DEVELOPING A TOOL FOR ACOUSTICAL PERFORMANCE EVALUATION THROUGHOUT THE DESIGN

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ABSTRACT

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Performance of the buildings has always been a concern for the architects. With the enhancements in the technology, it is possible to measure, analyze and evaluate the performance of an architectural design before it is built via simulation tools developed. With the evaluation of the analysis performance of the concerned space can be upgraded if simulation tools are employed throughout the design process. However, even though the simulation tools are developed for the acoustical simulation and performance analysis, it is not always simple to integrate the simulation tools to whole design process because of both specific knowledge required for the usage of the tools and the nature of the acoustical simulation tools. Within the scope of the thesis, a simulation tool, which does not require advanced knowledge on acoustics and which provides rapid feedbacks about the performance of the design for the enhancement of the performance is developed using method of image sources.

Keywords: Room Acoustics Software, Acoustical Performance, Acoustical Analysis, Acoustical Simulation, Image Source Method

ÖZ

AKUSTİK PERFORMANSIN TASARIM SÜRECİ BOYUNCA DEĞERLENDİRİLMESİ İÇİN BİR ARAÇ YARATILMASI

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Günümüzde, tasarım kararlarının ve/veya değişikliklerin sayısal ortamda modellenerek farklı biçimlerde deneyimlenmesi, önemli bir tasarım performans aracı olarak yaygınlaşarak kullanılmakta ve sayısal tasarım, performansa dayalı tasarım (performance based design) kavramıyla birlikte ele alınmaktadır. Bu bağlamda yapılan çalışmalarda, sanal gerçeklik kavramının yerine gerçek-benzeri deneyim (life-like experience) kavramı geçmektedir. Bu kavramla birlikte tasarımın sadece foto gerçekliği değil, farklı kuvvetlerle etkileşimi (statik, dinamik yükler, çevresel yükler vb), malzemesi, ışığı, sesi kısacası gerçek deneyime dair ve algıyı kurgulayan bütün bileşenlerinin sayısal ortamda da tasarlanması beklenmektedir. Günümüzde kullanılan bilgisayar destekli tasarım programlarında ise görsellik ön planda tutulmuş olup işitsel deneyim elde etmek için kullanıcıların yazılım üzerine uzmanlaşmasını gerektiren ve detaylı analizler sunan başka yazılımlar kullanmaları gerekmektedir ve bu aşamada yazılımlar arası dosya transferi sırasında bazı problemler ortaya çıkmakta, işitselliğin deneyimlendiği yazılımlar için yüksek lisan ücretleri ödenmek zorundadır.

Anahtar Sözcükler: Hacim Akustiği Yazılımları, Akustik Performans, Akustik Analiz, Akustik Simulasyon, Kaynak Yansıma Yöntemi

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Performance of buildings has always been a concern for the architects. Since ages, architects aimed to achieve the best performance for the buildings they design and construct like the highest, the most solid, the least energy consuming and such motives. Performance based design approach has become more and more popular with the enhancement in technology since computational medium provides tools for designing the better buildings regarding specific driving external and internal forces.

Hence, simulation tools, as achievements of the computational technologies play significant roles in the enhancement of the building performance allowing experiencing the response of the buildings to different forces, enabling further analysis and evaluations regarding the objective(s) of the design.

Room acoustics aiming to yield acoustically pleasant spaces and thus the sound is an important performance criterion in any design and its importance has been more pronounced in performance halls, recording and broadcasting spaces and in any public space. Since the aural comfort is an important driving factor for such spaces, it influences design decisions and thus has to be considered throughout the design process. There are a limited number of commercially available acoustic simulations tools employed to evaluate the acoustics of the enclosed spaces. Yet these are mostly developed as post design tools and it is relatively complicated to integrate them to the very early phases of the design process. Hence, their way of use is evaluation rather than integration and feedback since from the early phases of the design as performance based design approach requires.

Room acoustics is a specific discipline which is highly fed by engineering sciences and physics and is not necessarily provided in architecture education. Thus, designer who are not specialized in acoustics and are involved in the design process of an acoustically concerned architectural space may not necessarily have the required knowledge to provide inputs or read the information gathered from the acoustical analysis Thus, the major deficiency of these acoustic simulation tools are mostly related with requirement of “advanced knowledge literacy in acoustics” and the resulting complexity of the interface avoiding the user to incorporate those tools to the design process.

Second obstacle that is frequently encountered in the use of these simulation tools is related with the features of these tools. These are mainly developed for the evaluation of the acoustics rather than to develop and optimize the acoustical design in the course of design process. Hence these tools require precise input regarding starting from the solid model to material, from sound source to receiver positions as well as advanced knowledge on acoustics which is directly referred in the settings and interface of the programs. On the other hand, design is a process which evolves with feedbacks and it is a compromise of many knowledge domains. Hence, today design process since from the very early phases aims to achieve such an integration which serves as the basis of performance based design idea. Thus simulations should not be considered as post design tools but in design tools. Therefore present simulation tools should be re-designed to allow the designer to experience the design at any time and give feedback and guide the designer how the design should proceed to achieve the objectives.

1.2 OBJECTIVE AND SCOPE OF THE THESIS

In this thesis, it is intended to provide an easy to use acoustical analysis tool for the architects regardless of their expertise on acoustics. In the design and development of the tool, it is aimed to provide a simple easy to use interface providing the evaluation results complemented by the necessary feedbacks which can respond to simple to advanced analysis requirements during overall design process, even at very early stages of design. In the analysis, image source method is employed for the development of the algorithm which is based on the analogous principles of optics in physics requiring relatively less number of data, applicable to several geometrical configurations including L-shape spaces and obtaining results in relatively short computational time compared with ray tracing and hybrid algorithms in the analysis of relatively less complex geometries. In the context of the study,

The objectives of the thesis can be stated as follows:

1. To develop a computer program which is able to analyze the sound field and output relevant and comprehensible information for the evaluation of the acoustical performance of the room questioned by the designer,
2. To easily construct spaces in predetermined forms such as, rectangular room, arena, fan shaped room, or import geometries from other conventionally used computer aided design software,