopper which provides a great deal of flexibility for the user and is a program that many at Buro Happold are familiar with as they use it for many projects. The following three sections outline the essential parts of the program, split into:

- Adjustable parameters that are altered by the user to achieve the desired results.
- Reduce mesh workflow used to reduce the model to a simplified version.
- CATT file creation components used to generate the files that will create the model in CATT.

3.2.1 Adjustable Parameters

3.2.1.1 Step 1

The user sets the geometry that will be reduced. This geometry is the model that exists in Rhino and can be composed of meshes and BREPs. Three different models will be analysed, Model 1 has been used to show how the program operates. The screenshot of Model 1 can be found in Figure 3.20.

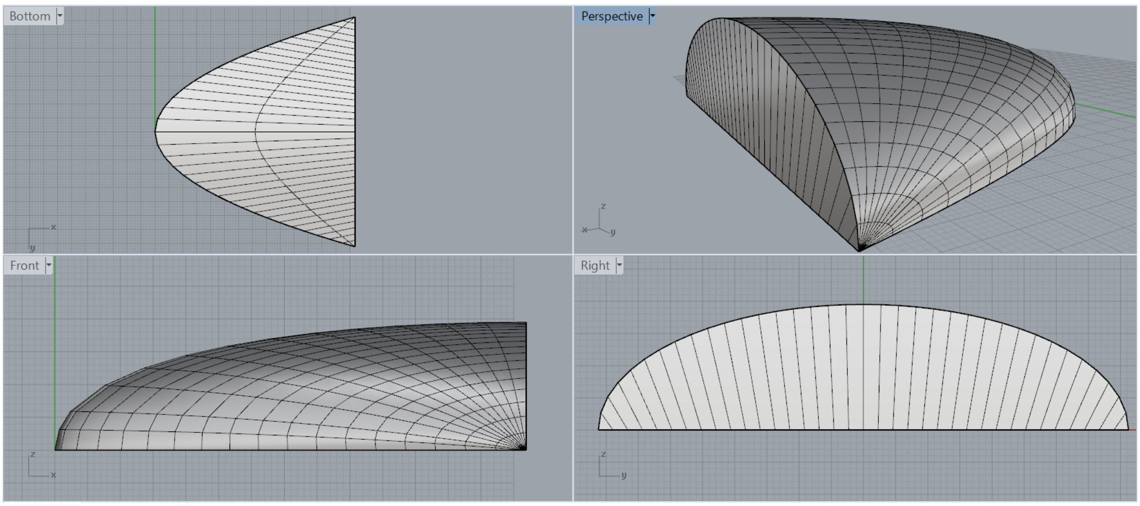


Figure 3.20: The original geometry of Model 1 in Rhino.

In order to see the newly generated simplified model, the original model must be hidden from view. These steps are all laid out in Figure 3.21.

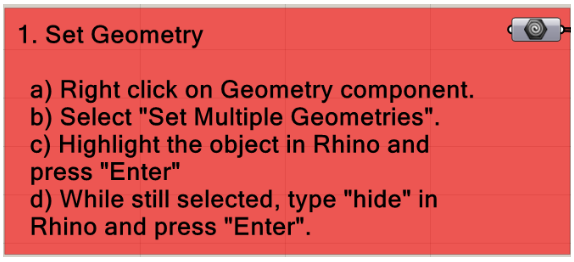


Figure 3.21: Step 1 of the program, setting the geometry.

3.2.1.2 Step 2

To see the simplified model the user must set the "Preview" toggle to "true". The reduced model can then be seen in Rhino and looks like that found in Figure 3.22.

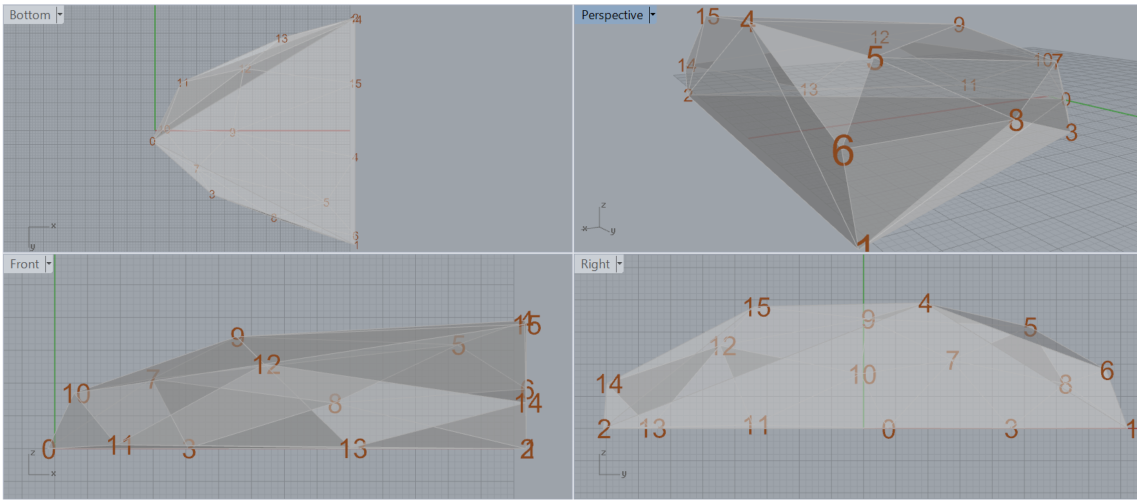


Figure 3.22: The preview of the simplified model with a 95% reduction.

Step 2 is where the user is given the most flexibility and power to affect the model how they wish. "With great power comes great responsibility,"[29] which is important for the user to keep in mind. They must be aware of how the model is simplified, i.e. if it looks too simple or if there are holes created. The main tool used for reducing the model is setting the number of desired planes in the "panel" component. The "Reduce Mesh" component reduces the mesh down to the target number of faces. Then later on in the workflow, if the "Merge Faces" is set to "True" then the resulting number of faces in the model will be smaller. Though as stated before, the model is then prone to more non-planar faces, the number of which can be seen in the panel. The "Quadrangulate" (and "Default") options will also reduce the number of faces, however, they will also be prone to creating non-planar faces. Therefore, it is recommended that triangulate be used since triangles will always be planar.

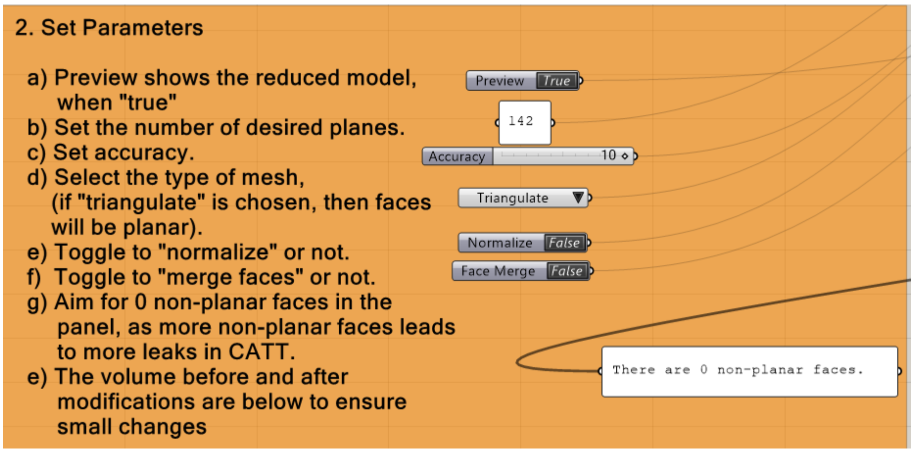


Figure 3.23: Step 2 of the program, setting the parameters.

Included in the workflow of the program is a section where the user can see the volumes and surface areas of the original model and the simplified model. As stated previously, these two factors (along with the absorption) determine the reverberation time of the room and consequently the characteristics of the room. Therefore it is important for the operator to be aware of how much these values have been altered due to the simplifications they made. The operator can also use the knowledge of the adjusted parameters to modify the absorption coefficients to counteract the change in volume and surface area.

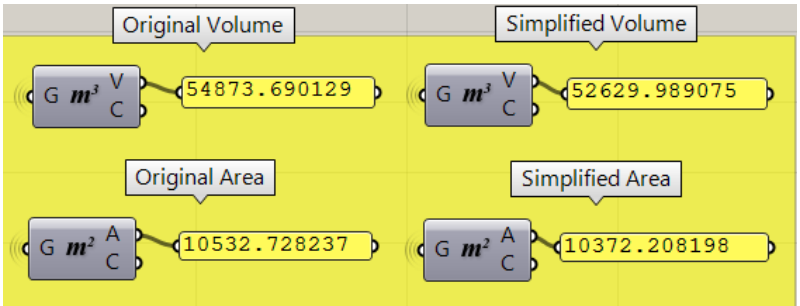


Figure 3.24: The volume and area displayed in the program, before and after simplifications are made.

3.2.1.3 Step 3

Step 3 is shown in Figure 3.25, which is where all the material information is handled.

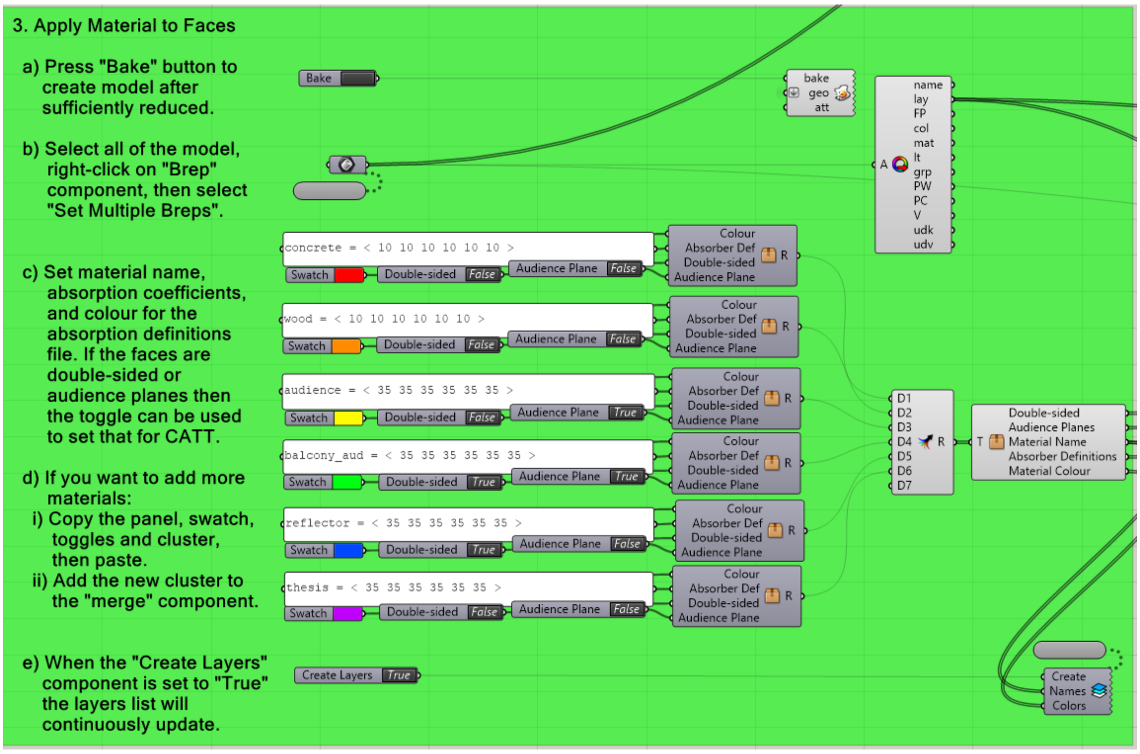


Figure 3.25: Step 3 of the program, applying material properties to the faces of the model.

To prepare the model for CATT the material needs to be applied to the model. The preview can be seen in Rhino in this stage, but nothing can be altered, which is where the "Bake" component comes in handy. Once the model has been reduced to the desired simplification then the user can press the "Bake" button, which will make the model adjustable. The user can also turn the preview off by going back to Step 2 if desired. The baked model can be seen in Figure 3.26.

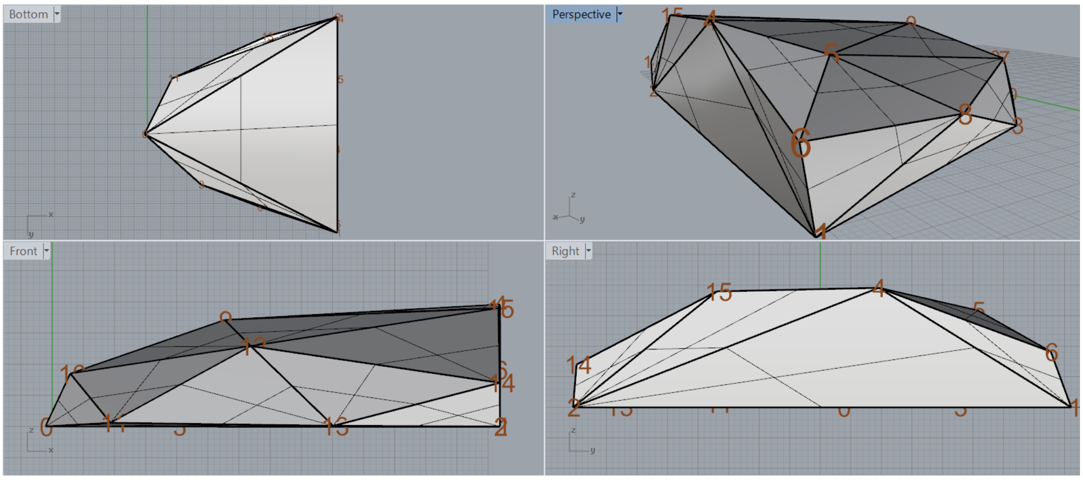


Figure 3.26: The baked simplified model with a 95% reduction.

The user will then select the newly created, reduced model and set the selected model in the BREP component. The absorption definitions can be written in the panels, which requires a material name and the absorption coefficients. And, a colour can be chosen for each material in the colour swatch. These definitions are turned into layers in Rhino that can then be applied to the new model, which are necessary for the acoustic analysis in CATT. In Figure 3.27 the layers have been applied to the model. The faces that will be used for the audience plane are those in yellow. Also to denote for the audience plane for the purposes of CATT, the toggle can be switched to "True", then all the faces that the material is applied to will be saved in a list and can be exported later. As well, since double-sided planes are important features in CATT, the user can set materials that are applied to double-sided planes by flipping the togglet to "True", then this will be reflected in the CATT files.

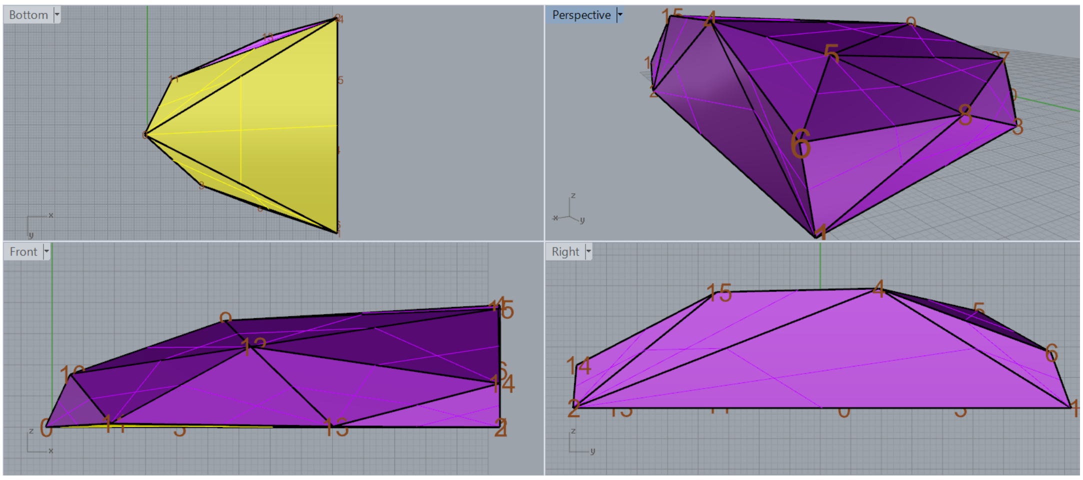


Figure 3.27: The baked simplified model with a 95% reduction, and materials applied.

In the models, the indices of each vertex can also be seen. The Grasshopper implementation of this is seen in Figure A.2 in Appendix A.

3.2.1.4 Step 4

Finally the files for CATT-Acoustic can be created in the desired folder. The destination folder is chosen using the first button. Then the files that are desired can be created by simply clicking the button. This can create all the necessary files for creating a model in CATT.

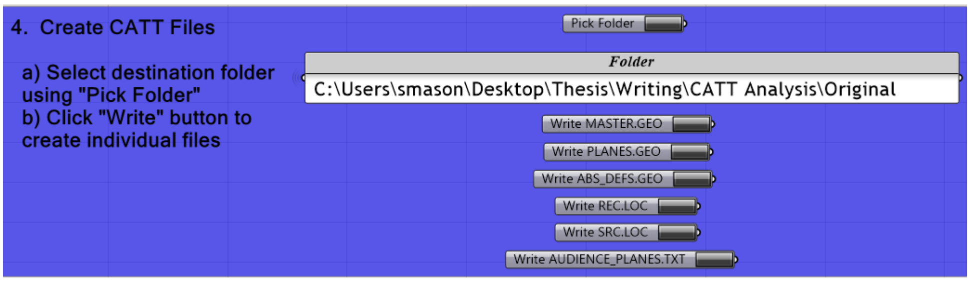


Figure 3.28: Step 4 of the program, exporting the files to CATT.

Compared to the SketchUp to CATT plug-in the only thing that cannot be created from this Grasshopper program is the "CATT Modeling" file, which is the session that runs in the CATT software. This is simple enough to create when the CATT software has been started. One additional thing that is created that does not exist in the existing programs (SketchUp to CATT plug-in) is a list of the plane IDs that the "audience" material is applied to. The numbers can be copied and pasted into the audience planes mapping. However, it would be better if the program created the ".dat" file that is used for audience mapping. The creation of this file can be found in Figure A.6 in Appendix A.

3.2.2 Reduce Mesh

The workflow of how the components have been combined together to create the mesh simplification program can be seen in Figure 3.29. As seen, it is straightforward, where the first step is to split the different geometries up into meshes and BREPs, turn the BREP into a mesh, then combine them together. The mesh is then reduced and turned into a polysurface, if it has no holes it will be closed and if there are holes it will be open. The two panels show how the number of faces has been reduced before and after.

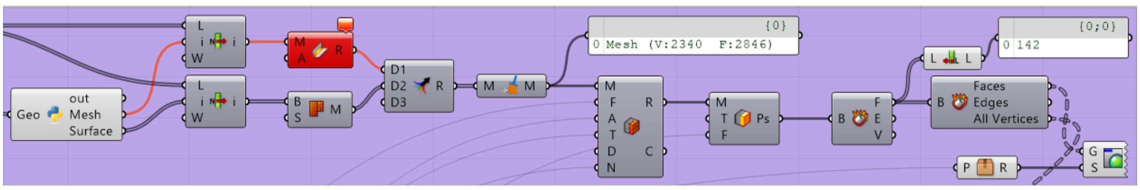


Figure 3.29: The components that fully simplify a model.

3.2.3 CATT File Creation

In order to create the individual CATT files that are necessary for a model to be created the individual bits of information from the Rhino model need to be extracted. The "Deconstruct Brep" component was very useful for this, in order to extract the faces, edges, and vertices. In the "MASTER.GEO" file the unique vertices are needed for the "CORNERS" section — a unique identifier and the xyz-coordinates.

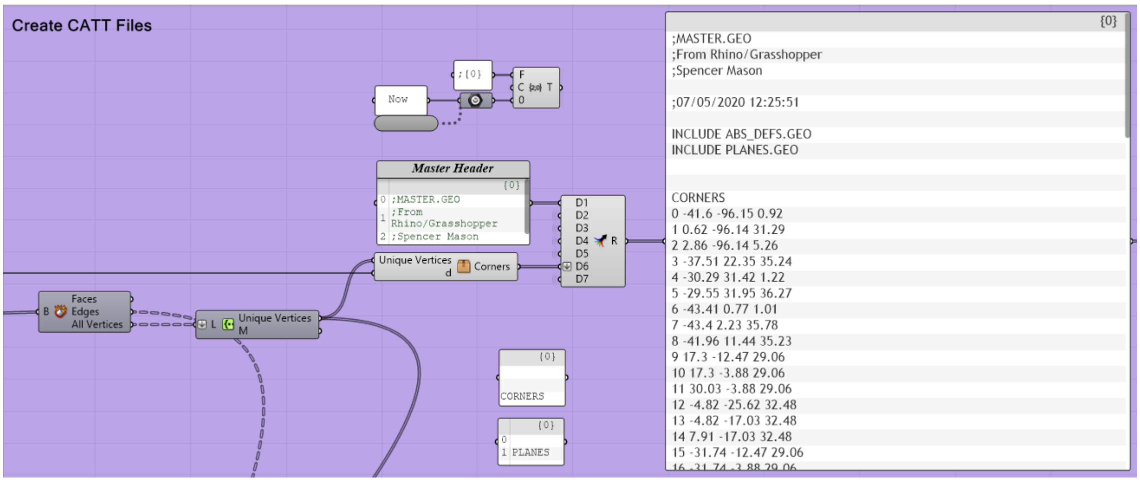


Figure 3.30: The components that create the master.geo file for CATT.

The "PLANES.GEO" file is the most complex as it requires information from multiple areas and determining how to create the model the correct way. Each plane requires its own unique identifier. Then it needs to reference the "CORNERS" section and use those IDs in the correct order. And, finally the material needs to be included in the definition.

This portion of the program utilizes the "Closest Point" component to compare the points of each face to the points in the list in "MASTER.GEO". The "End Points" component is used to determine the order in which these IDs should be written. Then the materials that are applied to each face are compiled into a list and added to the corresponding plane definition.

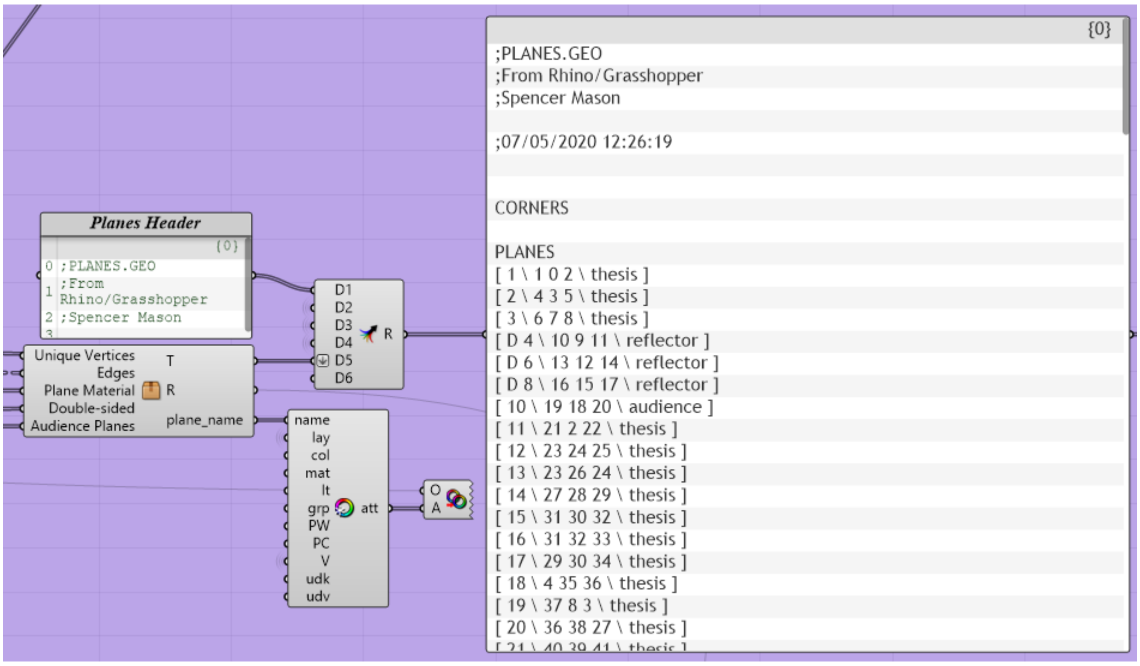


Figure 3.31: The components that create the planes.geo file for CATT.

The abs_def.geo file is created by taking the list of all the materials in the program and then comparing which materials were actually used in the model. If none of the materials have been applied to a plane then another absorption definition is created for the “Default” layer/material in Rhino. The main component used is the custom Python component, the Planes Material List component.

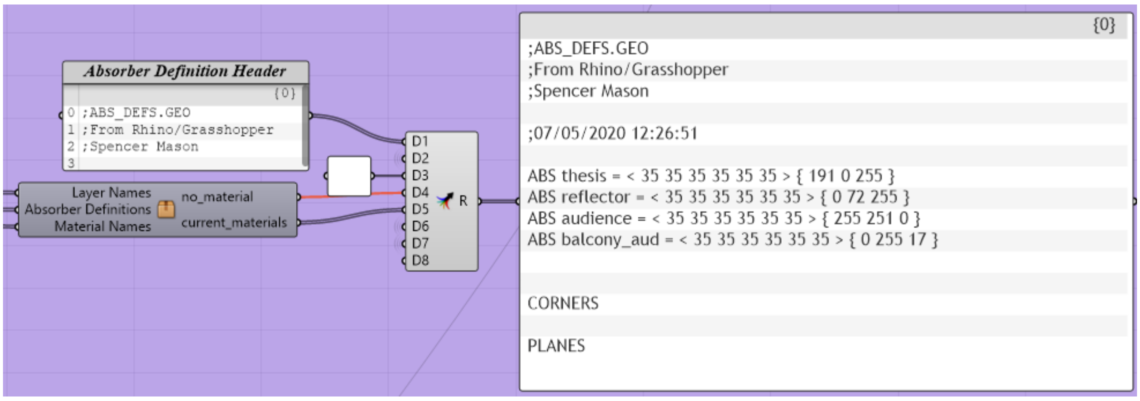


Figure 3.32: The components that create the abs_defs.geo file for CATT.

The other file creation steps can be found in Appendix A. These are:

- Receiver location file in Figure A.4
- Source location file in Figure A.5
- Audience plane mapping file in Figure A.6

3.3 Analysis

Once the CATT files are created, then the models are simulated and results are gathered. In Grasshopper the different levels of simplification are achieved by setting the number of target planes.

The "original" model is what would typically be used by an acoustician that directly exports a model from a CAD software like SketchUp. The original model can have twisted/warped planes or holes, creating leaks. If the percentage of leaks is small, then the acoustician will likely still use the results from the simulation. So if the percentage is small then this is a valid model to compare results to.

The 0% model is what would typically be used if the acoustician were to fix any leaks and successfully create a closed model, but did not do any work to reduce the model to a simplified version and therefore there are the same number of faces as the original. Though note that, due to the reduce mesh component in Grasshopper, the geometries of the individual faces changed.

The simplified models can then be created and compared to the original and the 0% to see the change in the five parameters: clarity (C_{80}), strength (G), sound pressure level (SPL), speech transmission (STI), and reverberation time (T_{30}). During analysis it was found that it was necessary to adjust the absorption coefficients as the volume and surface area changed, even if the absorption coefficients only changed by 0.01%. Since the volume and surface area change when the model is simplified, the adjusted absorption coefficients were found using Eyring's formula, Equation 2.3, where the reverberation time for the "original" model was calculated using the absorption coefficients for said model. Then the new target absorption coefficients were calculated using this reverberation time and the new volumes and surface areas. The absorption coefficient used in the "original" model was 35% for all octave bands.

In Chapter 4 each model is presented and their individual details can be seen further. For all models the scattering coefficients remained the same, i.e. the default values in CATT, which are found in Table 3.1.

	Frequency (Hz)					
Scattering Coefficients	125	250	500	1000	2000	4000
All Models	10%	10%	10%	10%	10%	10%

Table 3.1: The scattering coefficients used in the models for analysis in octave bands.

In the simulations there are two methods of analysis used to obtain results. First the source to receiver simulations, where one source and six receivers are placed in the model and then the results of the five parameters are analysed. The six receiver positions are averaged together to see the average results for the entire model, for each frequency octave band.

The second analysis in CATT is the audience maps. Using these the whole space in the different models can be compared for each parameter. This provides a visual result to see how the parameters vary throughout the space, and see how the patterns are affected as the models are simplified.

For both the source to receiver and the audience maps, the source emits an omnidirectional, white noise source with a sound pressure level of 100 dB. As well, for both types of simulation the suggested “number of rays” was used to see how that changed with the different reductions of the models, and to compare to the calculation time.

4

Models

4.1 Model 1

Model 1 is a simple model, with only exterior features (the shell of a structure) but is composed of three open meshes: the floor, the flat wall, and the curved ceiling. By reducing and reconstructing the mesh with triangular faces a closed mesh with only planar faces can be created ensuring no leaks.

The reduction iterations and modelling specifics used can be found in Table 4.1. The volume and surface area listed were the values use to calculate the adjusted absorption coefficients, and these calculated values can be found in Table 4.2

	Number of Created Planes	Number of Audience Planes	Volume (m^3)	Surface Area (m^2)	Map Step (m)	Audience Height (m)
Original	576	73	54874	10533	1	0.5
0%	576	85	54836	10530	1	0.5
50%	288	41	54736	10523	1	0.5
80%	114	18	54415	10483	1	0.5
95%	28	3	52630	10372	1	0.5

Table 4.1: The settings that were used to create the iteration of simplification for Model 1.

	Frequency (Hz)					
Adjusted Coefficients	125	250	500	1000	2000	4000
Original	35.00%	35.00%	35.00%	35.00%	35.00%	35.00%
0%	34.99%	34.99%	34.99%	34.99%	34.99%	34.99%
50%	34.96%	34.96%	34.96%	34.96%	34.96%	34.96%
80%	34.90%	34.90%	34.90%	34.90%	34.90%	34.90%
95%	34.27%	34.27%	34.27%	34.27%	34.27%	34.27%

Table 4.2: The absorption coefficients used in the iterations of Model 1 for analysis in octave bands.

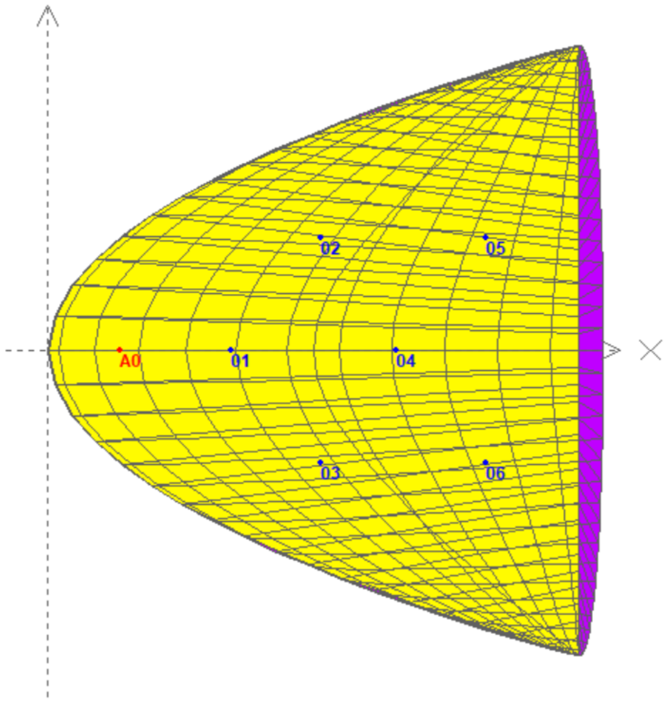


Figure 4.1: The top down view of the original iteration of Model 1 in CATT, with the one source position and the six receiver positions.

4.1.1 Simulation Time

Source To Receiver For the source to receiver tests in Table 4.3, there is a clear reduction in calculation time as the models are simplified. The number of rays was not affected much by the reduced number of planes. So the biggest contributing factor into the reduction of calculation time is the number of planes in the model.

Adjusted Coefficients

SxR	Number of Rays	Echogram Length (ms)	Calculation Time (hh:mm:ss)	Percent Leaks
Original	187778	5000	00:04:08	9.10%
0%	187784	5000	00:04:54	0%
50%	188220	5000	00:03:24	0%
80%	187478	5000	00:01:21	0%
95%	187927	5000	00:00:18	0%

Table 4.3: The number of rays and echogram length used in the source to receiver calculations in CATT, and the resulting calculation times and leaks, for Model 1.

Maps The results from the audience map analysis show similar results in Table 4.4 where the calculation time decreases as the model reduces in number of planes. It can also be seen that for both same and adjusted coefficients, the 0% model took longer than the original model. It is likely that the leaked rays were disregarded after escaping so the simulation did not continue to record the results from them.

Adjusted Coefficients

Maps	Number of Rays	Echogram Length (ms)	Calculation Time (hh:mm:ss)	Percent Leaks
Original	187779	5000	00:19:02	4.70%
0%	187785	5000	00:19:59	0%
50%	188220	5000	00:14:18	0%
80%	187479	5000	00:08:43	0%
95%	187927	5000	00:06:08	0%

Table 4.4: The number of rays and echogram length used in the map calculations in CATT, and the resulting calculation times and leaks, for Model 1.

4.2 Model 2

Model 2 is a more complex model, with a rounded wall on one end that is not created using a mesh, which leads to inability to use the original iteration model in CATT and is omitted from the results. Only the 0% iteration will be used to compare all the results to. Due to the high detail in this iteration there were some “garbage planes”, which are planes that are too small to have an affect on the results and “should be deleted”.

This model also contains a balcony that wraps around three walls of the space. Since the walls were not sectioned off properly and there were “floating” edges, edges that terminated with another face, the face was not properly connected to other faces. The balconies were not capable of being joined to the outer shell of the model, thus the model was reduced as multiple, separate BREPs, though it did try to keep the general relation between the separate BREPs. When reduced the balconies first had overlapping faces, so two faces in the same place to properly represent the geometry. However, when reduced even further holes in the balconies were created.

The final addition to this model was reflectors “hung” from the ceiling, they are free hanging so do not connect to any other face. Even in the 95% reduced model the reflectors were still intact, as there is some concern that they would disappear as the reduce mesh component would deem them as superfluous.

The reduction iterations and modelling specifics used can be found in Table 4.5. The volume and surface area listed were the values use to calculate the adjusted absorption coefficients, and these calculated values can be found in Table 4.6

	Number of Created Planes	Number of Audience Planes	Volume (m^3)	Surface Area (m^2)	Map Step (m)	Audience Height (m)
0%	2846	69	422029	43019	1	0.5
50%	1422	68	422029	43018	1	0.5
80%	570	61	422028	42013	1	0.5
95%	142	20	421656	41879	1	0.5

Table 4.5: The settings that were used to create the iteration of simplification for Model 2.

	Frequency (Hz)					
Adjusted Coefficients	125	250	500	1000	2000	4000
0%	35.00%	35.00%	35.00%	35.00%	35.00%	35.00%
50%	35.00%	35.00%	35.00%	35.00%	35.00%	35.00%
80%	35.67%	35.67%	35.67%	35.67%	35.67%	35.67%
95%	35.73%	35.73%	35.73%	35.73%	35.73%	35.73%

Table 4.6: The absorption coefficients used in the iterations of Model 2 for analysis in octave bands.

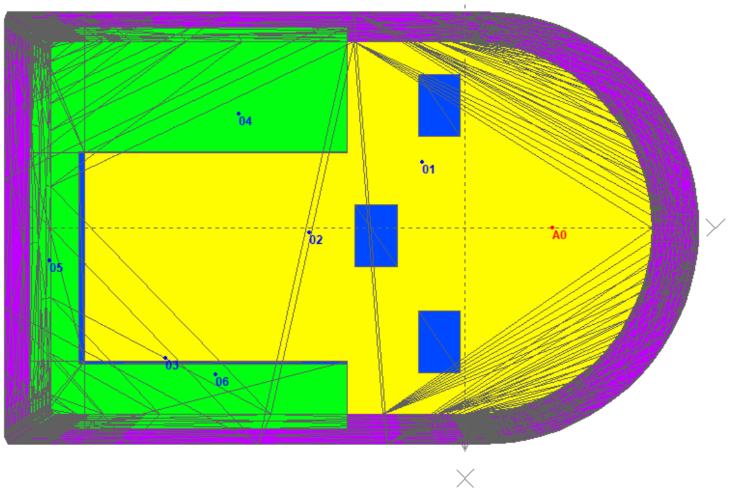


Figure 4.2: The top down view of the 0% iteration of Model 2 in CATT, with the one source position and the six receiver positions.

4.2.1 Simulation Time

Source To Receiver The results in Table 4.7 show again that the decrease in number of planes can greatly reduce simulation time. Even when the number of rays is increased for the 95% iteration the calculation time is decreased.

Adjusted Coefficients				
SxR	Number of Rays	Echogram Length (ms)	Calculation Time (hh:mm:ss)	Percent Leaks
0%	430780	5000	00:26:42	0%
50%	430780	5000	00:19:03	0%
80%	430823	5000	00:07:56	0%
95%	432171	5000	00:01:56	0%

Table 4.7: The number of rays and echogram length used in the source to receiver calculations in CATT, and the resulting calculation times and leaks, for Model 2.

Maps The simulations for the map results required a reduced number of rays and echogram length because using the suggested amount of rays caused the program to overload and crash. During simulation an error message pops up with "Access Violation" which is thought to mean that the computer does not have enough memory space to run with such high precision. Ironically, the usual recommended method to subvert this is to reduce the number of planes in the model, i.e. simplify the model. However, since the point is to look at high numbers of planes, the alternate method of reducing number of rays and echogram length was used. To know if the simulation will run is trial and error, running the model and waiting for it to crash or not, which can take some time to discover.

Adjusted Coefficients				
Maps	Number of Rays	Echogram Length (ms)	Calculation Time (hh:mm:ss)	Percent Leaks
0%	100000	4000	04:01:22	0%
50%	100000	4000	01:13:36	0%
80%	100000	4000	00:31:01	0%
95%	100000	4000	00:22:09	0%

Table 4.8: The number of rays and echogram length used in the map calculations in CATT, and the resulting calculation times and leaks, for Model 2.

4.3 Model 3

The third model under analysis is a real model provided to the acoustics team at Buro Happold, and thereby acts as a useful test of the program in a real-life situation. This model is a stadium with many flat and near planar surfaces, which accounts for the low number of leaks found later in Table 4.11. The small amount of leaks is useful because it means that the model could necessarily be used reliably without much alteration.

This model did contain some balconies and other features that were unable to join together with the main structure, so they were removed for ease of use. Alterations were performed, and note that it can be useful for the acoustician to make some manual alterations to the geometry before using the program. This is particularly necessary for many models, since all unjoined BREPs must first be joined together manually using Rhino. Also, because this model is made of BREPs the program first has to change it into a mesh, which creates more planes than are in the BREP model.

	Number of Created Planes	Number of Audience Planes	Volume (m^3)	Surface Area (m^2)	Map Step (m)	Audience Height (m)
Original	672	286	176404	26233	1	0.5
0%	672	260	176360	26086	1	0.5
50%	336	128	176194	25850	1	0.5
80%	134	46	175889	25554	1	0.5
95%	34	18	172560	24136	1	0.5

Table 4.9: The settings that were used to create the iteration of simplification for Model 3.

	Frequency (Hz)					
Adjusted Coefficients	125	250	500	1000	2000	4000
Original	35.00%	35.00%	35.00%	35.00%	35.00%	35.00%
0%	35.15%	35.15%	35.15%	35.15%	35.15%	35.15%
50%	35.38%	35.38%	35.38%	35.38%	35.38%	35.38%
80%	35.66%	35.66%	35.66%	35.66%	35.66%	35.66%
95%	36.74%	36.74%	36.74%	36.74%	36.74%	36.74%

Table 4.10: The absorption coefficients used in the iterations of Model 3 for analysis in octave bands.

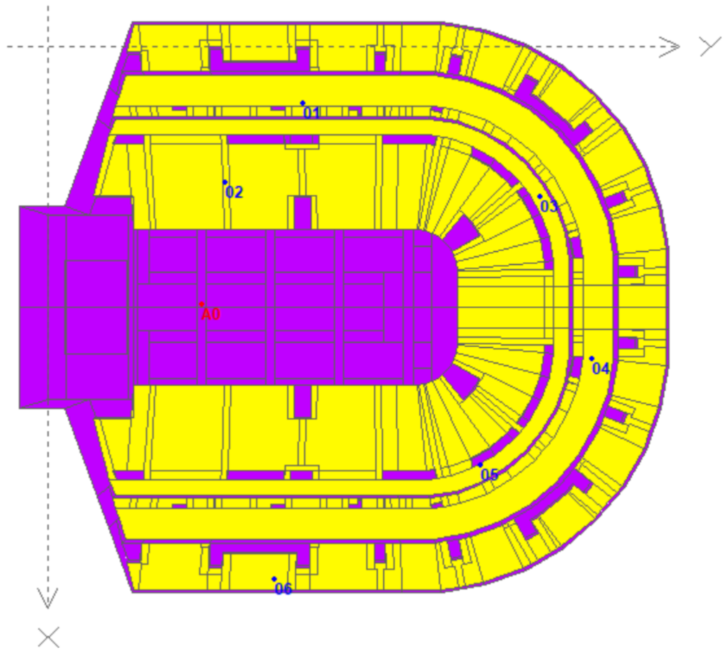


Figure 4.3: The top down view of the original iteration of Model 3 in CATT, with the one source position and the six receiver positions.

4.3.1 Simulation Time

Source To Receiver As with Model 1, the calculation time increases from the original to the 0%, possibly due to the occurrence of leaks in the original model. Though in these models the percentage of leaks is quite small. And, as seen in Model 3, the number of rays increases by a lot from 80% to 95% which would have a bit of an influence on the calculation time, though the calculation time is still lower.

Adjusted Coefficients

SxR	Number of Rays	Echogram Length (ms)	Calculation Time (hh:mm:ss)	Percent Leaks
Original	366546	5000	00:10:22	0.2%
0%	367252	5000	00:14:02	0%
50%	367736	5000	00:08:32	0%
80%	368723	5000	00:01:34	0%
95%	381400	5000	00:01:16	0%

Table 4.11: The number of rays and echogram length used in the source to receiver calculations in CATT, and the resulting calculation times and leaks, for Model 3.

Maps The audience map results follows the source to receiver results, and shows how a reduced model can decrease the calculation time by a large factor.

Adjusted Coefficients

Maps	Number of Rays	Echogram Length (ms)	Calculation Time (hh:mm:ss)	Percent Leaks
Original	366547	5000	01:10:14	0.1%
0%	367252	5000	01:17:44	0%
50%	367737	5000	00:39:59	0%
80%	368724	5000	00:27:27	0%
95%	381401	5000	00:24:35	0%

Table 4.12: The number of rays and echogram length used in the map calculations in CATT, and the resulting calculation times and leaks, for Model 3.

5

Results

5.1 Source To Receiver

The source to receiver results are presented using a singular value for each frequency octave band, which is calculated by averaging the receiver positions. The other analysis presented in the graphs is how the parameters differ between the unreduced models (original and 0%) and the simplified models (50%, 80%, 95%). These difference graphs show much each simplification deviates from the original model, also for averaged positions. The variance for each parameter and each model is also plotted in the graphs. These are the graphs found first in each subsection. Then the variance is removed for the rest in order to see the graphs in better detail. The variance is calculated for the averaged receiver positions, so the variance from the six different positions in each model. For some parameters the variance is quite high, which is to be expected since the values of the parameters can change quiet drastically within the space, which causes large variation is results.

For Model 1 two different analyses were performed to compare the results before and after adjusting the absorption coefficients. For each parameter the results for the same absorption coefficients are presented followed closely by the adjusted absorption coefficients. These plots can be used to compare the scenarios and determine the extent to which simplifying the models affects the five adjusted parameters, under the assumption that the unreduced models (original and 0%) are the most accurate models. Since it was found that it was indeed important to alter the coefficients only the adjusted coefficients were used for Model 2 and Model 3.

In the results graphs, there are shaded regions between the original and 0% plots, which is used to help analyse the simplified models. If the results from the simplified models fall within this range, then they are near similar to the original models. In the difference graphs, the shaded regions similarly show the range of the difference between each simplified model and the two unreduced models.

For all the source to receiver analysis, the energy echogram results were used. This is the results from CATT where each parameter is appended with "_E".

5.1.1 Clarity

5.1.1.1 Model 1

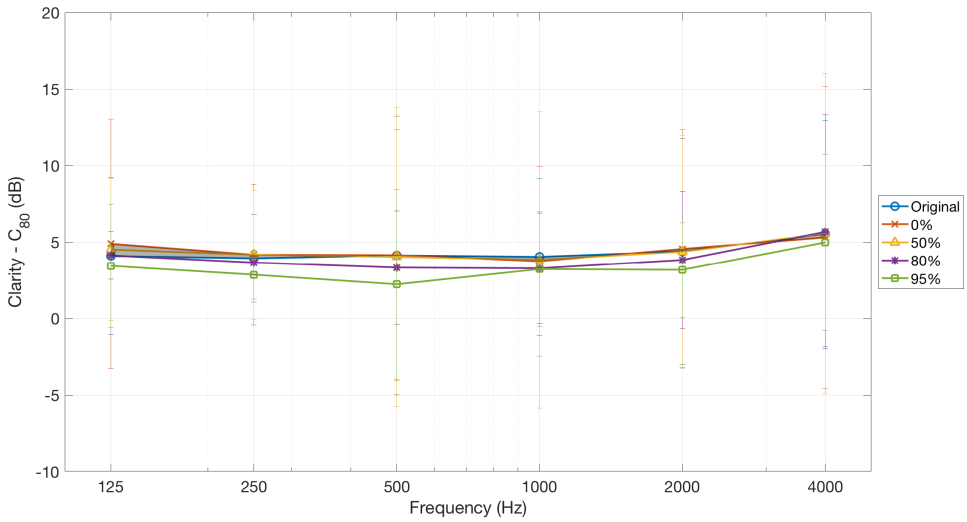


Figure 5.1: Clarity for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1. Variance included.

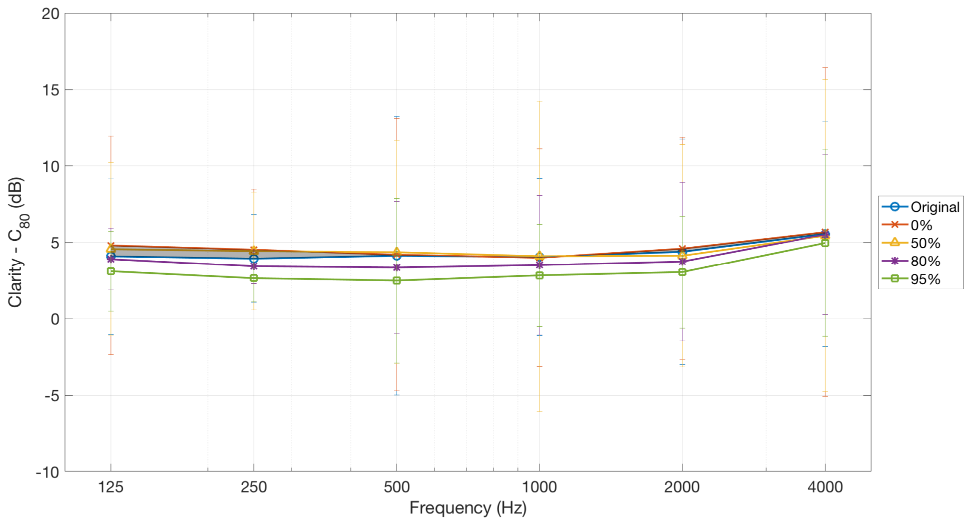


Figure 5.2: Clarity for the averaged receiver positions, using different absorption coefficients for all frequency bands, Model 1. Variance included.

For both the same and adjusted absorption coefficients, in Figures 5.3 and 5.4 the clarity decreases as the model is simplified, with the 50% model lying closely to the unreduced models.

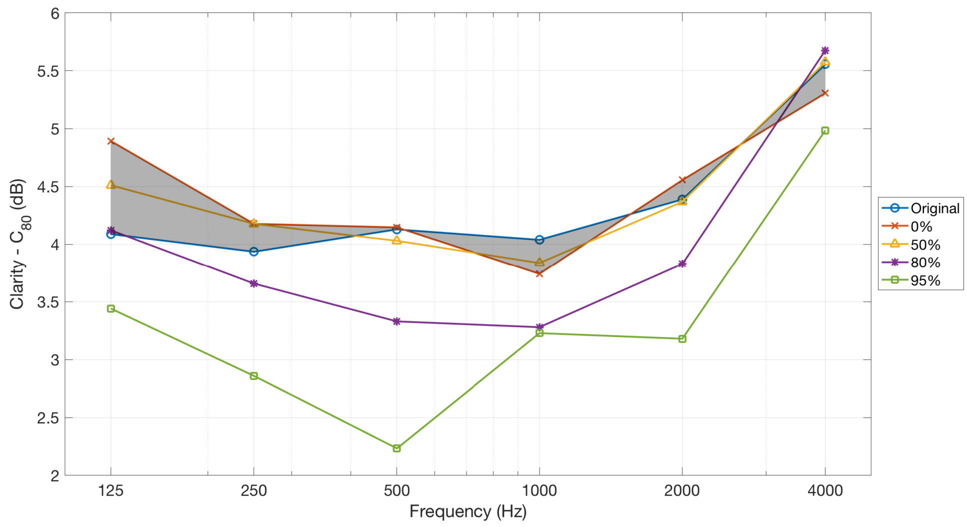


Figure 5.3: Clarity for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1.

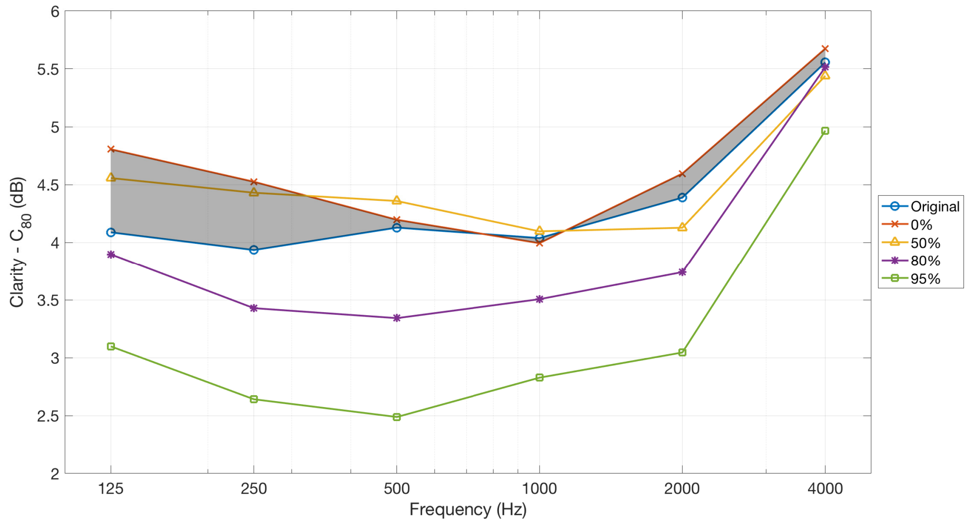


Figure 5.4: Clarity for the averaged receiver positions, using the adjusted absorption coefficients for all frequency bands, Model 1.

As seen in Figures 5.5 and 5.6 the values of the difference between simplified and original models is fairly unaffected, where the difference ranges from about -0.5 dB difference to 1.9 dB difference, for the same coefficients and adjusted. This is then a range of 2.4 dB. The trend of the graphs over frequency is very similar in the adjusted, the graphs take the same shape, with more varied low frequencies (125 Hz and 250 Hz) and very similar values for mid frequencies (500 Hz and 1000 Hz), then spacing out again for high frequencies (2 kHz and 4 khz).

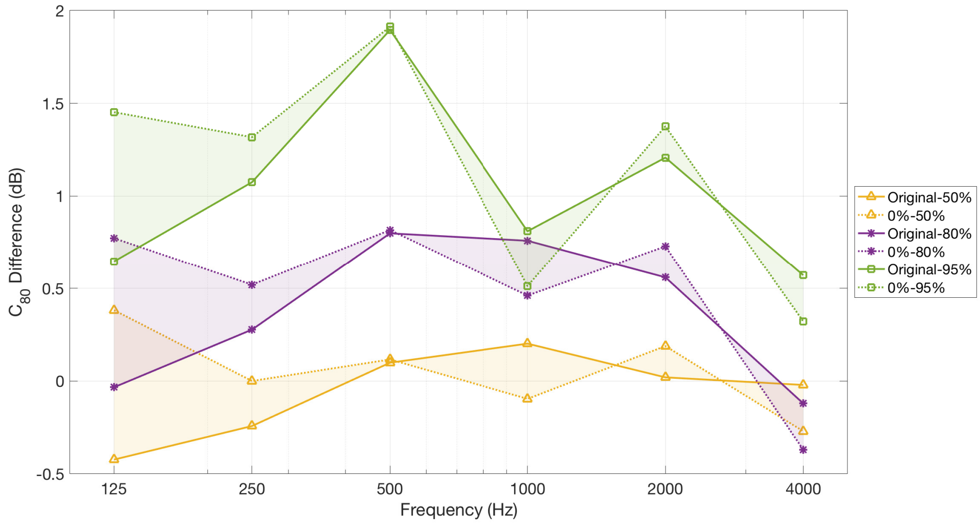


Figure 5.5: The difference between the original models and the simplified models for the Clarity parameter for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1.

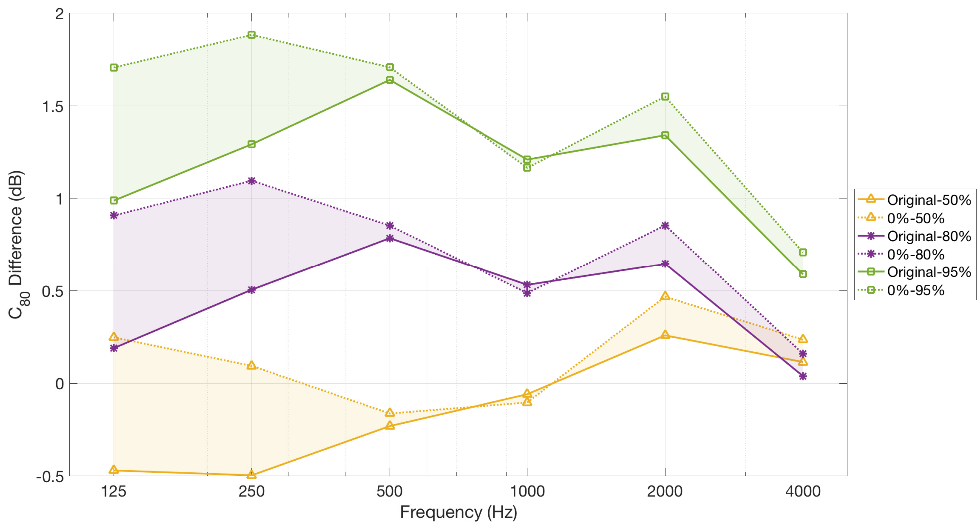


Figure 5.6: The difference between the original models and the simplified models for the Clarity parameter for the averaged receiver positions, using the adjusted absorption coefficients for all frequency bands, Model 1.

5.1.1.2 Model 2

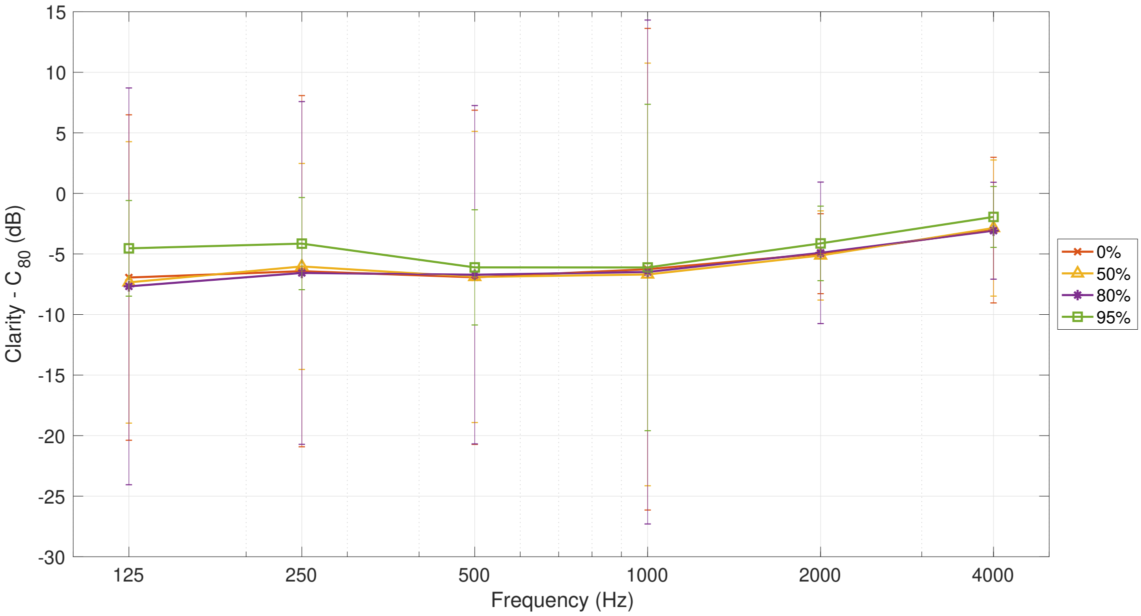


Figure 5.7: Clarity for the averaged receiver positions, Model 2. Variance included.

As seen in Figures 5.8 and 5.9 the 95% model has a large deviation from the 0% model for most octave bands. The largest difference for the 50% and 80% models is about 0.7 dB, whereas the 95% model has difference up to 2.5 dB.

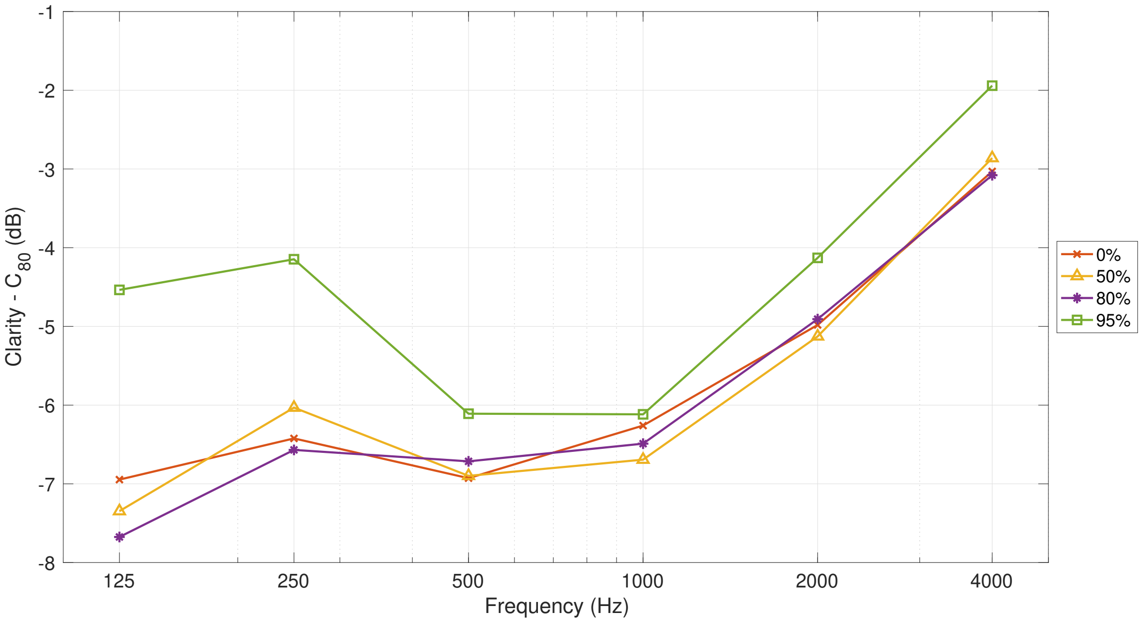


Figure 5.8: Clarity for the averaged receiver positions, Model 2.

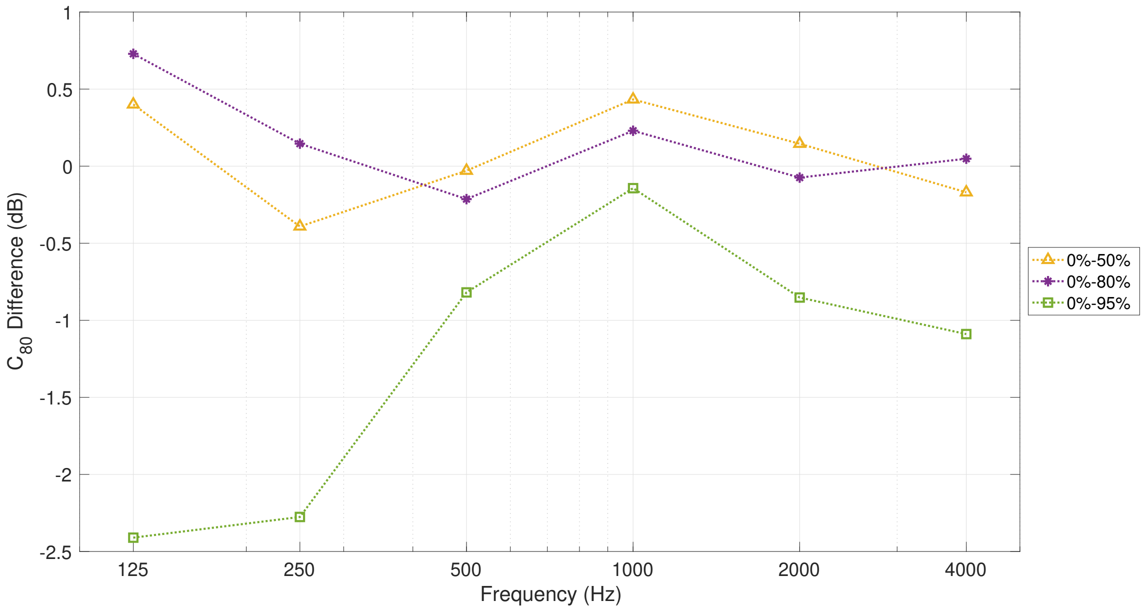


Figure 5.9: The difference between the original models and the simplified models for the Clarity parameter for the averaged receiver positions, Model 2.

5.1.1.3 Model 3

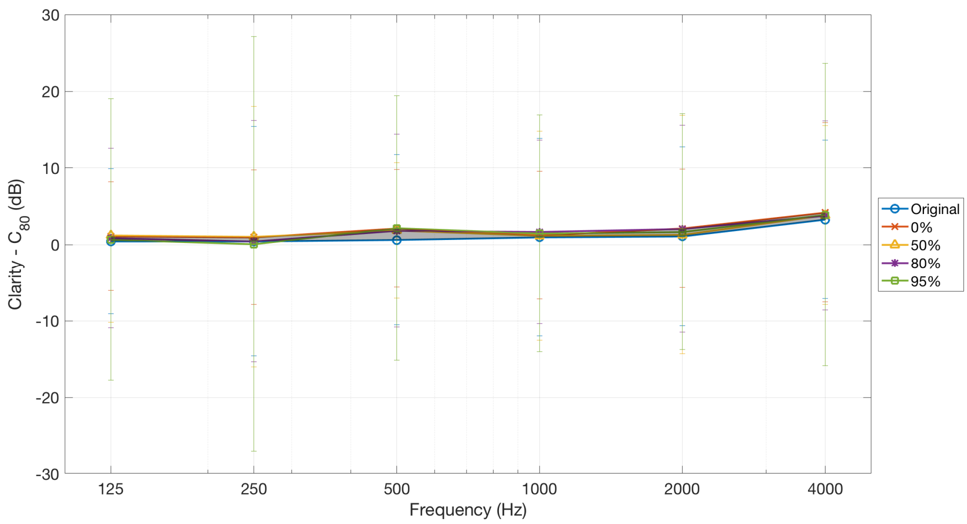


Figure 5.10: Clarity for the averaged receiver positions, Model 3. Variance included.

In Figures 5.11 and 5.12 the two different primary models, original and 0%, create the range that the other iterations lie within for most of the octave bands. The largest difference observed in the graphs is about 1.5 dB. The simplified iterations tend to follow the pattern of the 0% model rather than the original.

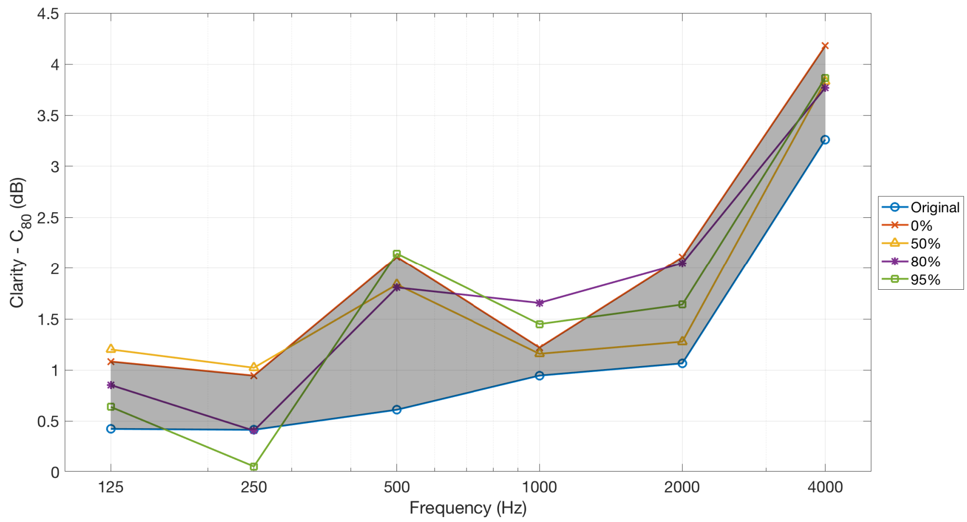


Figure 5.11: Clarity for the averaged receiver positions, Model 3.

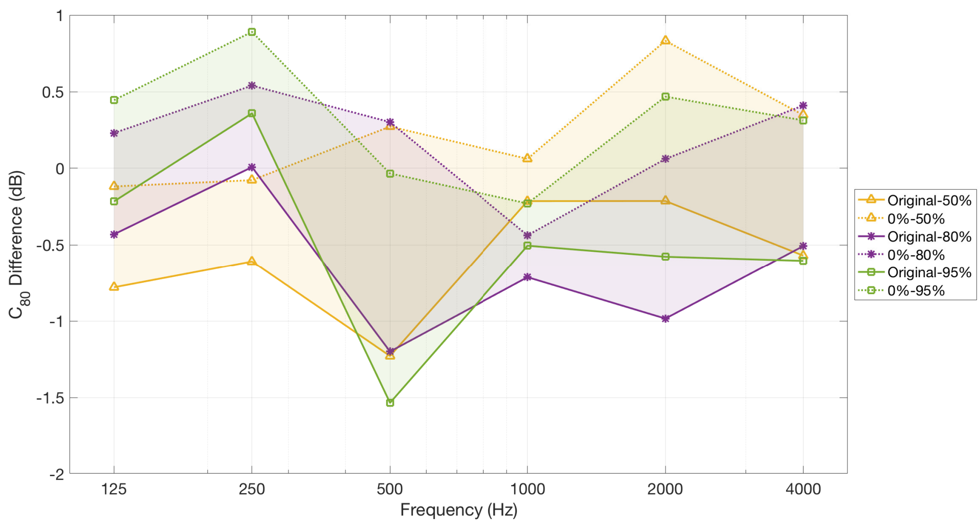


Figure 5.12: The difference between the original models and the simplified models for the Clarity parameter for the averaged receiver positions, Model 3.

5.1.2 Strength

5.1.2.1 Model 1

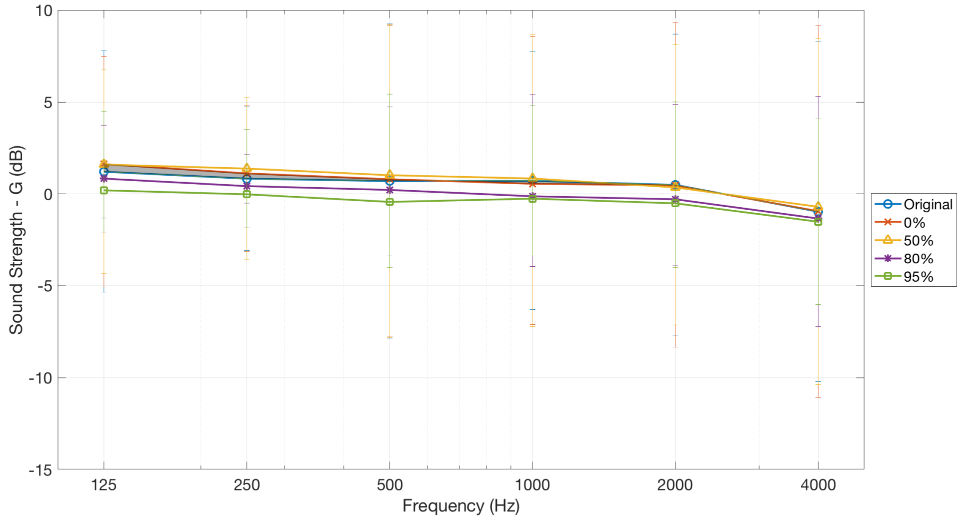


Figure 5.13: Sound Strength for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1. Variance included.

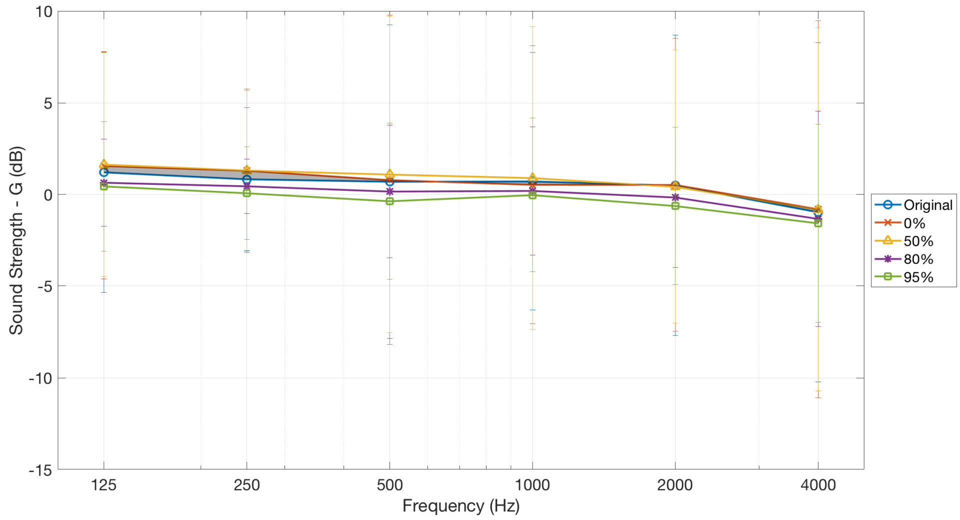


Figure 5.14: Sound Strength for the averaged receiver positions, using different absorption coefficients for all frequency bands, Model 1. Variance included.

Figures 5.15 and 5.16 show that as the model is simplified the strength parameter decreases, particularly at very high simplification, for both same and adjusted coefficients. However, it can be seen that the 50% lies above the unreduced models, by a small difference.

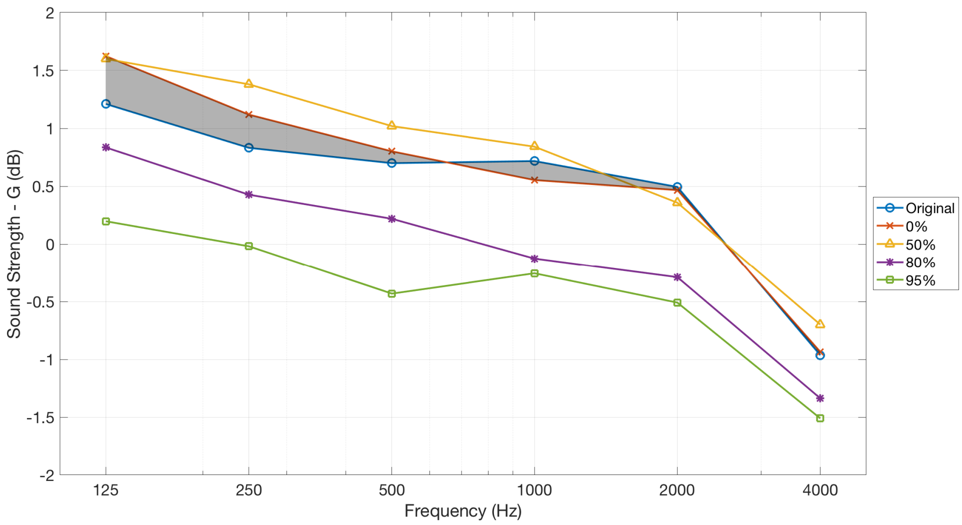


Figure 5.15: Sound Strength for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1.

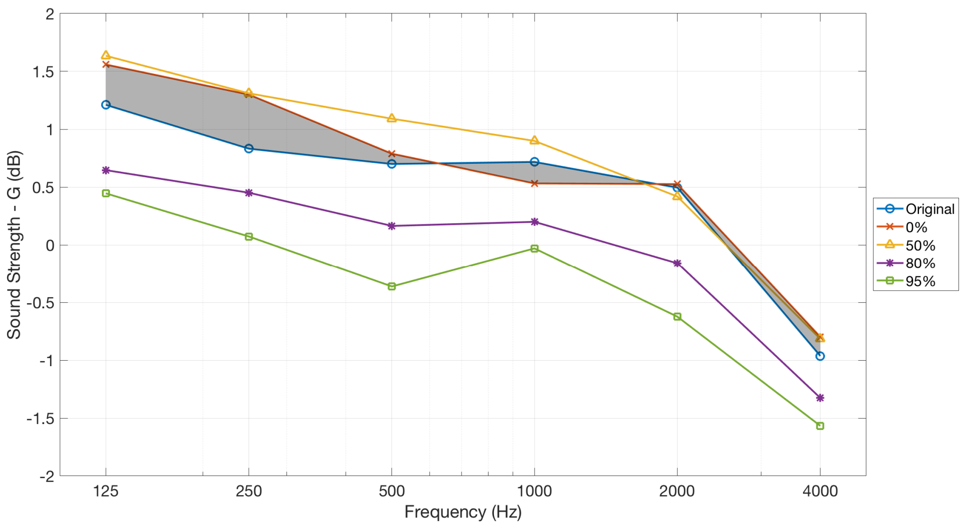


Figure 5.16: Sound Strength for the averaged receiver positions, using the adjusted absorption coefficients for all frequency bands, Model 1.

The sound strength differences can be seen in Figures 5.17 and 5.18, which show that the difference can vary between -0.5 dB and up to about 1.5 dB. For mid-frequencies it reaches about 1.6 dB range.

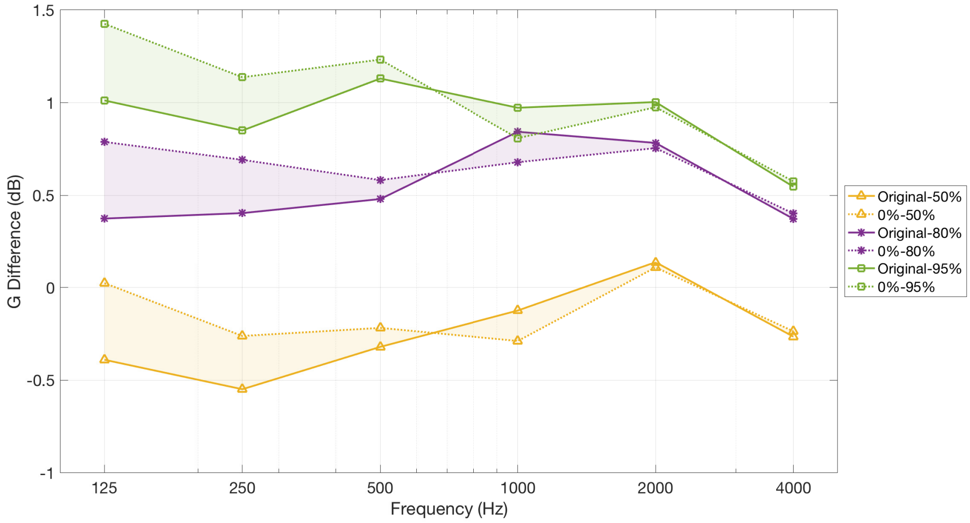


Figure 5.17: The difference between the original models and the simplified models for the Sound Strength parameter for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1.

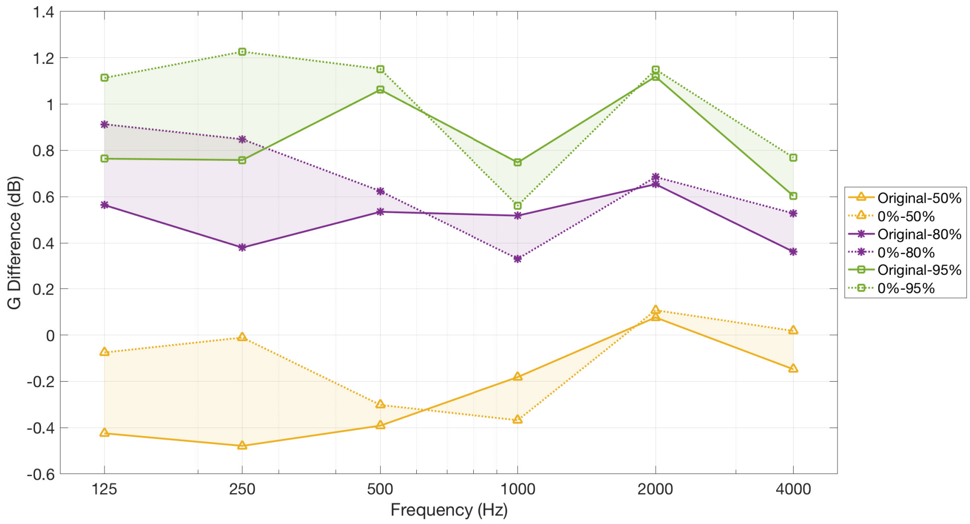


Figure 5.18: The difference between the original models and the simplified models for the Sound Strength parameter for the averaged receiver positions, using the adjusted absorption coefficients for all frequency bands, Model 1.

5.1.2.2 Model 2

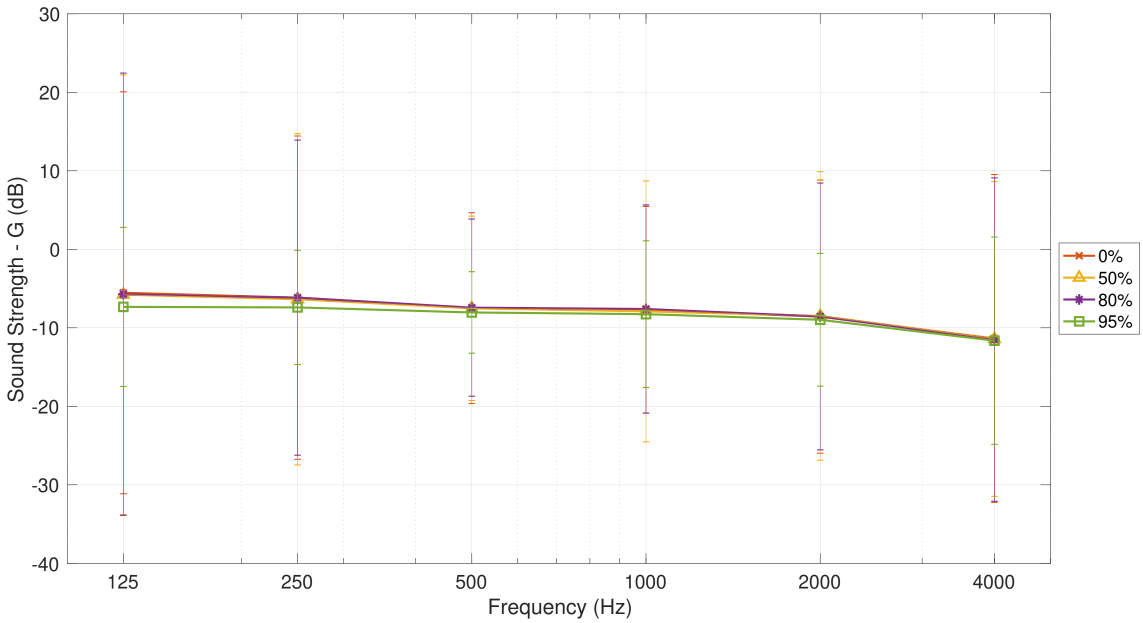


Figure 5.19: Sound Strength for the averaged receiver positions, Model 2. Variance included.

As seen with the clarity, the 95% model is the outlier in with the largest difference in values, with a difference of up to 1.8 dB. The other two iterations have a max difference of about 0.2 dB.

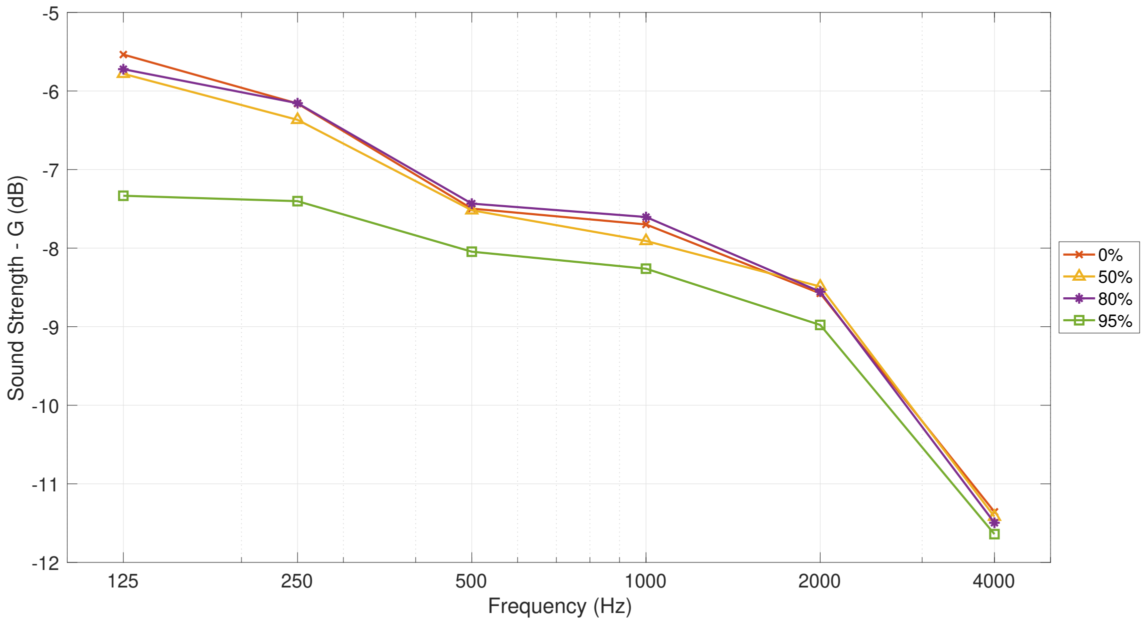


Figure 5.20: Sound Strength for the averaged receiver positions, Model 2.

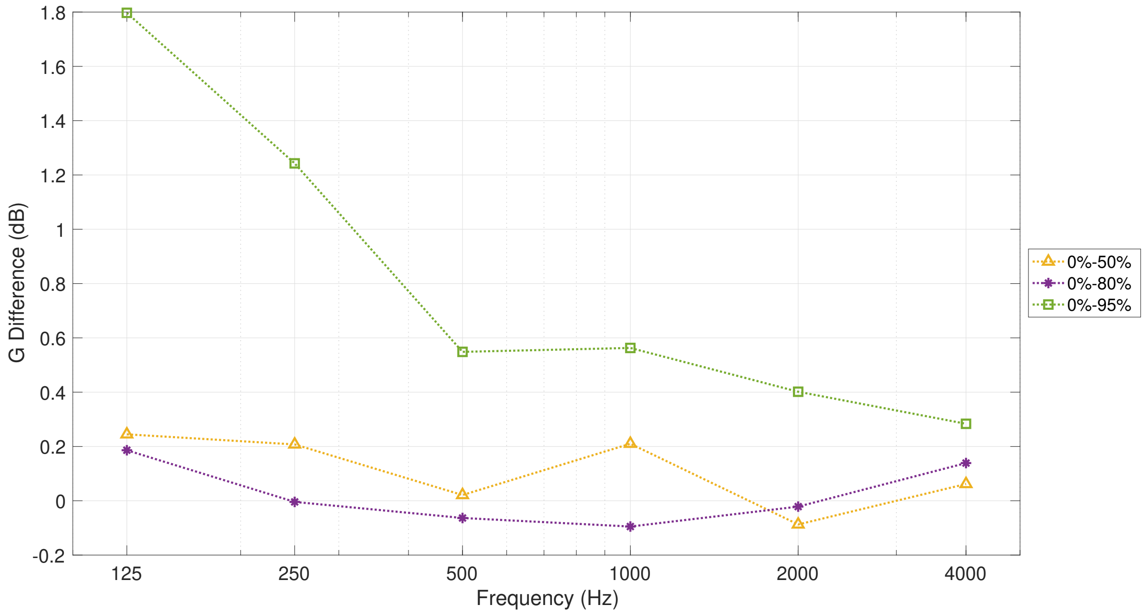


Figure 5.21: The difference between the original models and the simplified models for the Sound Strength parameter for the averaged receiver positions, Model 2.

5.1.2.3 Model 3

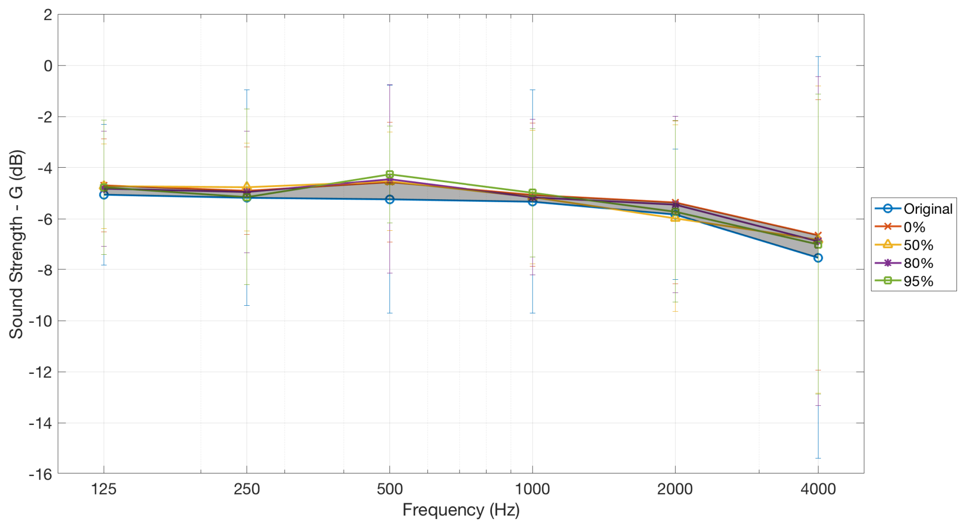


Figure 5.22: Sound Strength for the averaged receiver positions, Model 3. Variance included.

With Model 3, the same thing is seen as with clarity, where the original model and the 0% model create bounds where the results from the other iterations fall within. And, the models tend to follow the trend of the 0% more than the original. The largest difference is about 1 dB, though many of the octave bands fall within 0.4 dB difference.

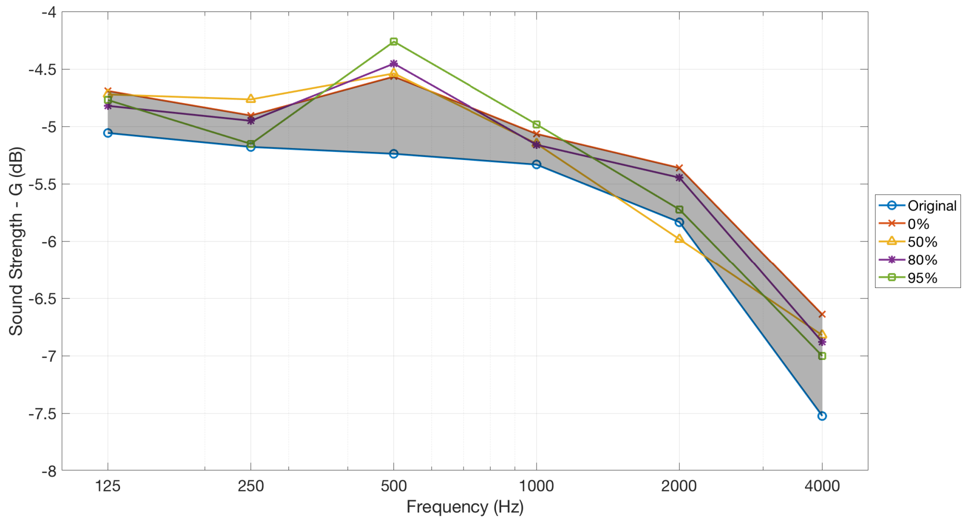


Figure 5.23: Sound Strength for the averaged receiver positions, Model 3.

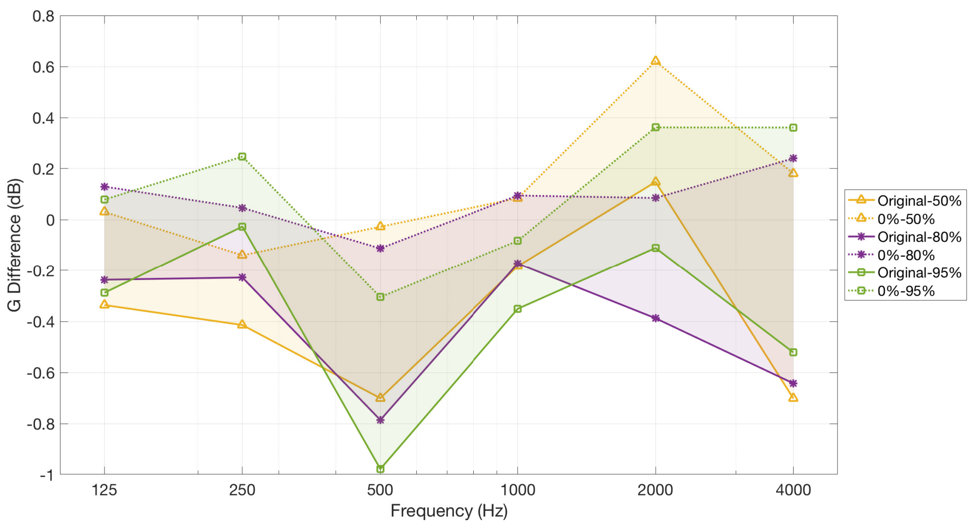


Figure 5.24: The difference between the original models and the simplified models for the Sound Strength parameter for the averaged receiver positions, Model 3.

5.1.3 Sound Pressure Level

5.1.3.1 Model 1

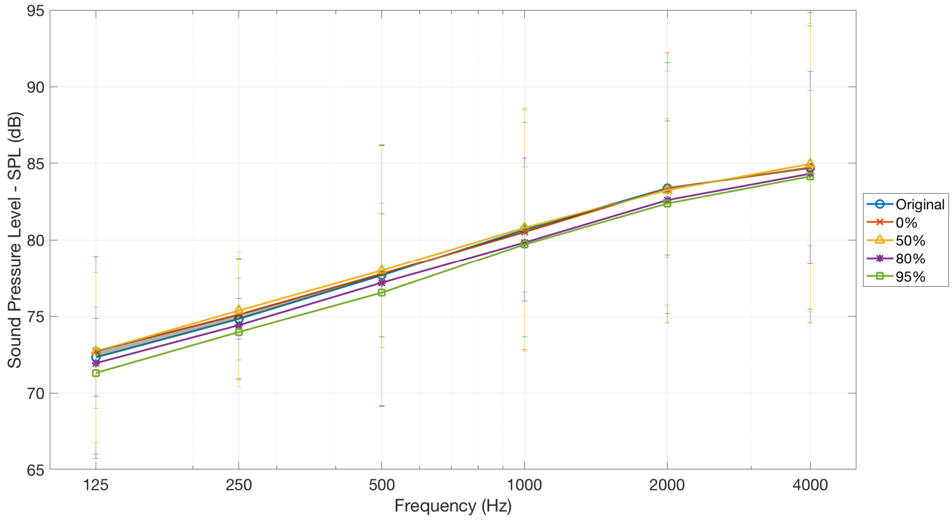


Figure 5.25: Sound Pressure Level for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1. Variance included.

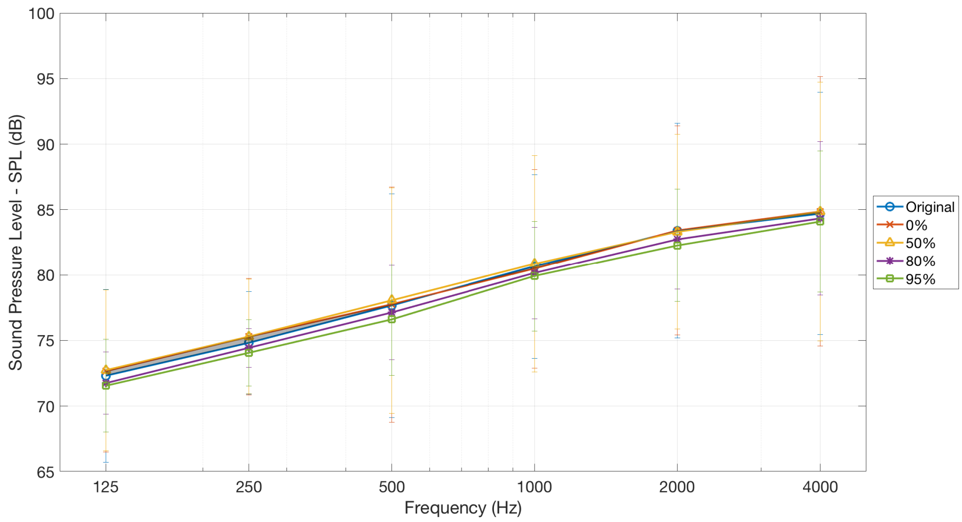


Figure 5.26: Sound Pressure Level for the averaged receiver positions, using different absorption coefficients for all frequency bands, Model 1. Variance included.

As with other parameters, the 80% and 95% models fall below the unreduced models for both same and adjusted coefficients.

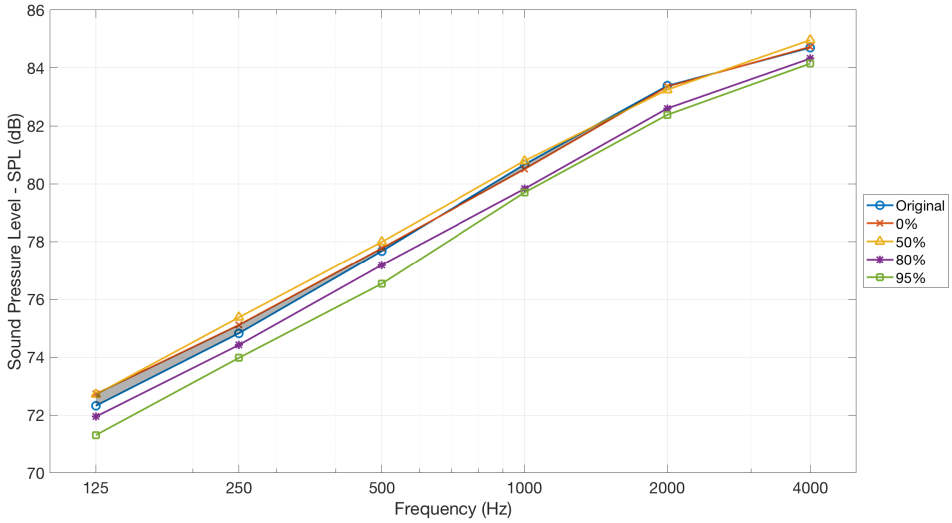


Figure 5.27: Sound Pressure Level for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1.

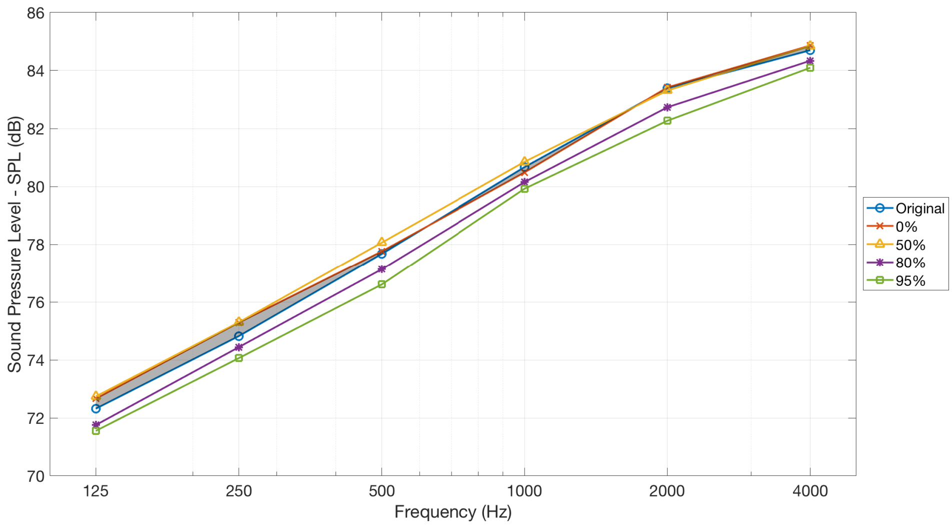


Figure 5.28: Sound Pressure Level for the averaged receiver positions, using the adjusted absorption coefficients for all frequency bands, Model 1.

The difference plots seen in Figures 5.29 and 5.30 show the decrease in difference for both 80% and 95% when the coefficients are adjusted. The range in the max values decreasing from 2 dB to about 1.6 dB. The 95% model has the largest difference over the frequency octave bands.

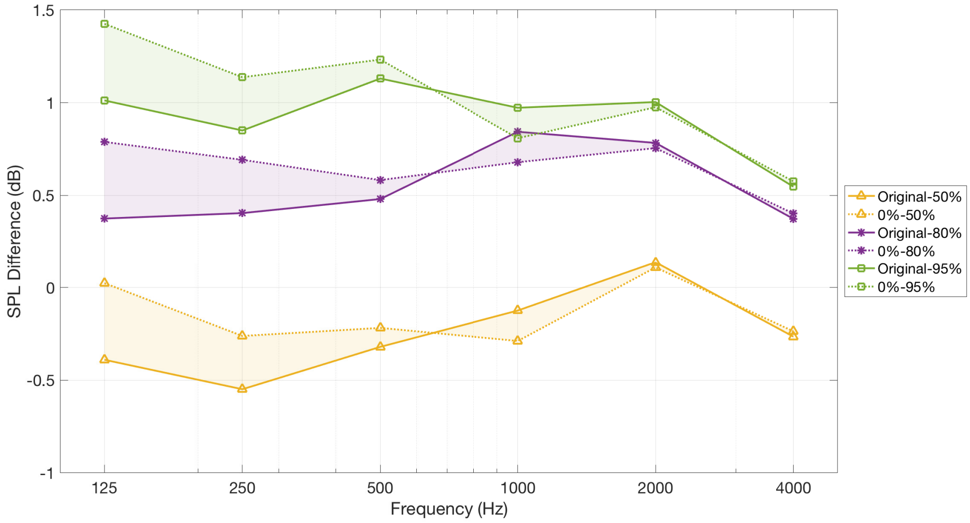


Figure 5.29: The difference between the original models and the simplified models for the Sound Pressure Level parameter for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1.

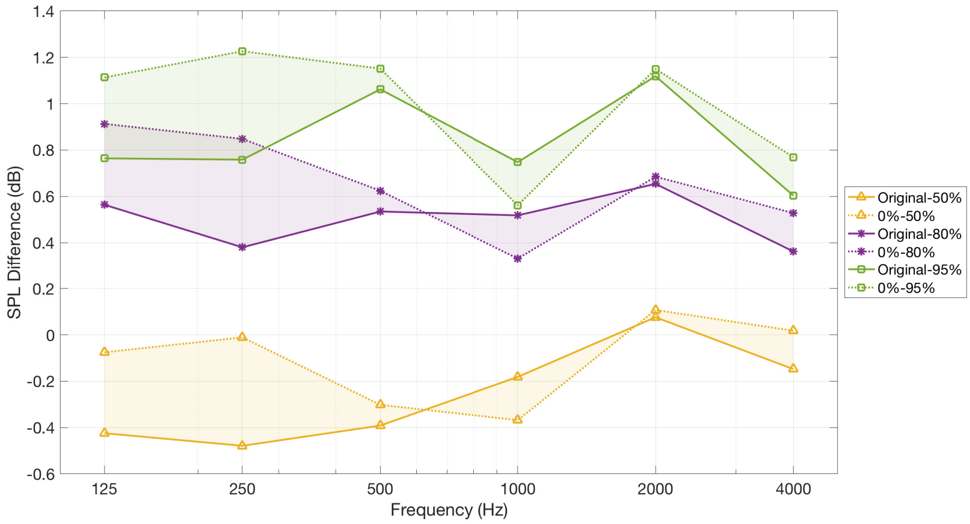


Figure 5.30: The difference between the original models and the simplified models for the Sound Pressure Level parameter for the averaged receiver positions, using the adjusted absorption coefficients for all frequency bands, Model 1.

5.1.3.2 Model 2

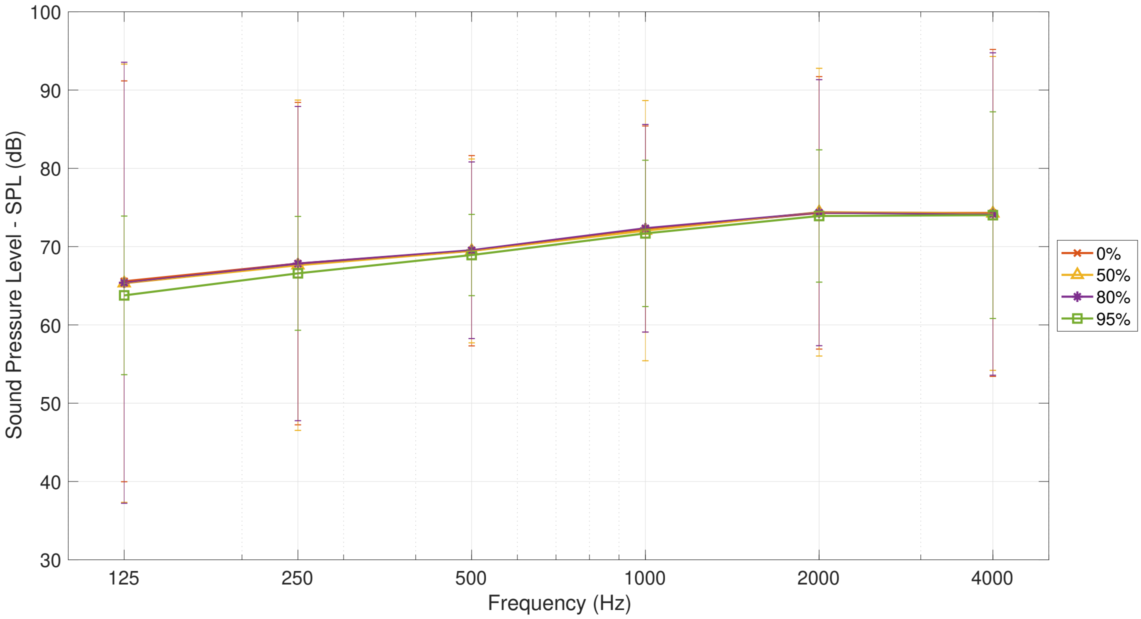


Figure 5.31: Sound Pressure Level for the averaged receiver positions, Model 2. Variance included.

Following the strength, similar results are seen in the sound pressure level results, with the largest difference being 1.8 dB and that is for the 95% model. The other simplifications are at most about 0.2 dB.

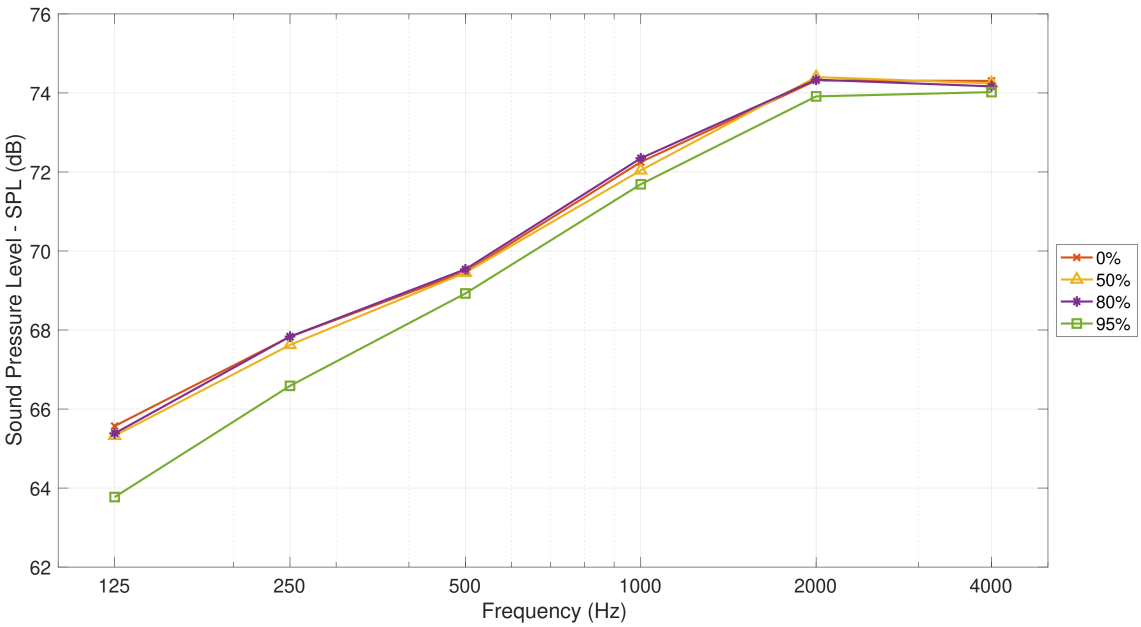


Figure 5.32: Sound Pressure Level for the averaged receiver positions, Model 2.

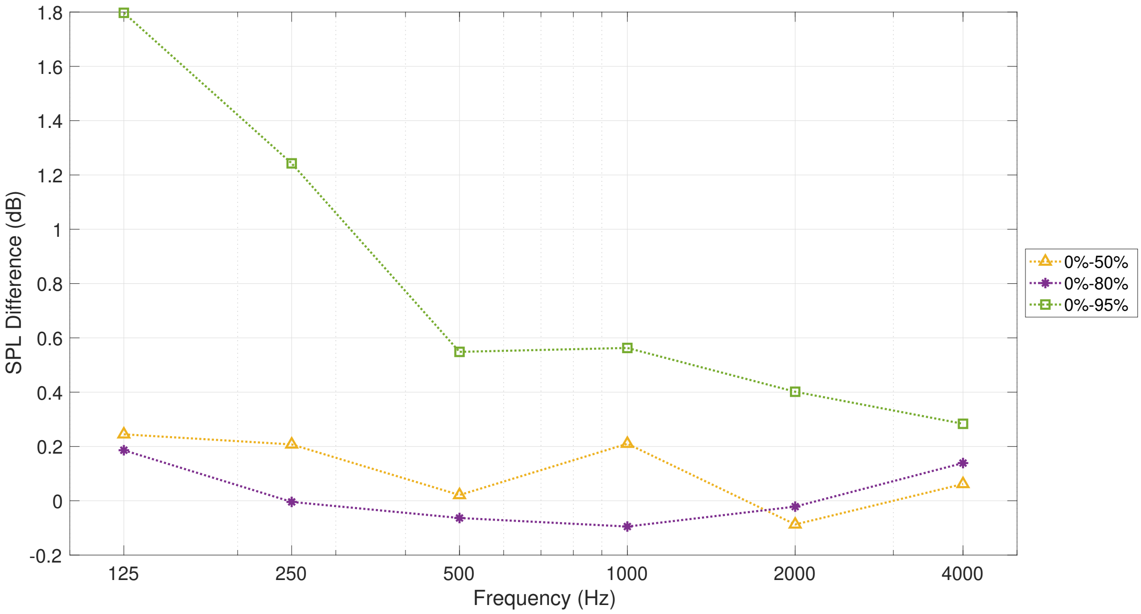


Figure 5.33: The difference between the original models and the simplified models for the Sound Pressure Level parameter for the averaged receiver positions, Model 2.

5.1.3.3 Model 3

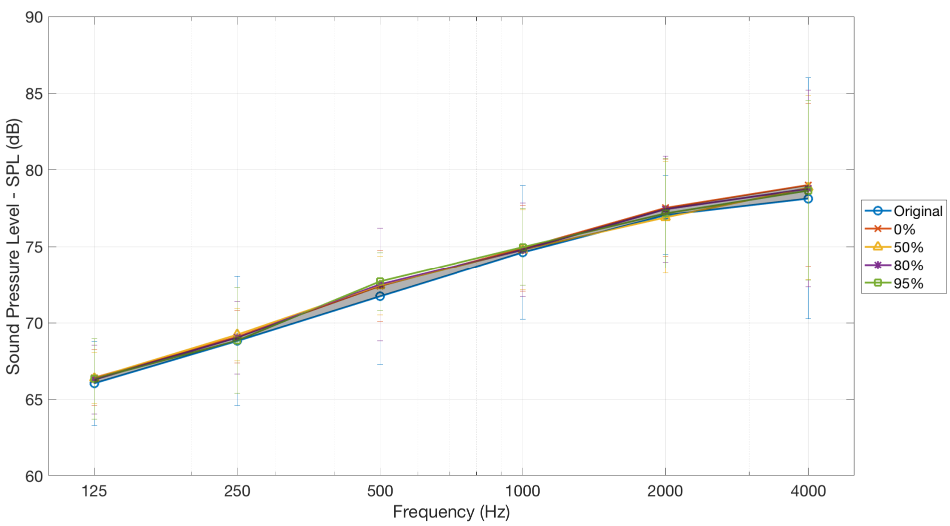


Figure 5.34: Sound Pressure Level for the averaged receiver positions, Model 3. Variance included.

And, not many differences for Model 3, with the largest difference being about 1 dB. The 50% and 80% model show close similarity to the unsimplified models.

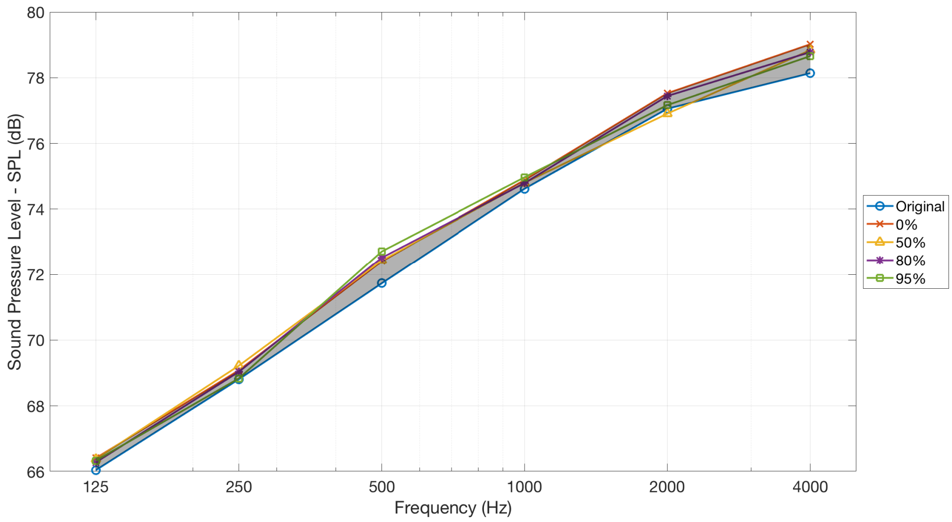


Figure 5.35: Sound Pressure Level for the averaged receiver positions, Model 3.

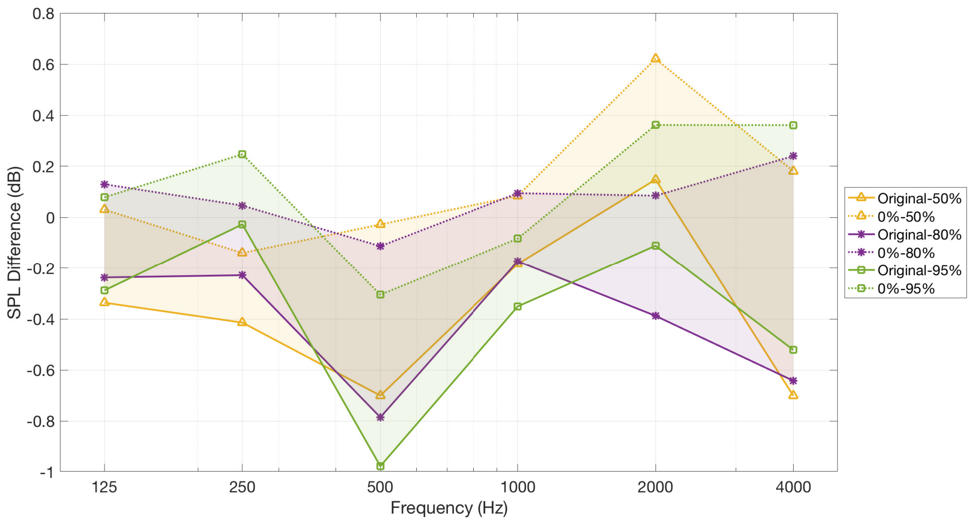


Figure 5.36: The difference between the original models and the simplified models for the Sound Pressure Level parameter for the averaged receiver positions, Model 3.

5.1.4 Speech Transmission Index

5.1.4.1 Model 1

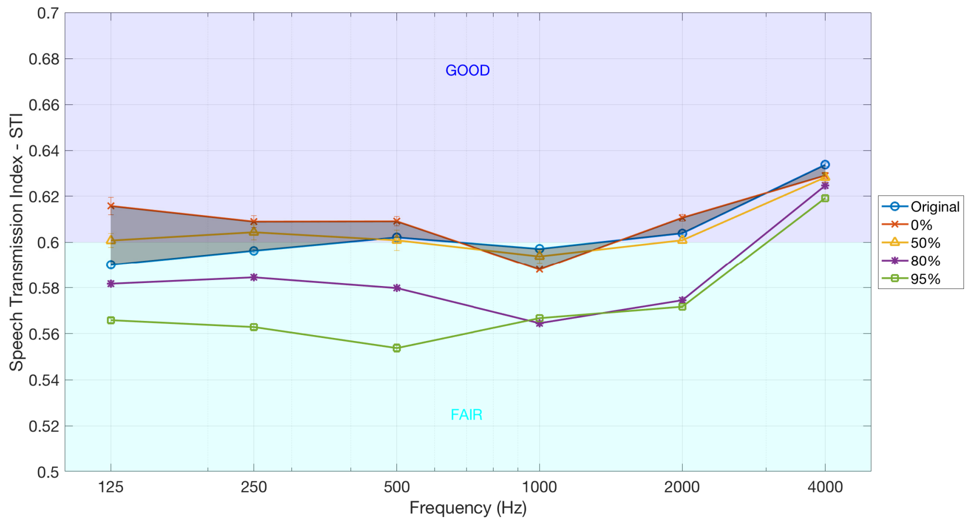


Figure 5.37: Zoomed in version of the Speech Transmission Index for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1. Variance included.

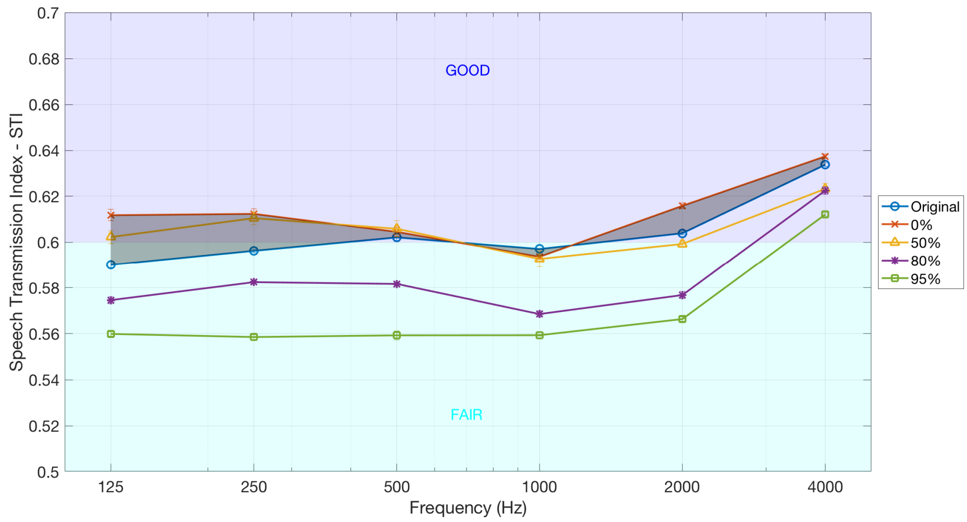


Figure 5.38: Zoomed in version of the Speech Transmission Index for the averaged receiver positions, using different absorption coefficients for all frequency bands, Model 1. Variance included.

Figures 5.39 and 5.40 show the results over the full range of STI in order to help illustrate the ranges that are dealt with. As seen, with a small shift, the curves could move from one category to another. The zoomed in plots have been included as well to help with the analysis. These zoomed in graphs are Figure 5.41 and Figure 5.42. As well, for all the results no background noise was used.

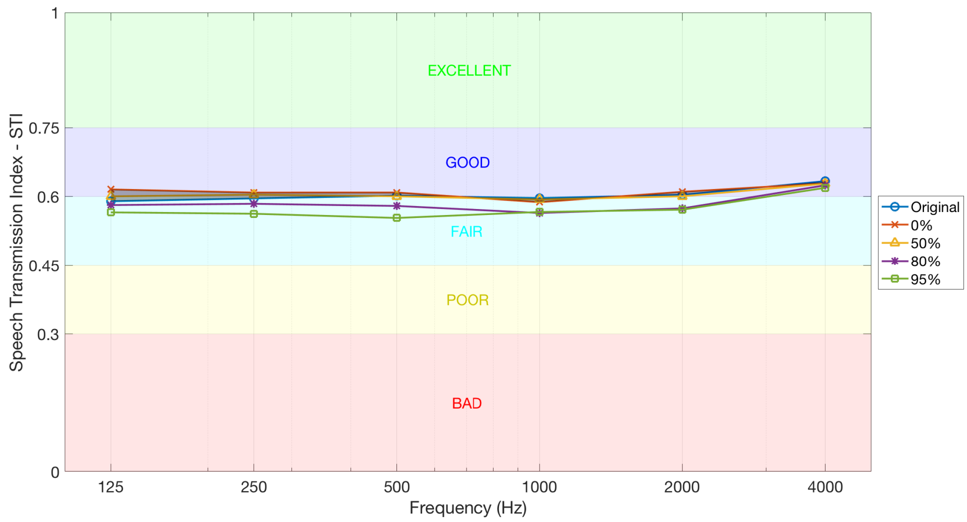


Figure 5.39: Speech Transmission Index for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1.

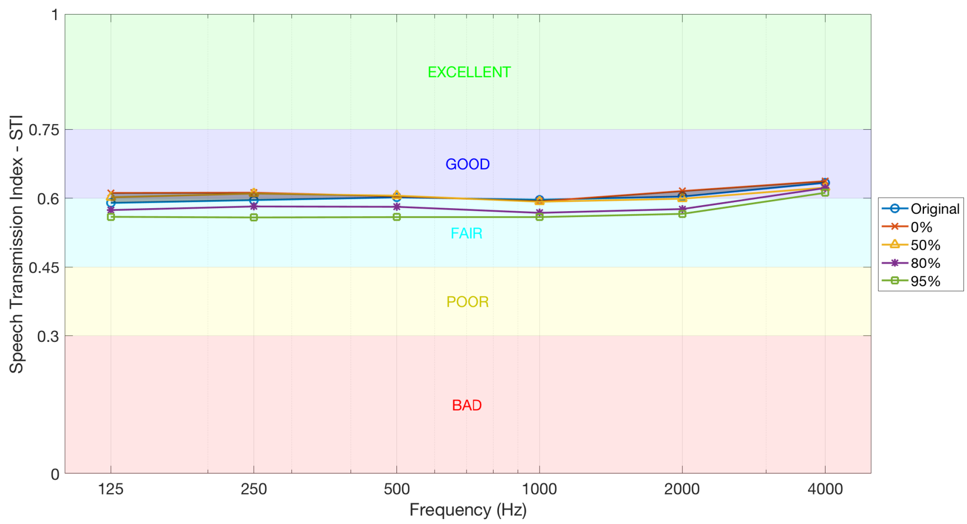


Figure 5.40: Speech Transmission Index for the averaged receiver positions, using the adjusted absorption coefficients for all frequency bands, Model 1.

In the two zoomed in graphs, the three simplified models show similar trends of 50% the most similar to the unsimplified, and then moving away as the model is more simplified. The shaded area between the two original plots is about the same for the same and adjusted coefficients.

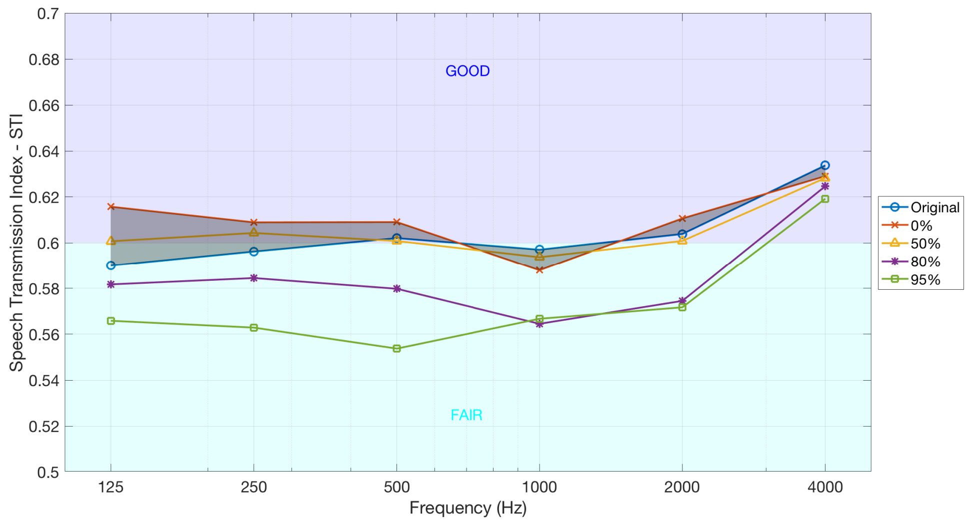


Figure 5.41: Zoomed in version of the Speech Transmission Index for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1.

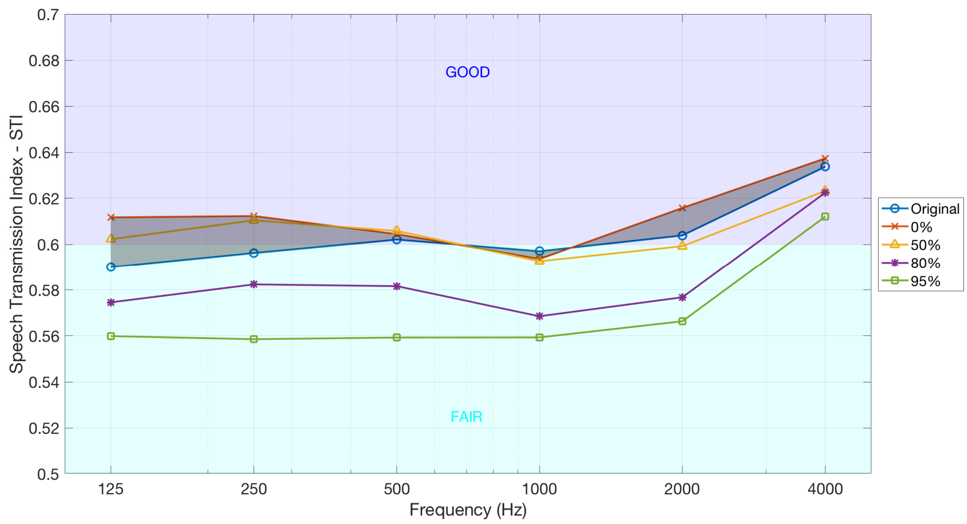


Figure 5.42: Zoomed in version of the Speech Transmission Index for the averaged receiver positions, using the adjusted absorption coefficients for all frequency bands, Model 1.

In the difference graphs, Figures 5.43 and 5.44, the area between the graphs again are similar, and only show a small variation in the pattern of the graph. The max deviation reached for both is about 0.055.

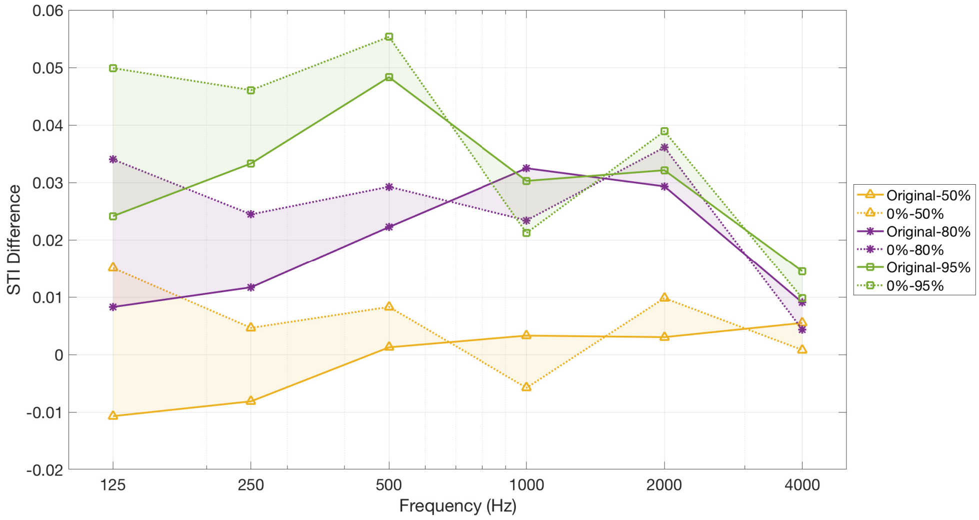


Figure 5.43: The difference between the original models and the simplified models for the Speech Transmission Index parameter for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1.

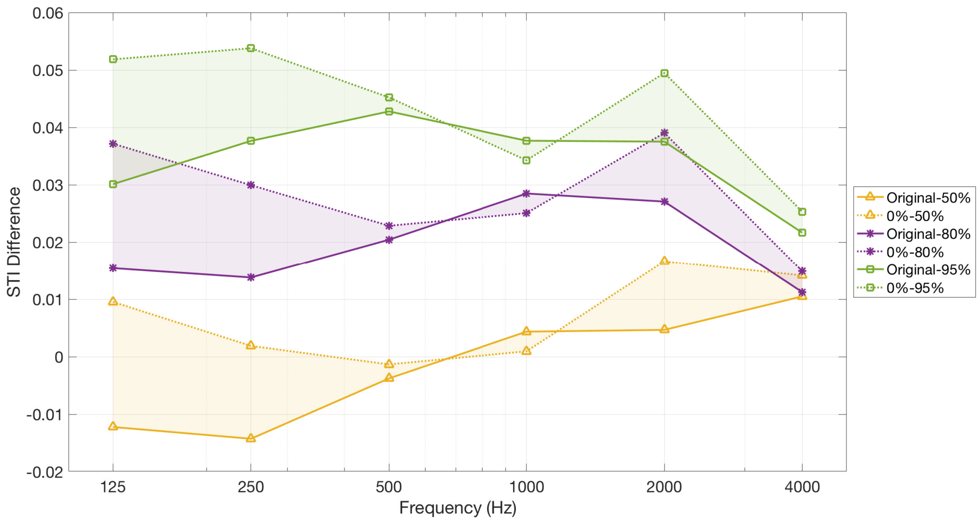


Figure 5.44: The difference between the original models and the simplified models for the Speech Transmission Index parameter for the averaged receiver positions, using the adjusted absorption coefficients for all frequency bands, Model 1.

5.1.4.2 Model 2

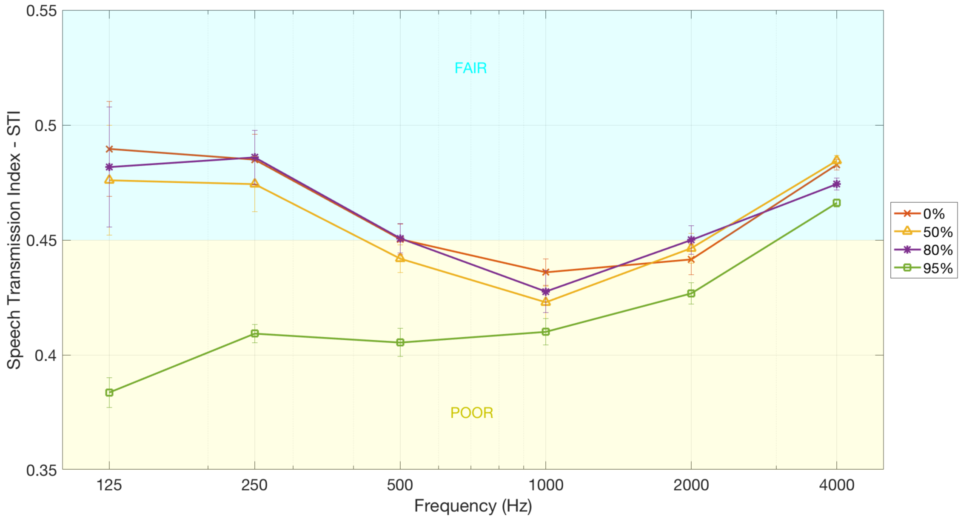


Figure 5.45: Zoomed in version of the Speech Transmission Index for the averaged receiver positions, Model 2. Variance included.

As seen in Figures 5.46, 5.47, and 5.48 the 80% iteration is the closest to the 0% model, followed by 50%, then with 95% having the biggest difference. The max difference is about 0.105.

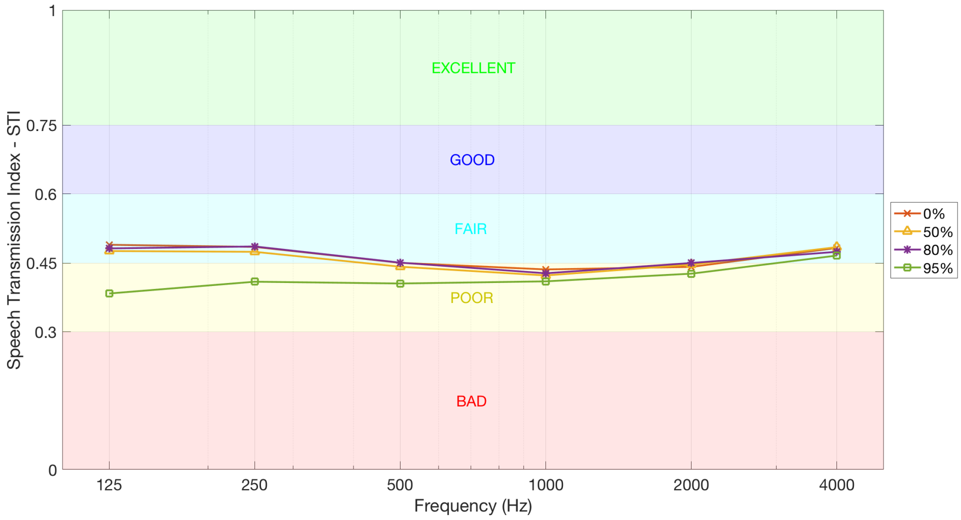


Figure 5.46: Speech Transmission Index for the averaged receiver positions, Model 2.

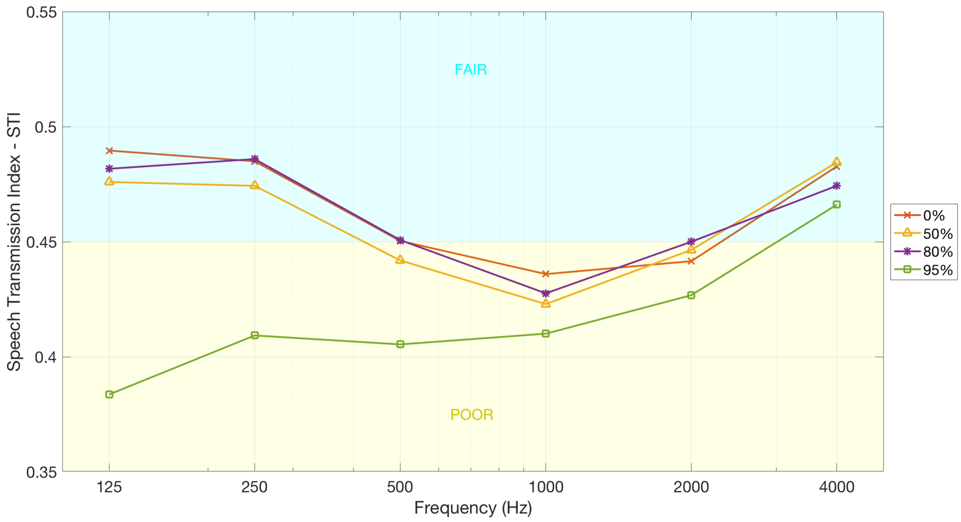


Figure 5.47: Zoomed in version of the Speech Transmission Index for the averaged receiver positions, Model 2.

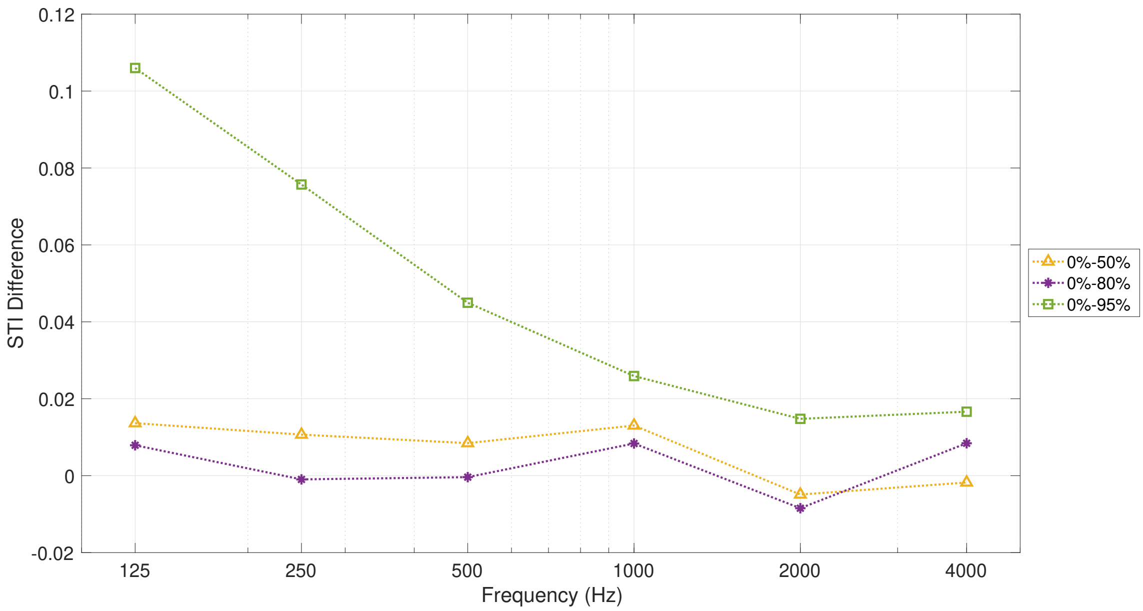


Figure 5.48: The difference between the original models and the simplified models for the Speech Transmission Index parameter for the averaged receiver positions, Model 2.

5.1.4.3 Model 3

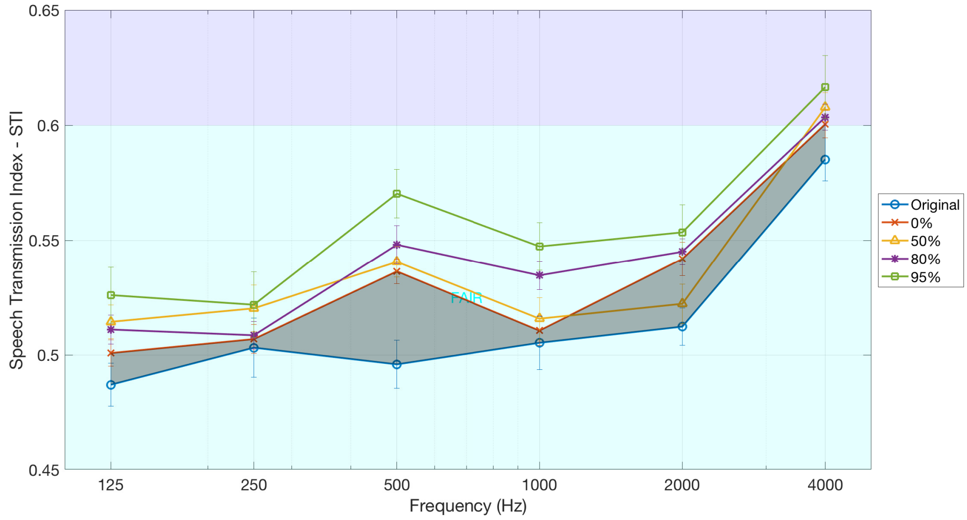


Figure 5.49: Zoomed in version of the Speech Transmission Index for the averaged receiver positions, Model 3. Variance included.

For the third model, Figures 5.50, 5.51, and 5.52 the closest are the 50% and the 80%, depending on the frequency, and they are close to the 0% model. The biggest difference is the 95% iteration with a difference of 0.075.

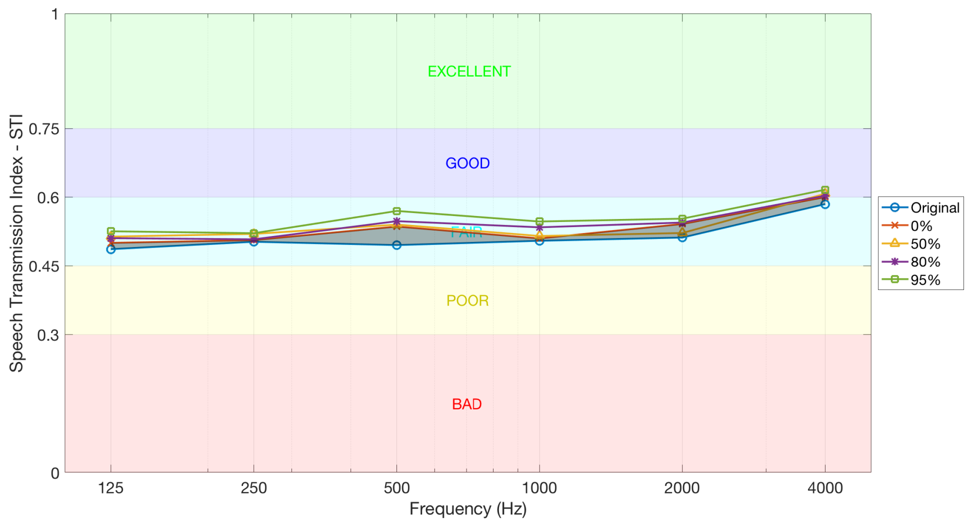


Figure 5.50: Speech Transmission Index for the averaged receiver positions, Model 3.

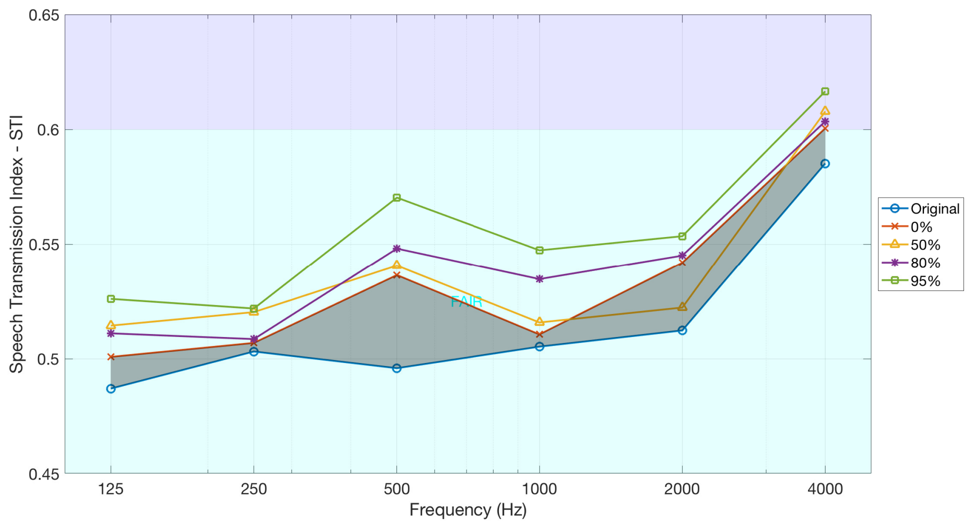


Figure 5.51: Zoomed in version of the Speech Transmission Index for the averaged receiver positions, Model 3.

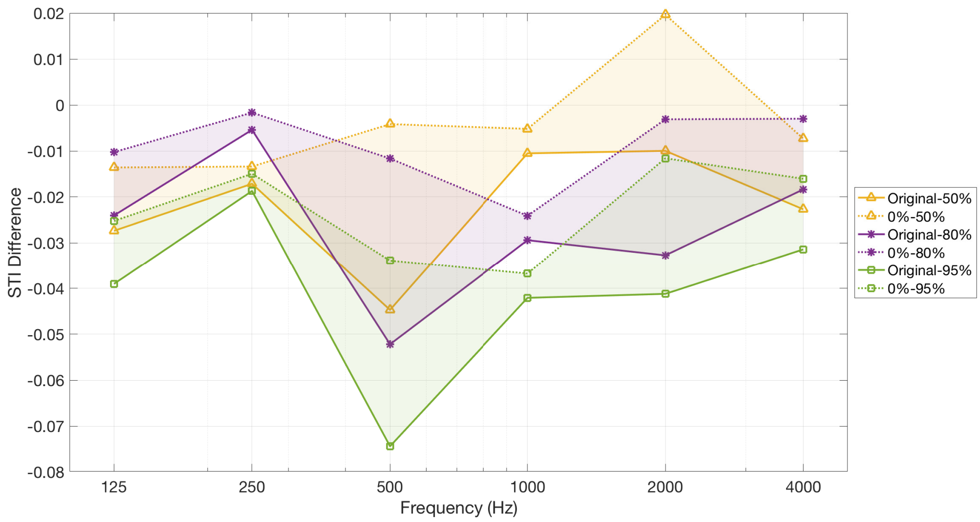


Figure 5.52: The difference between the original models and the simplified models for the Speech Transmission Index parameter for the averaged receiver positions, Model 3.

5.1.5 Reverberation Time

5.1.5.1 Model 1

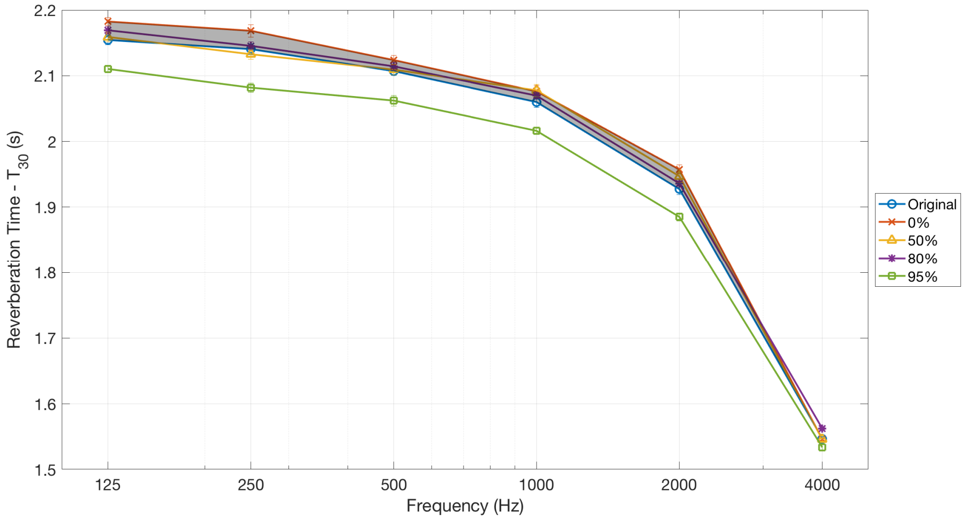


Figure 5.53: Reverberation Time for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1. Variance included.

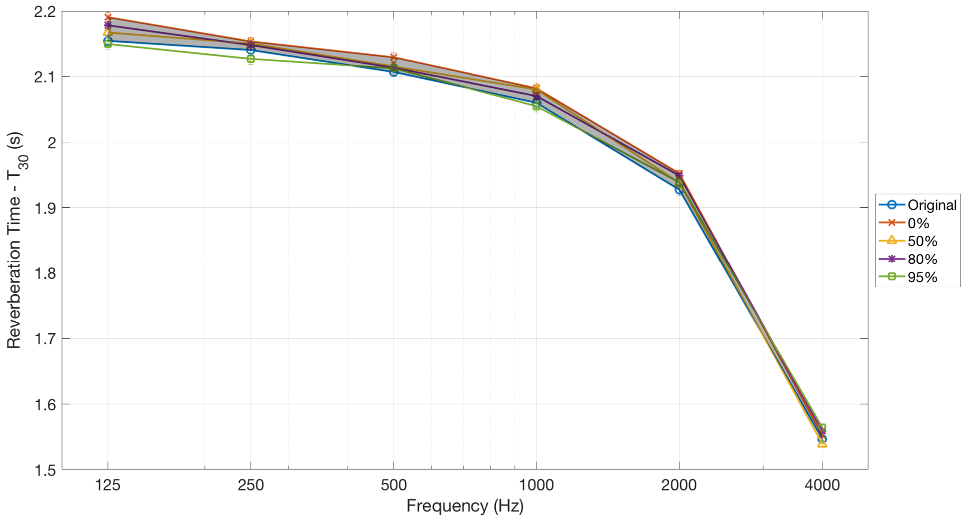


Figure 5.54: Reverberation Time for the averaged receiver positions, using different absorption coefficients for all frequency bands, Model 1. Variance included.

In comparing Figures 5.55 and 5.56 there is a noticeable difference with the change in absorption coefficients, particularly for the 95% reduced model. Which can be further seen in the difference graphs.

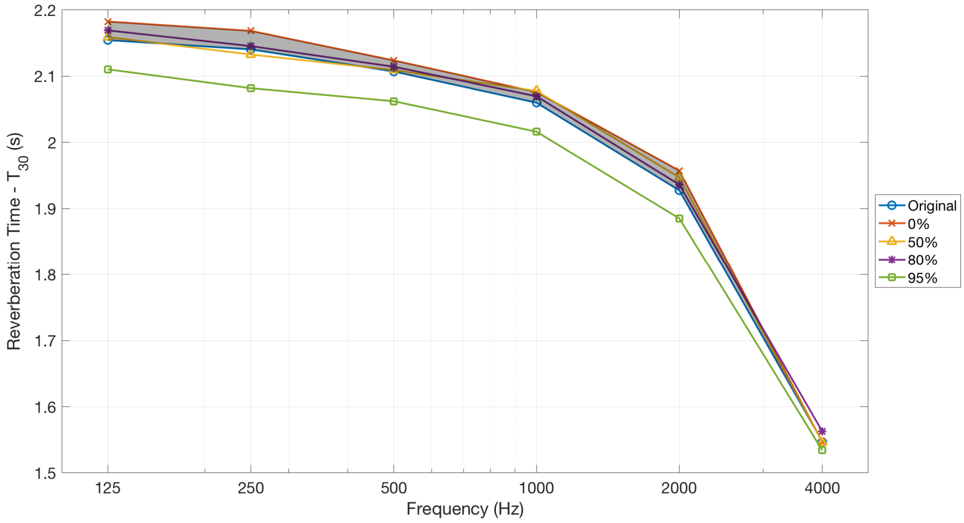


Figure 5.55: Reverberation Time for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1.

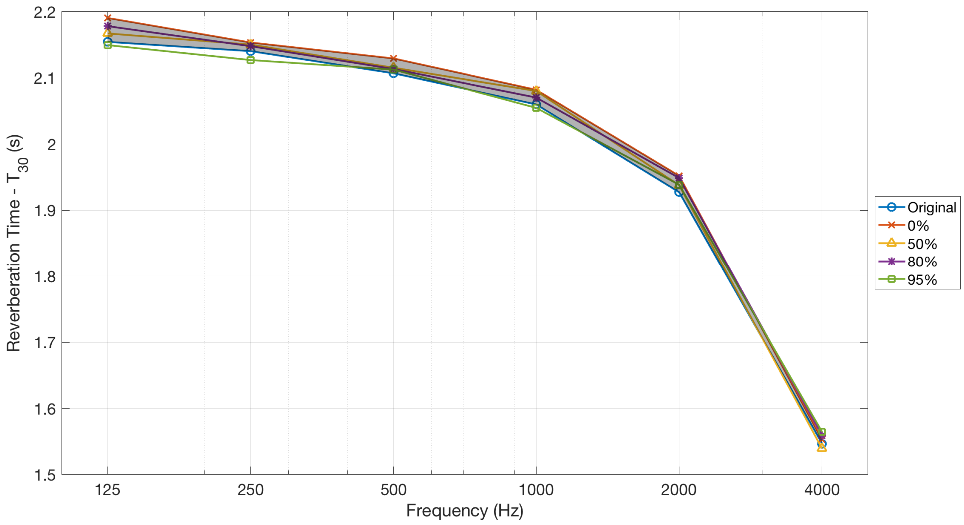


Figure 5.56: Reverberation Time for the averaged receiver positions, using the adjusted absorption coefficients for all frequency bands, Model 1.

The range of values that the reverberation time varies between is more than halved, with the range going from 0.1 s to about 0.065 s. The change is mostly due to the reduction in the 95% model, with the max difference decreasing from about 0.085 s to 0.04 s. However, the difference range between the difference from the unreduced models does actually increase for the 125 Hz band.

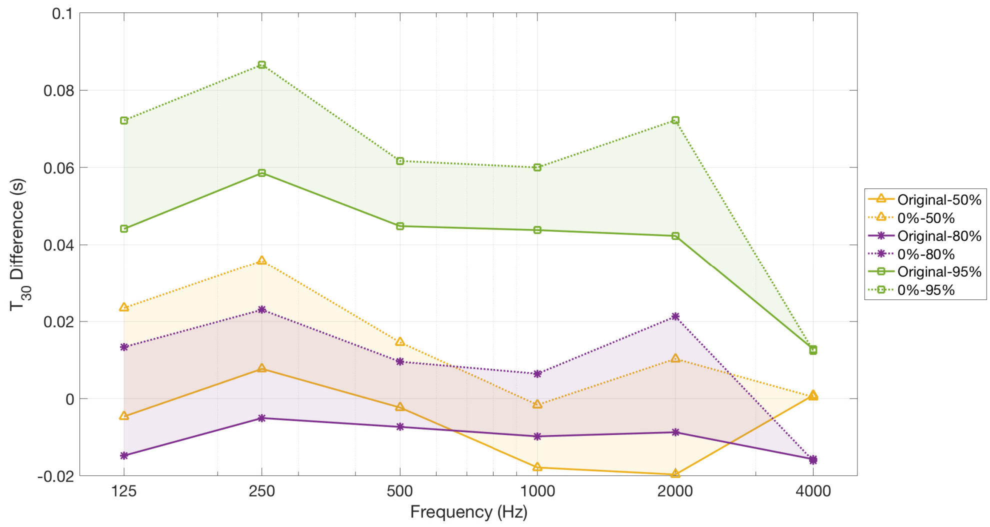


Figure 5.57: The difference between the original models and the simplified models for the Reverberation Time parameter for the averaged receiver positions, using the same absorption coefficients for all frequency bands, Model 1.

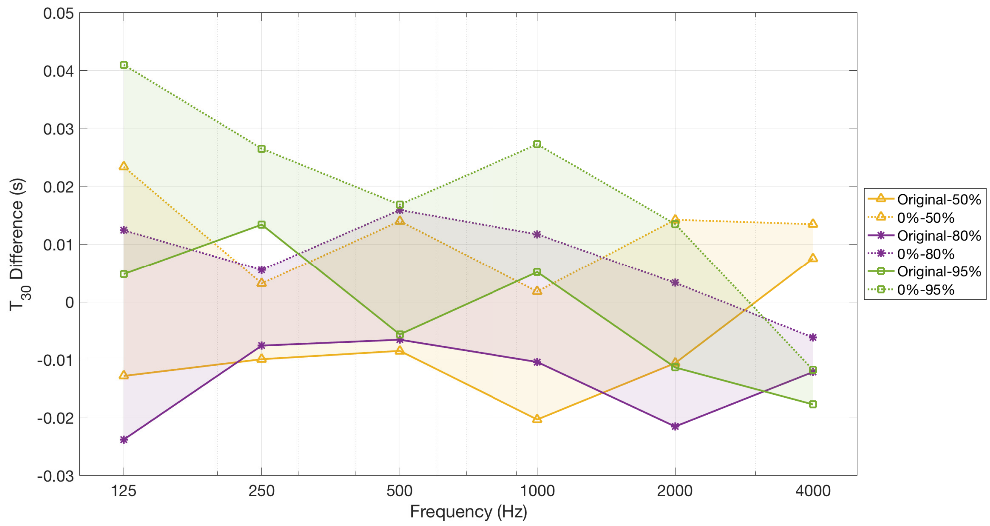


Figure 5.58: The difference between the original models and the simplified models for the Reverberation Time parameter for the averaged receiver positions, using the adjusted absorption coefficients for all frequency bands, Model 1.

5.1.5.2 Model 2

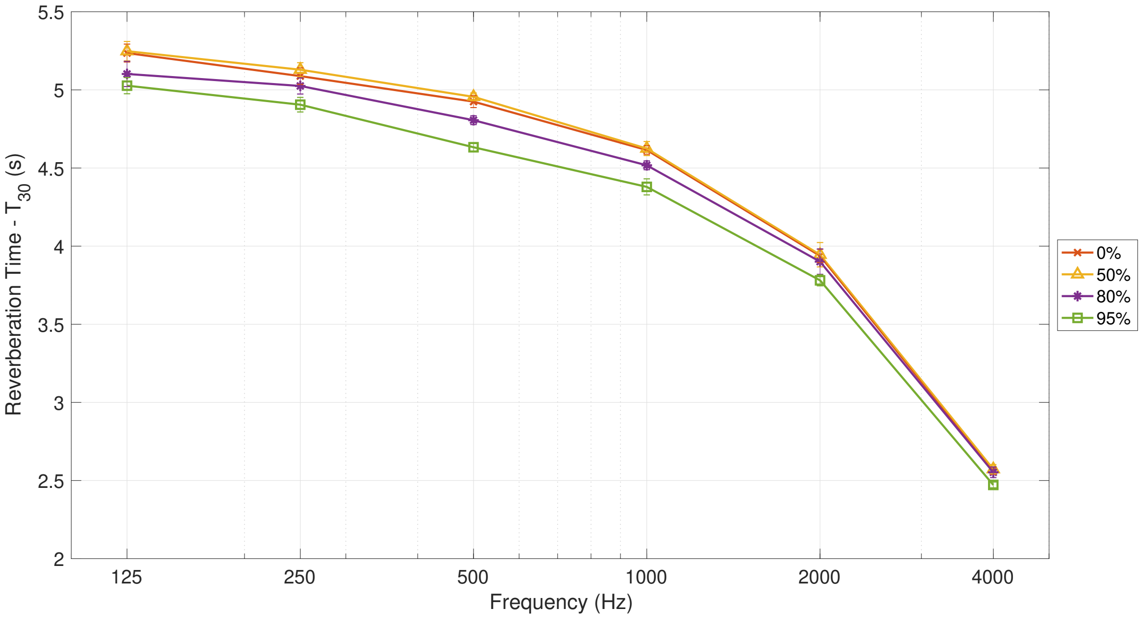


Figure 5.59: Reverberation Time for the averaged receiver positions, Model 2. Variance included.

In Figures 5.60 and 5.61 show that as Model 2 is simplified the difference from the unsimplified increases. The difference for 50% is max 0.05 s, where as the max for 95% is 0.3 s.

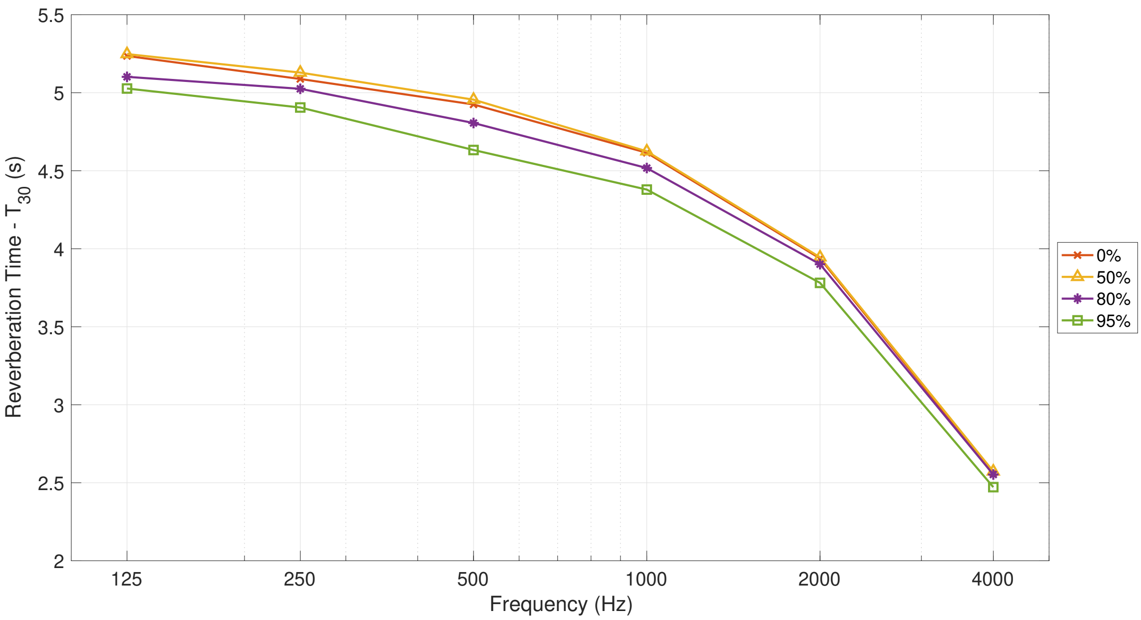


Figure 5.60: Reverberation Time for the averaged receiver positions, Model 2.

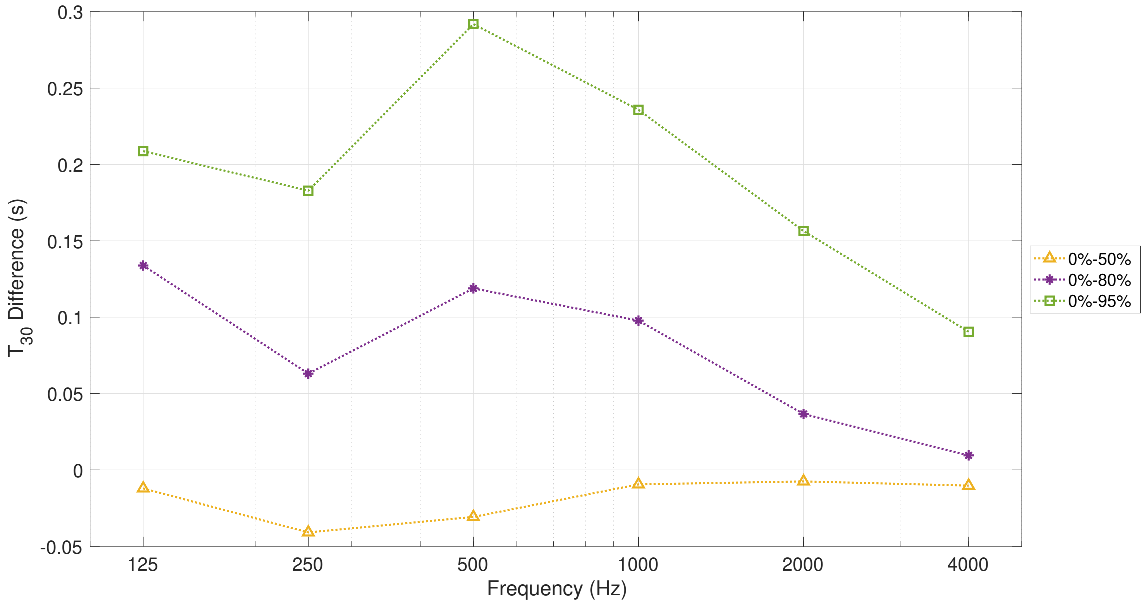


Figure 5.61: The difference between the original models and the simplified models for the Reverberation Time parameter for the averaged receiver positions, Model 2.

5.1.5.3 Model 3

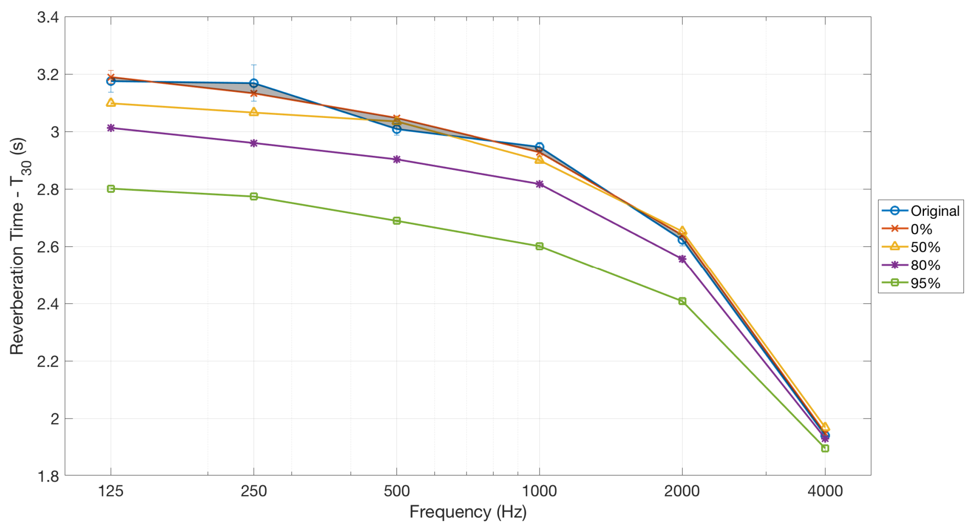


Figure 5.62: Reverberation Time for the averaged receiver positions, Model 3. Variance included.

Figures 5.63 and 5.64 show the same as Model 2, where the more simplified the larger the difference. Also, there is not a noticeable difference between the results compared to the original and 0%. The 95% has a difference of up to 0.4 s.

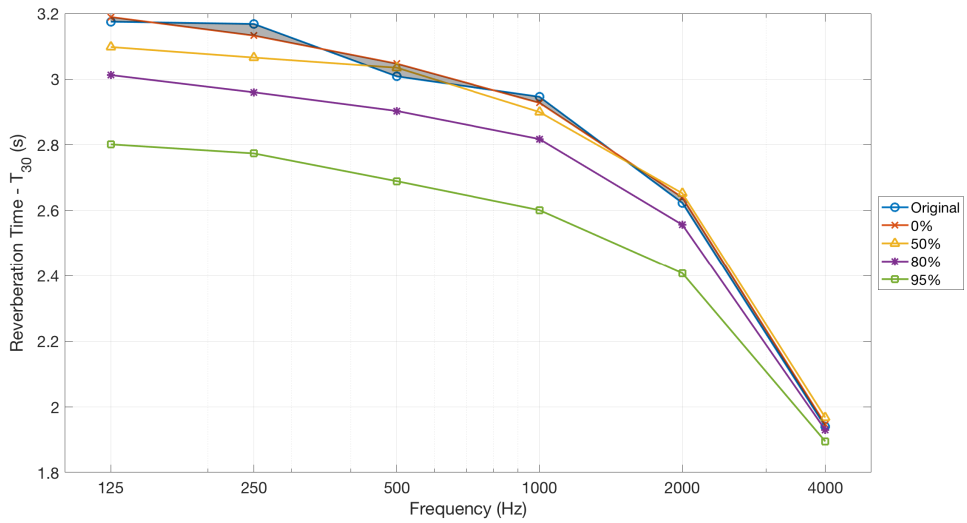


Figure 5.63: Reverberation Time for the averaged receiver positions, Model 3.

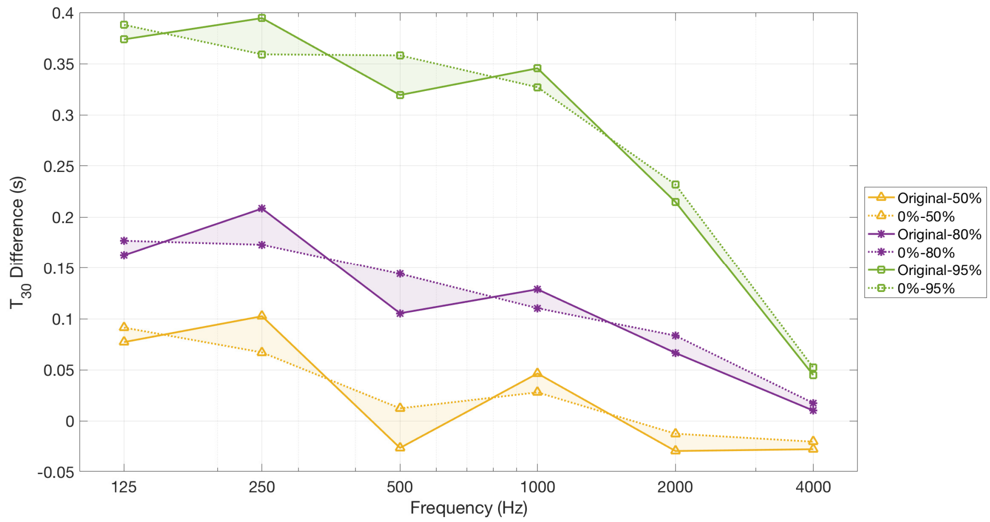


Figure 5.64: The difference between the original models and the simplified models for the Reverberation Time parameter for the averaged receiver positions, Model 3.

5.2 Maps

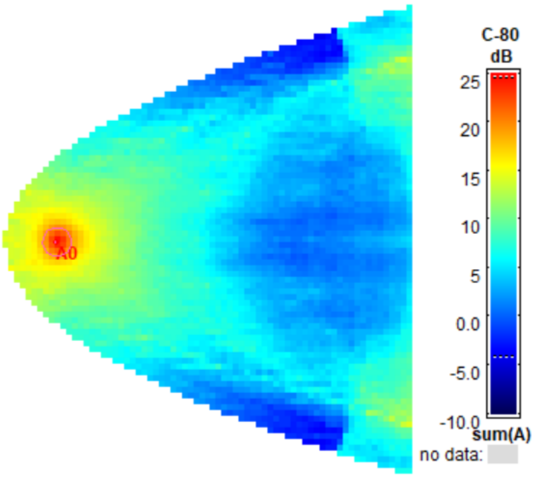
At each step along the audience map the parameters are calculated and presented on the visual map. The values of the step size (resolution) and height at which the audience is placed above the plane can be found in Tables 4.1, 4.5, and 4.9. The source is in the same position as it was for the source to receiver measurements, seen in Figures 4.1, 4.2, and 4.3. The maps are used to see the patterns in the parameter distribution through the space, and analyse how the pattern changes as the models are reduced.

Only the maps from the models with the adjusted coefficients are presented as the results from the source to receiver analysis showed that the parameters from the adjusted coefficients were more closely related. The maps analysis also uses only a low scattering coefficients, the ones that are set as the default, which means there is not a very high diffusivity in the space due to scattering. Therefore the maps show the scenarios of very minimal diffusivity, the worst case scenario. Since the strength is the ratio of the sound pressure level, these maps are not included in the analysis as they will be very similar to the sound pressure level.

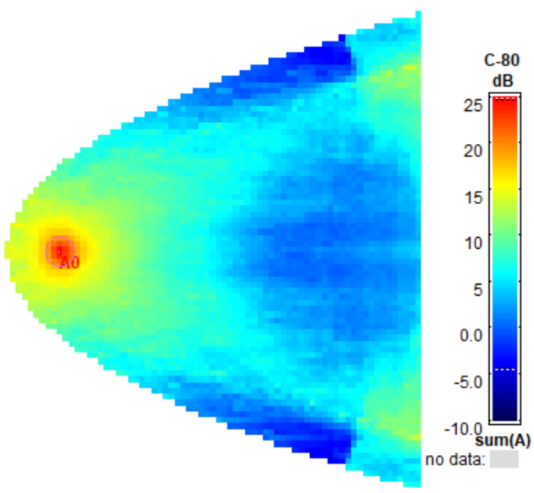
5.2.1 Clarity

5.2.1.1 Model 1

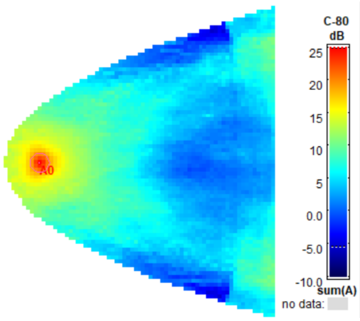
As seen in Figure 5.65 the original model and the 0% model are nearly identical in pattern over the map. Even 50% is very similar, though some of the symmetry begins to fade. Then as the models start simplifying further they become altered and less like the originals, with values changing by up to 5 dB near the walls.



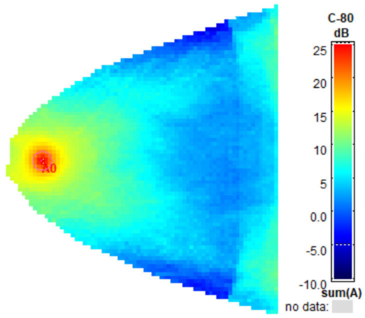
(a) Original



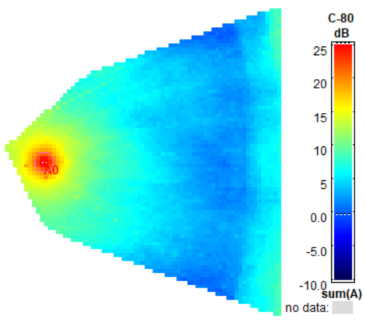
(b) 0%



(c) 50%



(d) 80%

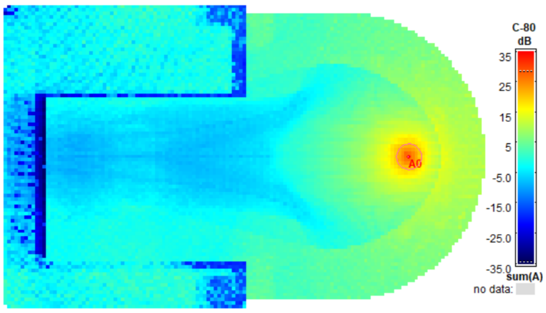


(e) 95%

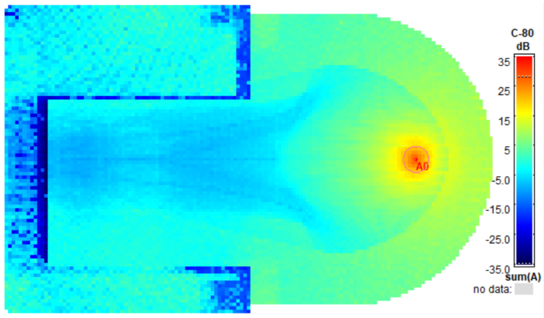
Figure 5.65: The Clarity audience maps of the five adjusted models for Model 1.

5.2.1.2 Model 2

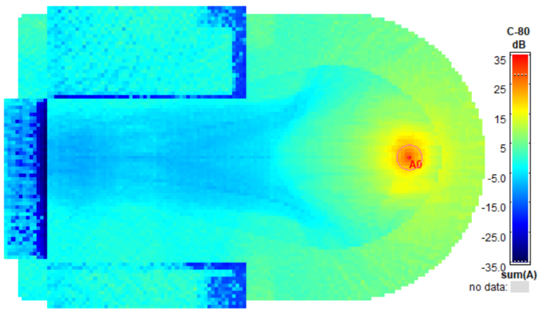
The 50% iteration is nearly identical in the map pattern compared to the 0% model, particularly the result caused by the curved wall. The 80% model is near identical except for the patch of higher clarity near the source which is not present in the other models. And, of course the 80% and 95% models lost the detail in the balcony due to the reduction.



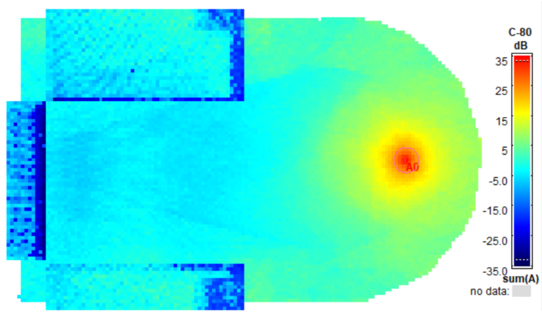
(a) 0%



(b) 50%



(c) 80%

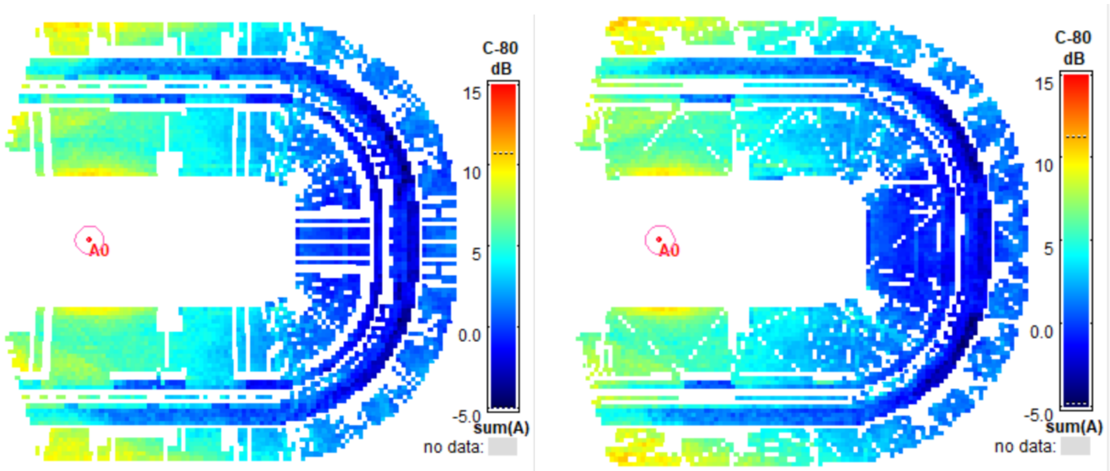


(d) 95%

Figure 5.66: The Clarity audience maps of the four models for Model 2.

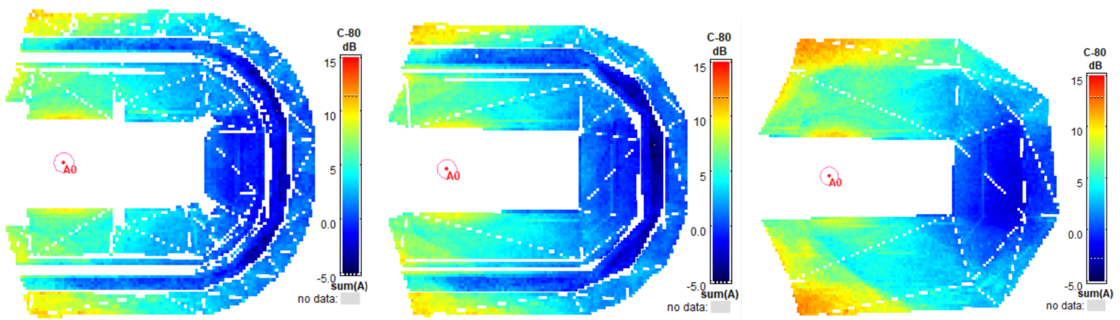
5.2.1.3 Model 3

The first four models are quite similar in the results, however compared to the original, 0%, 50%, and 80% have slightly higher clarity in the corners with a slightly larger spread. This become even larger in the 95% model, which varies greatly compared to the rest. Part of the change is due to the two flat levels in the audience bowl that disappeared and became raked as the model was reduced so significantly.



(a) Original

(b) 0%



(c) 50%

(d) 80%

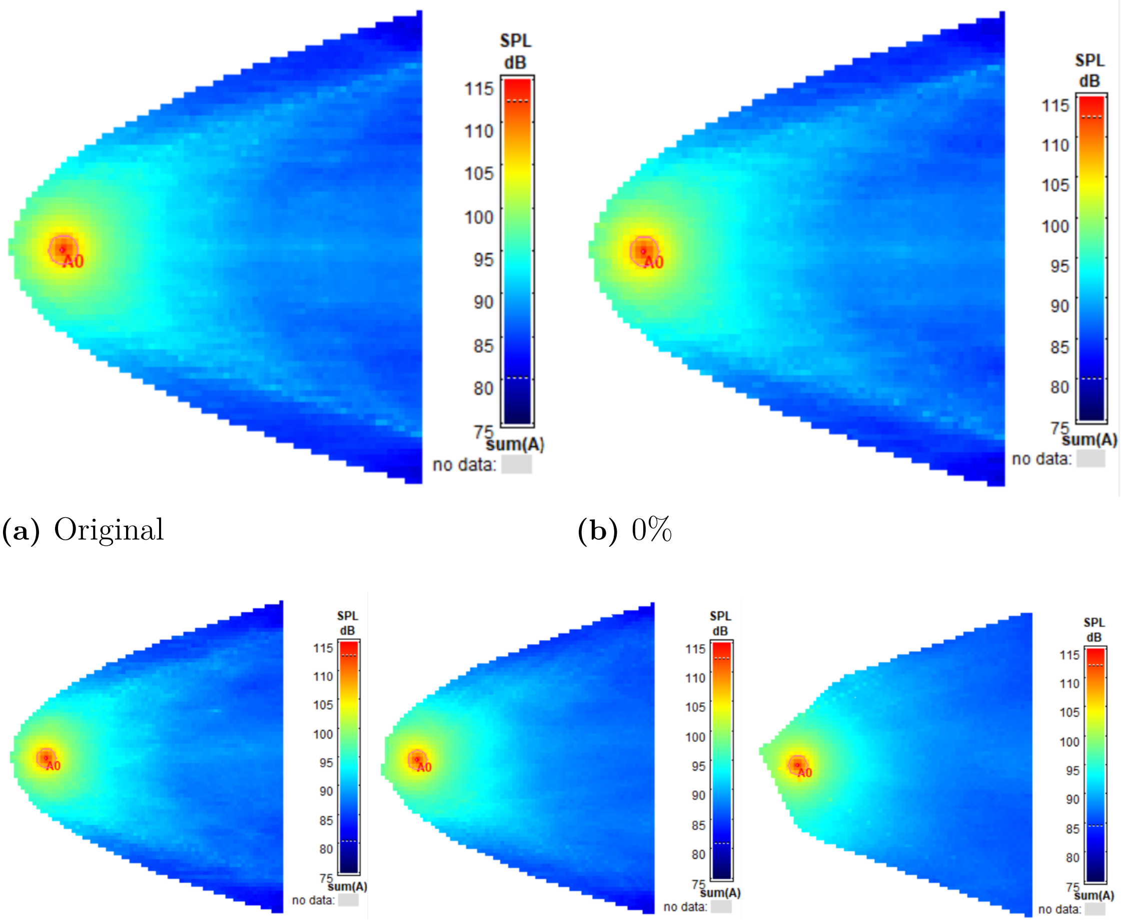
(e) 95%

Figure 5.67: The Clarity audience maps of the five models for Model 3.

5.2.2 Sound Pressure Level

5.2.3 Model 1

The sound pressure level in the unreduced maps are nearly identical, and the 50% and 80% are very similar to the unreduced, with some slight changes in the pattern. The 95% map is again where the largest difference is seen, with a very even distribution of sound pressure level, less patterns seen due to the geometry of the building.



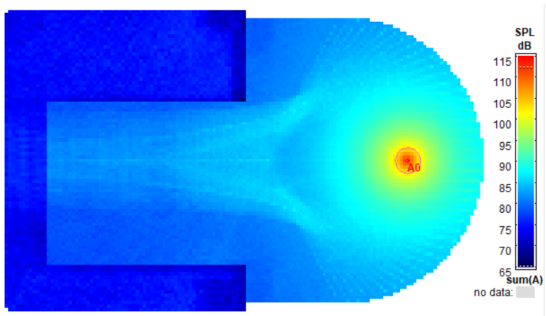
(a) Original **(b)** 0%

(c) 50% **(d)** 80% **(e)** 95%

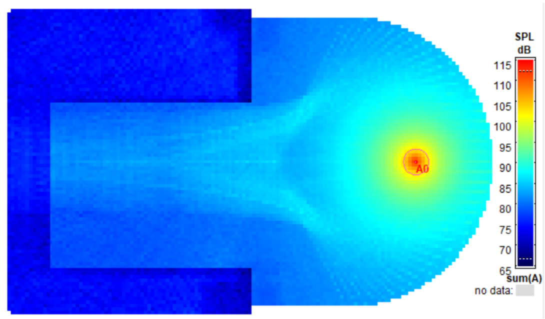
Figure 5.68: The Sound Pressure Level audience maps of the five adjusted models for Model 1.

5.2.3.1 Model 2

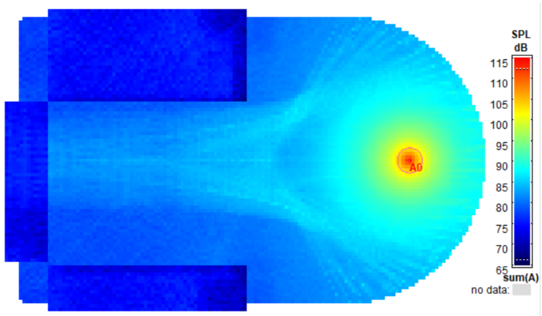
The pattern is similar for the first three models, 0%, 50%, 80%, the noticeable difference being the number of lighter coloured striations. These are due to the finite number of faces used to approximate the rounded wall, where the higher the detail and more faces the higher the number of striations. The 95% model starts to lose the pattern in the center of the model compared to the others, though the sound pressure level is similar in value.



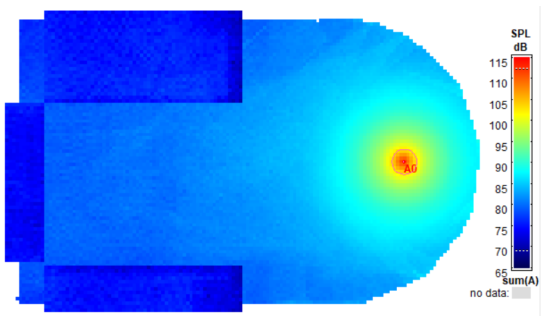
(a) 0%



(b) 50%



(c) 80%

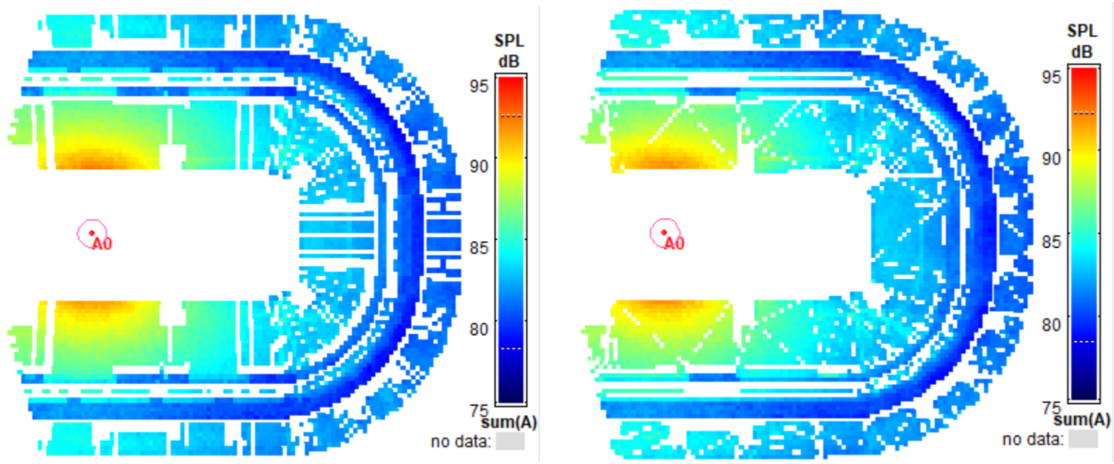


(d) 95%

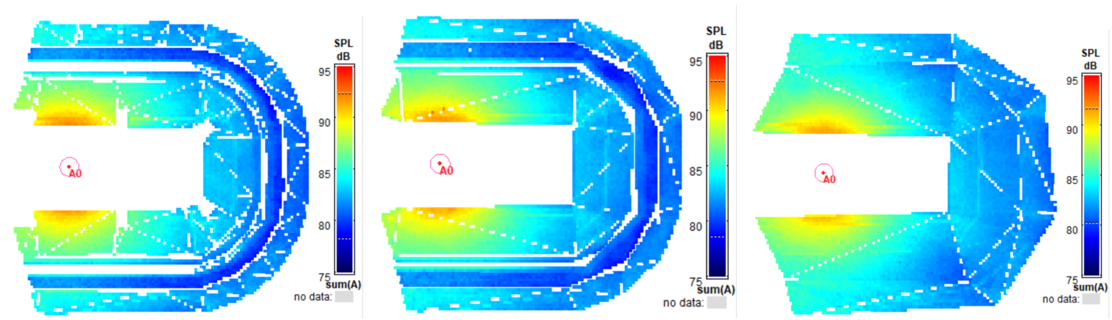
Figure 5.69: The Sound Pressure Level audience maps of the four models for Model 2.

5.2.3.2 Model 3

The first four models are quite similar in pattern and sound pressure levels. The 95% model again has the largest differences, and again this is partly due to the loss of the flat portions of the model in the audience bowl.



(a) Original **(b)** 0%



(c) 50% **(d)** 80% **(e)** 95%

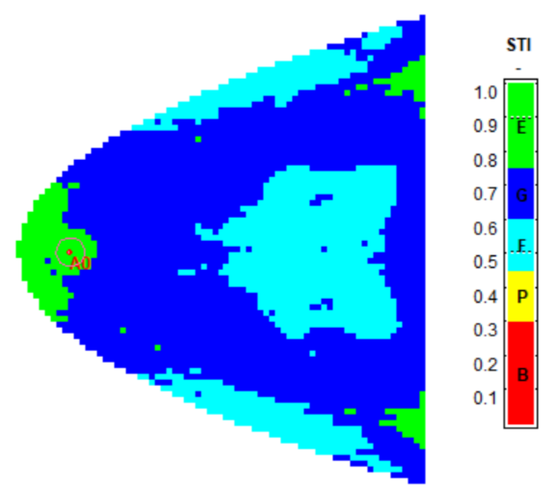
Figure 5.70: The Sound Pressure Level audience maps of the five models for Model 3.

5.2.4 Speech Transmission Index

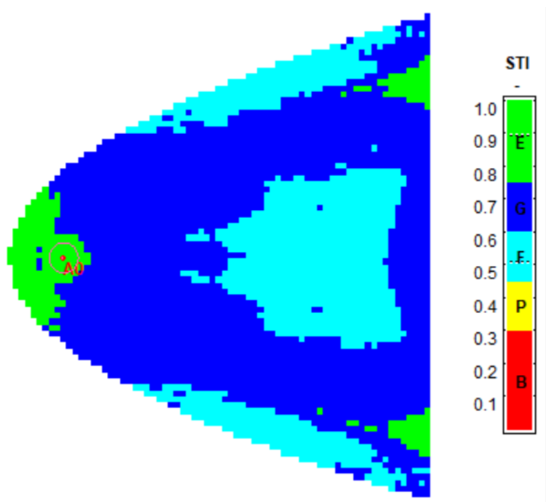
5.2.4.1 Model 1

To analyse the STI maps in Figure 5.71, the ranges were used to display the data on the maps rather than the values, it will decrease the precision but will help illustrate the changes caused. As well, these ranges are what an acoustician will work with. As well, for the results no background noise was used.

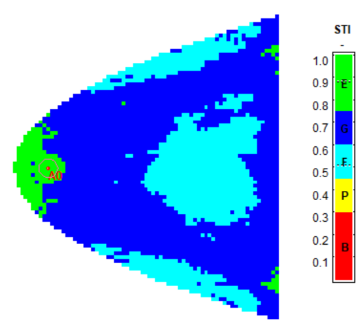
The original and 0% maps differ in results, mostly near the edges, however, both are very symmetric. Already at the 50% model there are some big changes throughout, with continually changing results as the model is simplified more. The even spread of “good” is a consistent pattern caused by the heavy reduction.



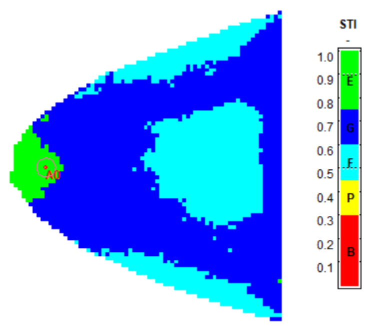
(a) Original



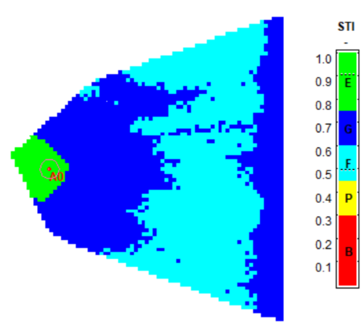
(b) 0%



(c) 50%



(d) 80%

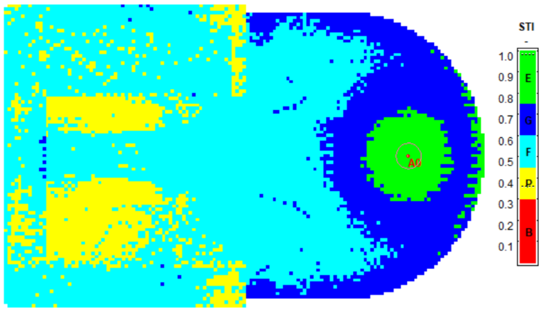


(e) 95%

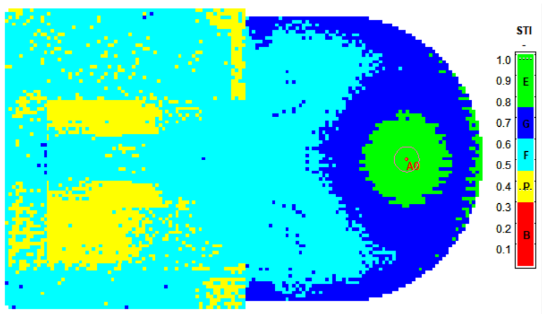
Figure 5.71: The Speech Transmission Index audience maps of the five adjusted models for Model 1. The STI ranges, excellent, good, fair, poor, and bad, are used to display the data.

5.2.4.2 Model 2

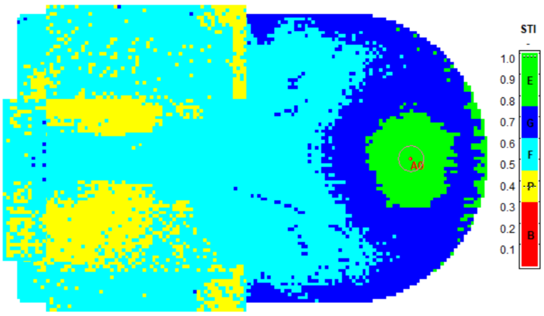
With only some slight differences the first three models are very similar in terms of speech transmission index, with the 95% model the least similar to the 0% model.



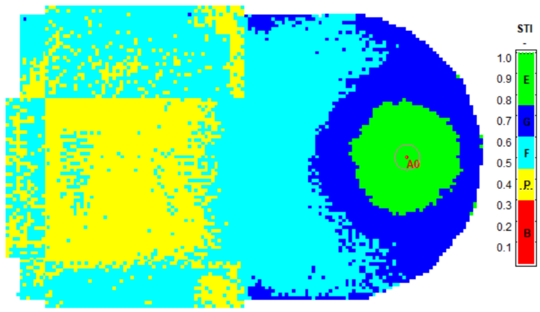
(a) 0%



(b) 50%



(c) 80%

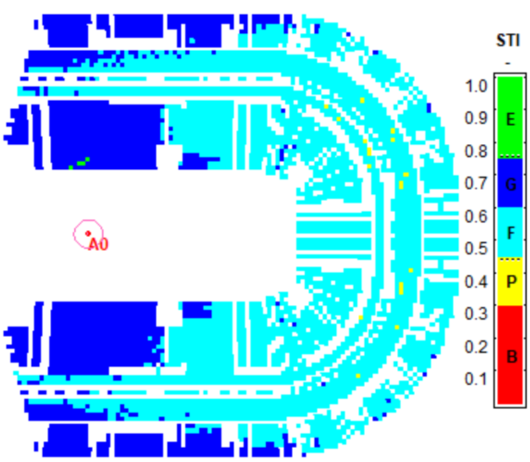


(d) 95%

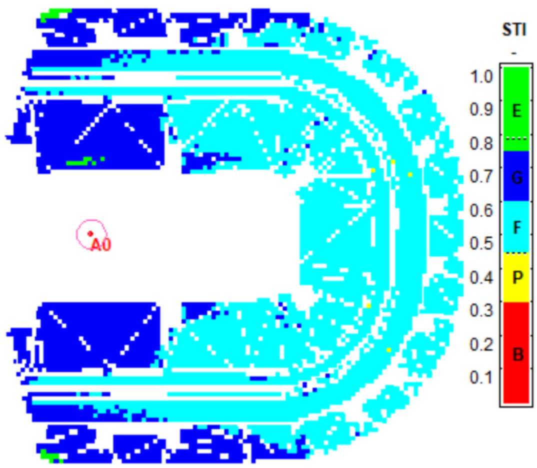
Figure 5.72: The Speech Transmission Index audience maps of the four models for Model 2. The STI ranges, excellent, good, fair, poor, and bad, are used to display the data.

5.2.4.3 Model 3

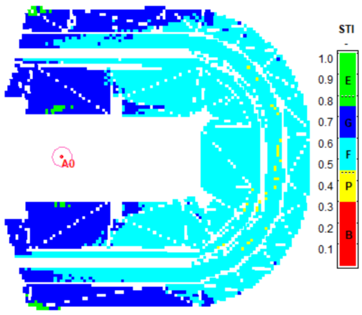
For the 50% and the 80% model the pattern is very similar to the 0% including the slightly higher STI in the top corners of the audience maps. All, except the 95%, maps are comparable with only small differences.



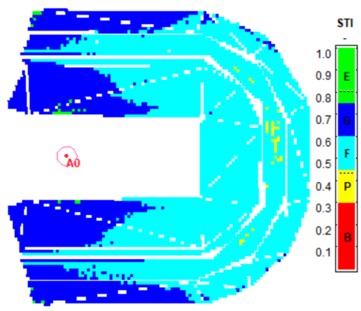
(a) Original



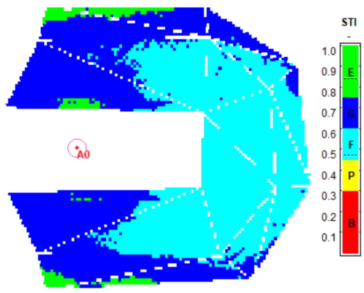
(b) 0%



(c) 50%



(d) 80%



(e) 95%

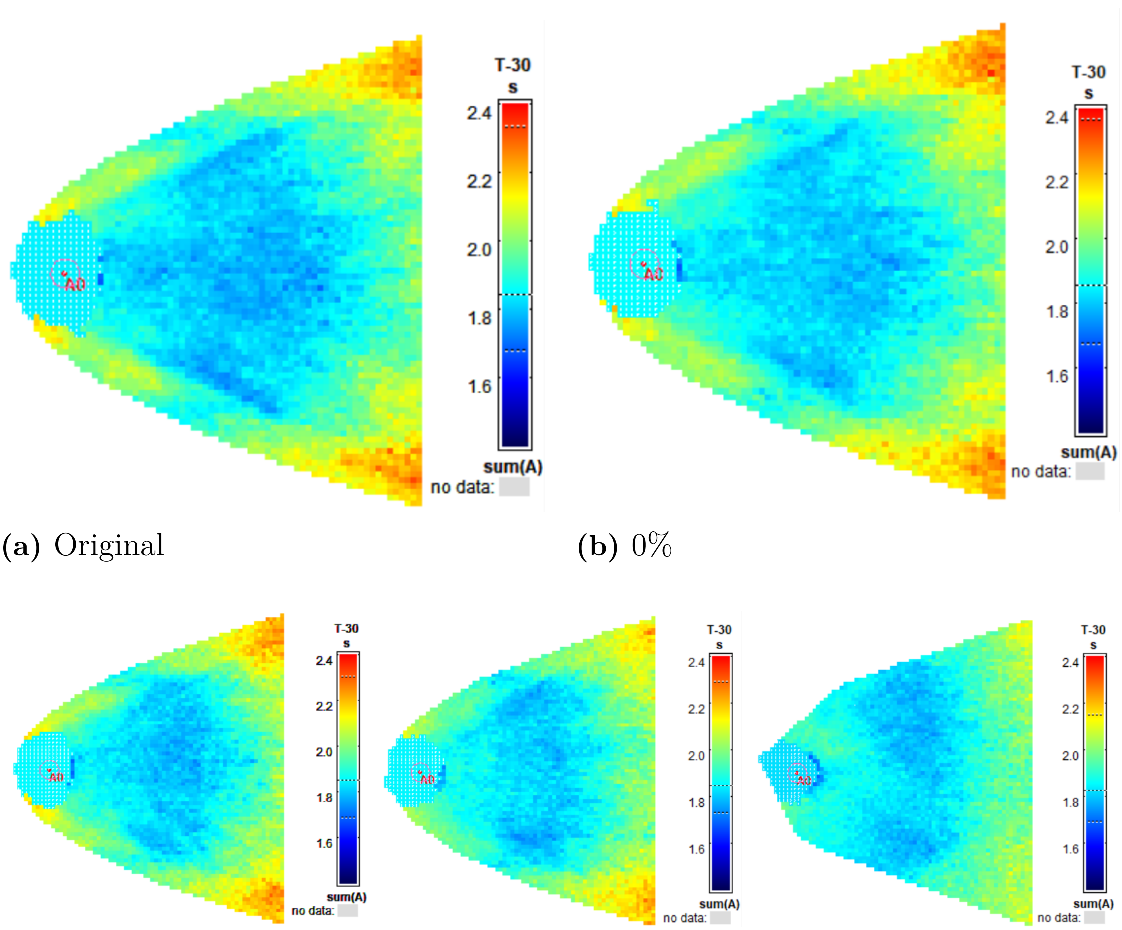
Figure 5.73: The Speech Transmission Index audience maps of the five models for Model 3. The STI ranges, excellent, good, fair, poor, and bad, are used to display the data.

5.2.5 Reverberation Time

5.2.5.1 Model 1

While reverberation time is often presented as a singular value for the whole space,[10] it feels important to include these results to further see the effects of simplified models. As well, the singular value is calculated based on an average of the entire space.

In Figure 5.74 the pattern for both of the unreduced models is very similar. A slight difference begins to appear at the 50% map, then again continually changing as the model is reduced. In the 95% the range of values has also changed, with the max value decreased by 0.1 s. Though the symmetry is quite consistent through all.



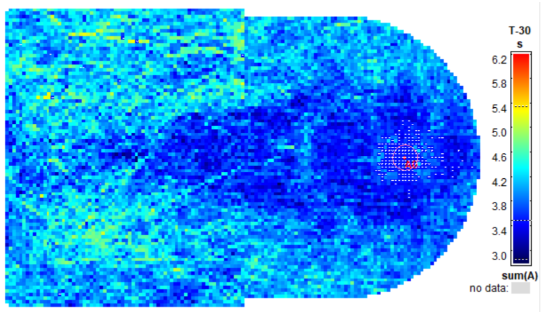
(a) Original (b) 0%

(c) 50% (d) 80% (e) 95%

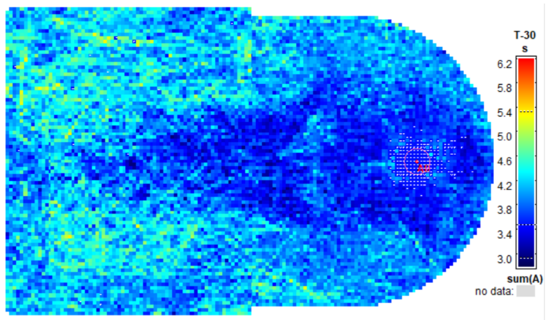
Figure 5.74: The Reverberation Time audience maps of the five adjusted models for Model 1.

5.2.5.2 Model 2

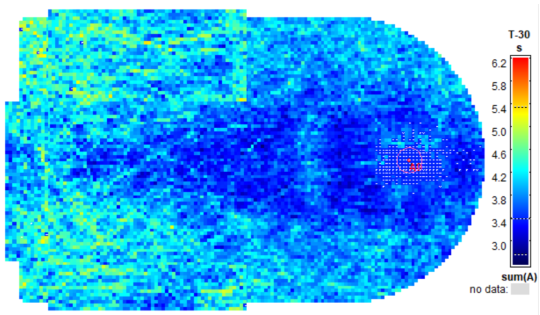
The 50% model is very similar to the 0% model, and then changes noticeably for the 80% and further. It is important to note for these maps that the echogram was reduced in order to obtain these results, which would have had an effect on the outcome. The echogram should be long enough to fully capture the reverberation time results, and by shortening it the results are not as accurate. There are values up to 5.4 s but the echogram length was 4 s, because any longer would have crashed the simulation, therefore the echogram was not long enough to measure those higher reverberation time values.



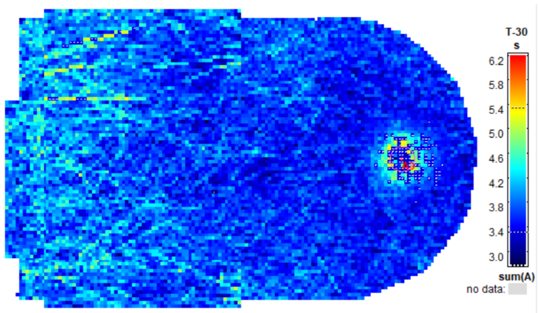
(a) 0%



(b) 50%



(c) 80%

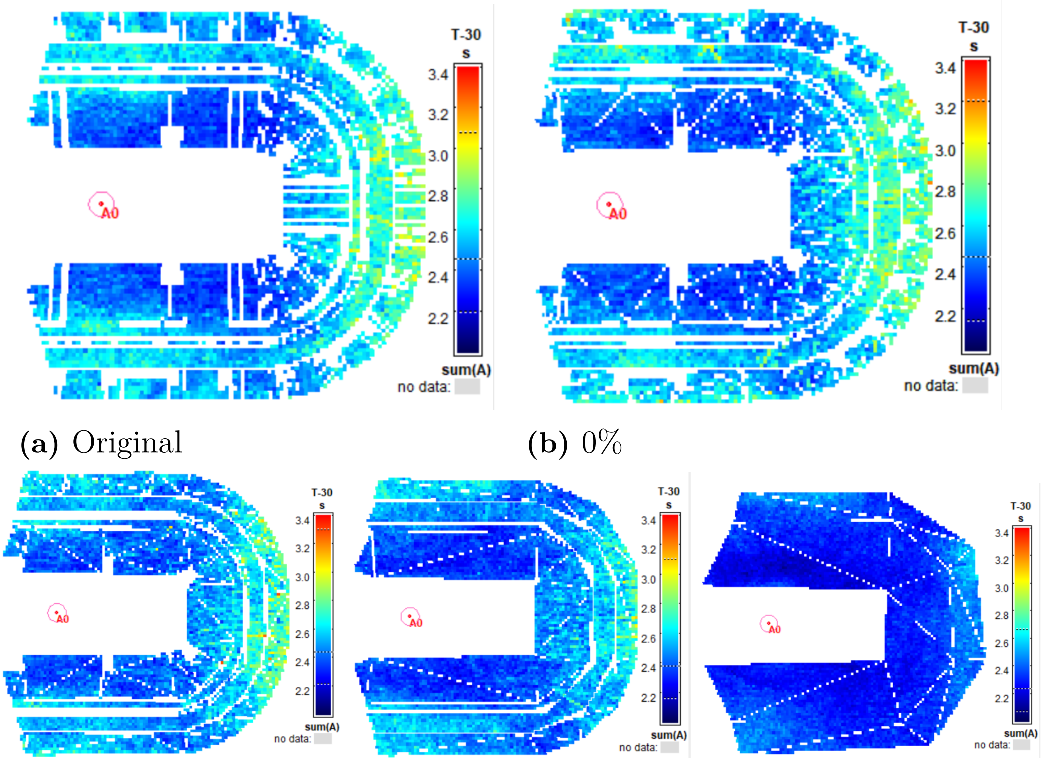


(d) 95%

Figure 5.75: Reverberation Time audience maps of the four models for Model 2.

5.2.5.3 Model 3

The 50% map is similar to both the original map and the 0% map, then the more simplified iterations losing likeness.



(a) Original **(b)** 0% **(c)** 50% **(d)** 80% **(e)** 95%

Figure 5.76: Reverberation Time audience maps of the five models for Model 3.

5.3 Discussion

Firstly it should be noted that for both the source to receiver analysis and the audience map analysis, due to unknown issues the model, in CATT, was considered open and could not suggest an echogram/impulse response. Therefore, the value had to be chosen. The value of 5000 ms, used for most of the models, was chosen as it would be sufficiently long to record the reverberation time (T_{30}) decay, which is the parameter most affected by the echogram length as seen with the poor results from Model 2.

Tendency for the difference from simplified to original and 0% to vary and thus difficult say if one was better to compare to than the other. Though note that original has leaks, which should be avoided. Along the same lines, by following acoustic theory and looking at the results from the simulations, the absorption coefficients should be adjusted as the volume and surface area are changed due to the simplification. Even, as seen from the results for the 80% reduced model, a change in absorption of 0.1% can have an effect and brought the results closer to unreduced models.

The 95% consistently has the largest differences, so there should be care when reducing the model so that it does not become too reduced, going back to the point that it is important for the acoustician to know what they are doing. Particularly with the shape of the model, since the loss of symmetry in the geometry leads to loss of symmetry in the results of the audience maps.

Overall, the calculation time can be reduced by simplifying the model without too detrimental effects. A reduction up to about 80% model is suggested as this is where the difference starts to deviate. Though again there is onus of the acoustician to use their training and education to make the decision of how much is too much. If the shape is not changing, for example, a rectangular box made up of hundreds of smaller faces, then a very high reduction could be used without a detriment to the original geometry.

Table 5.1 shows the maximum deviation that occurs for each model simplification and for each parameter. Green displays where the deviation has not exceed the allowance, and red where the allowance has been exceeded. The more green cells an iteration has, the more reliable that level of simplification is compared to the others. As seen, 50% is the most reliable for Models 1, 2, and 3, with 80% in second place. This table is a summary of the information already analyzed in the past subsections, and further discussed in the following subsections.

	C_{80} (dB)	G (dB)	SPL (dB)	STI (-)	T_{30} (s)
Allowance	3	2	2	0.05	0.1
Model 1	C_{80} (dB)	G (dB)	SPL (dB)	STI (-)	T_{30} (s)
50%	0.5	0.5	0.5	0.015	0.02
80%	1	0.9	0.9	0.04	0.025
95%	1.9	1.2	1.2	0.055	0.04
Model 2	C_{80} (dB)	G (dB)	SPL (dB)	STI (-)	T_{30} (s)
50%	0.5	0.2	0.2	0.015	0.05
80%	0.7	0.2	0.2	0.01	0.15
95%	2.5	1.8	1.8	0.105	0.29
Model 3	C_{80} (dB)	G (dB)	SPL (dB)	STI (-)	T_{30} (s)
50%	1.2	0.7	0.7	0.045	0.1
80%	1	0.8	0.8	0.052	0.21
95%	1.5	1	1	0.075	0.4

Table 5.1: The maximum deviation of the simplification iterations for each parameter. If the deviation falls below the allowance it is green, if it is above then it is in red.

Getting down to this level of specificity can be difficult in acoustics, but some general guides can be followed, and were used to determine the tolerances that would be allowed to judge the simplifications. And, while room acoustic software has improved over the years, there can be variances with each model created even compared to the real-life building, and "is strongly dependent on the input data".[8] And, the most accurate models are those that have been simplified.[3][21] The allowances were determined through several different means and are outlined as follows:

- Clarity - half the range of a typical concert hall, as seen in the Theory Section. The range being 6 dB, so if a number were to fall in the middle of the range then plus or minus 3 dB would still be within the acceptable range.
- Strength - same method as clarity, but with typical range of about 5 dB, so being on the safe side rounding down to 2 dB.
- Sound Pressure Level - based on knowledge of acoustics and the decibel scale, where 2 dB difference in sound pressure level is indiscernible, and then 3 dB is a doubling in sound energy and 6 dB is a doubling in sound pressure.[9]
- Speech Transmission Index - based on a paper where the deviation for a single source is 0.05.[5] As well, since the scale of speech transmission index of 0 to 1, then 0.05 is a small change.
- Reverberation Time - since reverberation time is sensitive to changes and reverberation time is measured down to the hundreds of milliseconds, 0.1 s was set as the allowance.

5.3.1 Clarity

In analyzing the results of clarity in Model 1, the results are not greatly affected by the adjusted absorption coefficients. Then looking at the three different models, with simplification, the clarity can range by up to 2.5 dB, which can start to become significant. Though most of the results were below this and therefore fairly safe to used simplified models without greatly affecting clarity.

5.3.2 Strength

The 95% reduced model shows the largest difference in values with 80% following, though with the adjusted coefficients, the largest range for the three different models is about 1.8 dB. When dealing with parameters relating to sound pressure level, this is not too concerning, and falls within the standard range of deviation from the target of 2 dB, but is getting close.

5.3.3 Sound Pressure Level

The largest difference in the adjusted models is about 1.8 dB which was in Model 2, with Model 1 following closely with 1.6 dB, which again is not too significant. Note that this is for the averaged positions and there can be larger differences in certain positions in the model.

5.3.4 Speech Transmission Index

In Model 1, when comparing the same coefficients to the adjusted coefficients the difference and the area do not change significantly. The reduced models generally showed that the 50% iteration was the closest to the unsimplified models, and the max difference was 0.105, which is an 10.5% difference. This starts to become significant as it can move the octave band from one category to another, i.e. from “fair” to “good”. However, this was for the 95% reduced model, which is constantly showing strong deviations.

5.3.5 Reverberation Time

There is a decrease in difference for the 95% model when the adjusted coefficients are applied, which is important since a 0.1 s difference begins to become significant. For Model 1 the simplification does not have a large affect on the reverberation time parameter. Model 2 and 3 though are much more affected by the simplification, with a max difference reaching up to 0.4 s which is significant. Therefore, when looking at reverberation time, it is very important to not oversimplify the model, the 50% had much more reliable results.

5.3.6 Program Performance

In summary of the program, the tools was successfully created and works effectively and efficiently. As with all the related acoustic programs, user knowledge and training is necessary. The biggest thing to be wary of as a user is how the different structures of the model in Rhino are connected. If the vertices of a mesh are not lined up properly there could be issues when joining them together, and thus are two different entities. Then, being separate, the meshes will be reduced irrespective of the other and could then be reduced quite differently, thereby the edges and vertices not meeting up creating large gaps (or holes) in the model. A similar/related issue was seen with Model 2, where parts of the balcony disappeared as the model was reduced. This was because the wall that the balcony is “attached to” did not have any vertices where the balcony existed, therefore the balcony could not be joined at the point. The balcony existed as its own entity and was reduced independently from the other structures in the model.

Then, of course, another thing that will alter the results within the model is the actual simplification. The model will be reduced causing walls to be more planar, less curved and less detailed. In some situations this would not be a problem, however, if the model is simplified too much (as seen with the 95% models) some of the important curvatures or angles of walls can be lost. This change affects the geometry, which is crucial to geometrical acoustics. So through the analysis, as seen, if the geometry is not changed too drastically then the results should vary only slightly. Further to the reduction is that if simplified too much, details such as doors and windows, which are more crucial to the design and acoustic analysis, could be lost. If, however, they are lost then the acoustician can alter the absorption coefficients such that the new wall is a conglomeration of the old wall and the specimen (door, window, etc.) that was lost.

6

Conclusion

The Grasshopper program was created successfully, incorporating many of the different components that exist within the Grasshopper framework and plug-ins, with some additional Python routines created for more complex sorting. The first part successfully converts geometries into a mesh then reduces it to the user's specified target. Additional functionality exists to allow for different levels of accuracy, which will alter the shape of the model, and to allow for face merging, which leads to a higher risk of leaks from the model.

A big portion of the program is the transfer of the model to CATT-Acoustic, with multiple routines set up to create and export the files. The first important feature is the creation, "bake", of the reduced model, which can be modified with colour representing the material that that surface will be made of with corresponding absorption coefficients. All of this can be set by the user. The user can also specify if the surface is double-sided and/or an audience plane. Once complete the acoustician is then able to create the files for CATT with a click of a button. The files are generated, and when the user opens CATT the model is there ready to be analyzed. To save time a file with all the planes that are "audience planes" is generated and the list can simply be copied and pasted into CATT.

After all this the results from CATT were analysed to see how the acoustic parameters of SPL, T_{30}, STI, C_{80}, and G were affected by the simplification of the models. The most noticeable differences were with the 95% reduced model, whereas the 80% and 50% reduced models were close to the unsimplified models. Therefore it is suggested that if the models are simplified with this method, then they should not be simplified much past 80% reduction. However, specifically for reverberation time the model should not be simplified much past 50% as the higher reduced models returned largely deviated results.

Finally, as seen with the results of the simulations and the calculation time for these simulations, there is significant time saved using the program to reduce models with little detriment to the final results. It is required for the user to have an understanding and background in acoustic theory and design to be aware of how their decisions affect the results. The reduce mesh portion of the program was the main focus and is the determining factor of how the results are affected. Many other features were created to extend the program further. The ability to add material interactively is useful to the acoustician. The secondary goal of creating the CATT files was achieved, which was extended to also create the audience plane file.

The hope is that this program can be used to save time and manpower in fiddling with models, and can help the aocusticians at Buro Happold approach the analysis phase faster. But further, hopefully the pieces of the program and the routines built can be extracted and repurposed to other projects and programs as Grasshopper becomes more and more prevalent in parametric design.

There are packages being developed for more acoustic analysis done in Grasshopper, some of which are currently being developed at Buro Happold. However, these would need to be validated in the coming years as they are fully developed. Meaning that in the time being acousticians are still greatly reliant on software like CATT-Acoustic, and transferring data among the different software.

6.1 Further Work

One improvement of the existing program would be to create a routine that shifts vertices of BREPs to make the entire face properly planar. This would help with the face merging component that already exists. The current issue is that the face merge will merge near coplanar faces, but for CATT they must be exactly coplanar. By shifting the vertices to a common plane, then it can be ensured to be planar. The routine for meshes has been created before, but is limited to meshes with maximum four vertices, whereas BREPs can have many more vertices, but the BREPs are also handled differently in the RhinoCommon C# development tools. So more research would need to be done in order to create the tool.

When running the models in CATT that were exports from Grasshopper/Rhino, they were always considered “open” or “there are 100% absorbing surfaces”, even a simple rectangular box with simple vertices. And, as seen from the results the “leaks” were 0%. So it would seem there is an issue with CATT. Perhaps it is the version of CATT that the models were run on, but it is a strange error with no real cause.

Locking vertices and certain faces in place so they do not get shifted nor disappear due to the reduction program. As well as, preserving the volume and surface area so the absorption coefficients need not be altered.

Creating the audience plane file with the proper file extension and source code so that all you have to do is load it in.

Bibliography

[1] Embedded Acoustics. Speech Transmission Index.

[2] Bengt-Inge Dalenbäck. CATT-A v9.1 User's Manual CATT-Acoustic TM v9.1, 2016.

[3] Bengt-Inge Dalenbäck. Whitepaper: What is Geometrical Acoustics (GA)? 2018.

[4] F. Alton Everest and Ken C. Pohlmann. *Master Handbook of Acoustics*. 6th edition, 2015.

[5] L Gomez, C Nestoras, S Dance, and S Murano. COMPARISON OF SPEECH INTELLIGIBILITY MEASUREMENTS IN A DIFFUSE SPACE. Technical report, Cairns, Australia.

[6] Andrew Heumann. Human, food4Rhino, 2019.

[7] hisa041. Snail, food4Rhino, 2019.

[8] Bork Ingolf. A Comparison of Room Simulation Software-The 2nd Round Robin on Room Acoustical Computer Simulation. Technical report, Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38ll6, Braunschweig, Germany, 2000.

[9] Mendel Kleiner. Acoustics and Audio Technology (3rd Edition) - Knovel.

[10] Heinrich Kuttruff. *Room Acoustics, 4th Edition*. Spon Press, Aachen, Germany, 4 edition, 2000.

[11] Marshall Long. *Architectural Acoustics*. Elsevier Academic Press, 2006.

[12] Theo Marchal. Esquissons, food4Rhino, 2020.

[13] Robert McNeel & Associates. ReduceMeshParameters Class, RhinoCommon.

[14] Robert McNeel & Associates. Mesh, Rhinoceros, 2015.

[15] Nathan Miller. LunchBox, food4Rhino, 2018.

[16] Attila B Nagy, András Kotschy, Anders Christian Gade, and Hallur Johannessen. ROOM ACOUSTICAL MODELLING DIFFERENCES AND THEIR CONSEQUENCES. Technical report, Internoise, Lisbon, 2010.

[17] Daniel Piker. Kangaroo Physics, food4Rhino, 2017.

[18] Helmut Pottman, Andreas Asperl, Michael Hofer, and Axel Kilian. Architectural Geometry - Knovel, 2007.

[19] Michael Pryor. Pufferfish, food4Rhino, 2020.

[20] Philip W Robinson, Samuel Siltanen, Tapio Lokki, and Lauri Savioja. Concert Hall Geometry Optimization with Parametric Modeling Tools and Wave-Based Acoustic Simulations. Technical report, Department of Media Technology Aalto University, Aalto, Finland, 2014.

[21] Lauri Savioja and U. Peter Svensson. Overview of geometrical room acoustic modeling techniques. *The Journal of the Acoustical Society of America*, 138(2):708–730, 8 2015.

[22] Thomas Scelo. Integration of acoustics in parametric architectural design. *Acoustics Australia*, 43(1):59–67, 4 2015.

[23] Armin Seltz. Creating and writing to a text file, Grasshopper Discussion Board, 2016.

[24] Samuel Siltanen, Tapio Lokki, Lauri Savioja, and Claus Lynge Christensen. Geometry reduction in room acoustics modeling. *Acta Acustica united with Acustica*, 94(3):410–418, 5 2008.

[25] Dassault Systèmes Spatial Corp. The Main Benefits and Disadvantages of BRep Modeling, 2019.

[26] Jerry O Talton III. A Short Survey of Mesh Simplification Algorithms. Technical report, University of Illinois at Urbana-Champaign, Urbana, 2004.

[27] Technical Committee : ISO/TC 43/SC 2 Building acoustics. ISO 3382-2:2008(en) Acoustics — Measurement of room acoustic parameters — Part 2: Reverberation time in ordinary rooms. 2008.

[28] Arthur The Acoustician. Pachyderm Acoustical Simulation, food4Rhino, 2020.

[29] Laura Ziskin and Ian Bryce. Spider-Man, 2002.

A

Appendix A

Figure A.1 is a routine in the program that generates the text files into a specified folder. This routine was provided by Armin Seltz from a Grasshopper discussion board.[23]

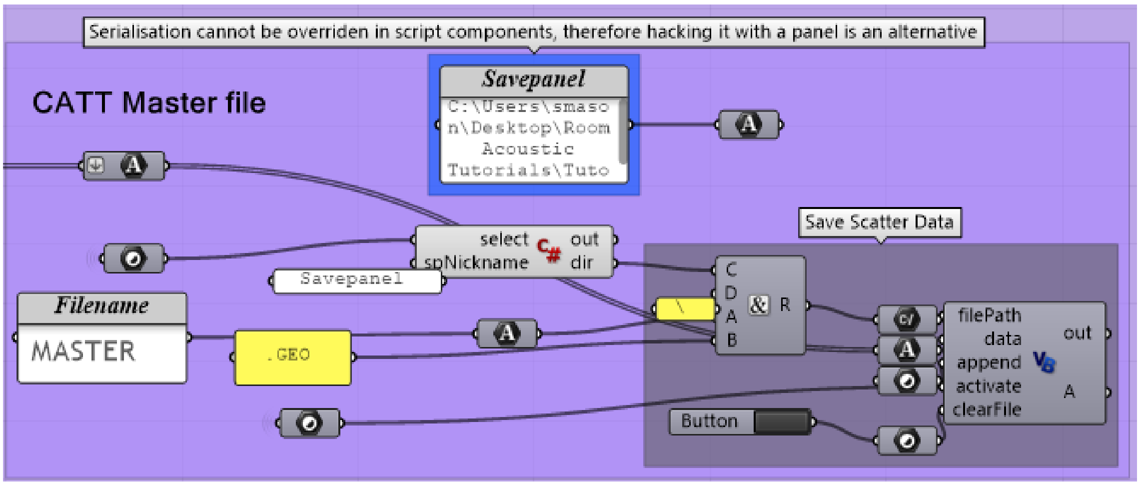


Figure A.1: The components that create text files from a given input.

The following figures are from the program created in Grasshopper and are apart of the workflow. As seen Figure A.2 visualizes the vertex numbers on the model in Rhino.

Figure A.2: Implementation of the visualization of all the vertex indices in the Rhino model.

The collection of components in Figure A.3 is used to the set the desired decimal place precision for the "corners" in the CATT master.geo file as well as the planarity test. Two to three decimal places is generally sufficient, because that then is on the order of centimetres and millimetres, which is more than precise enough for structures in the built environment.

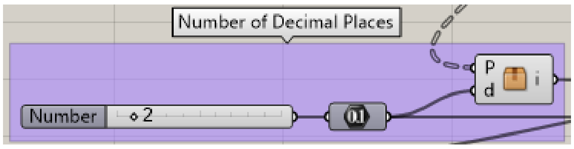


Figure A.3: Used to set the number of decimal places used.

Figure A.4 creates the file for the receiver locations, where the positions are set by typing in the panel component.

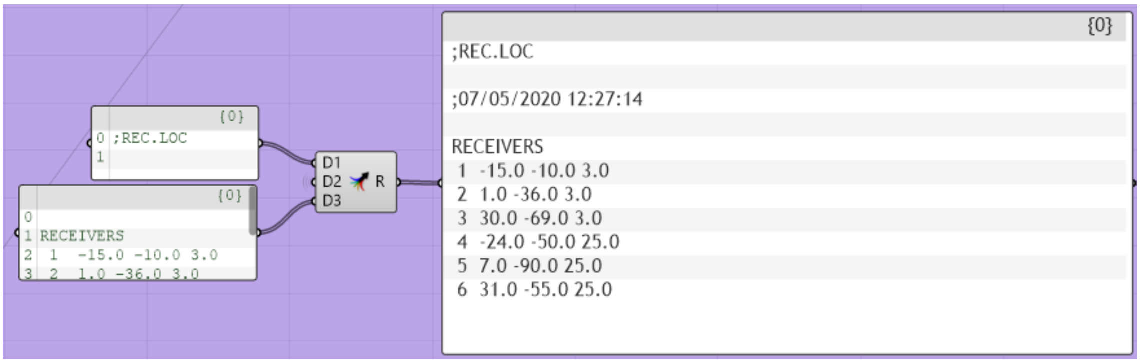


Figure A.4: The components that create the rec.loc file for CATT.

Figure A.5 creates the file for the source definitions and locations, where the sources are set by typing in the panel component.

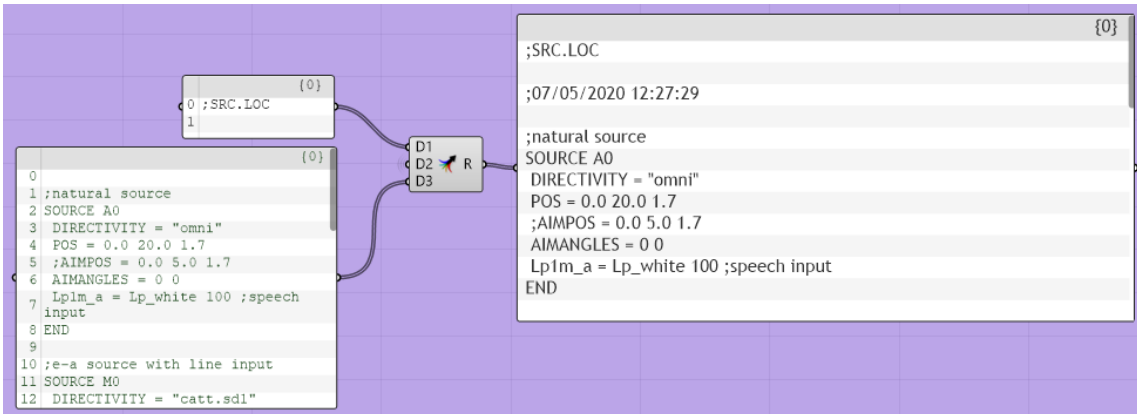


Figure A.5: The components that create the src.loc file for CATT.

Figure A.6 returns a file of the plane IDs that contain the material defined as "audience". This helps the user quickly copy and paste the numbers into the "Audience plane mapping" portion of CATT so they do not have to spend time looking for the number for each audience plane.

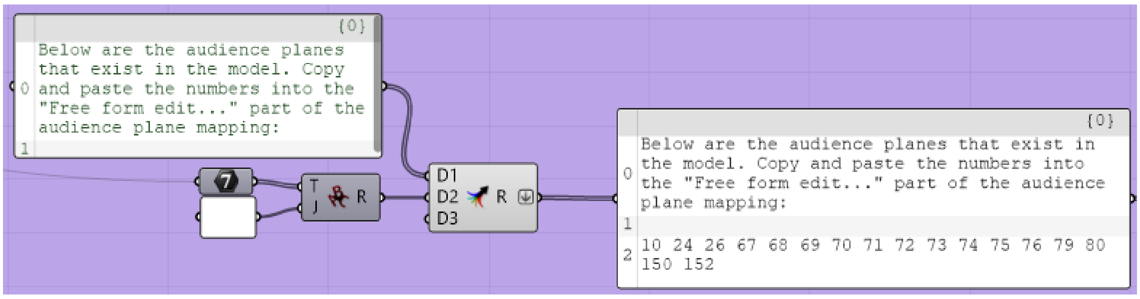


Figure A.6: The components that create the audience_planes.txt file for CATT.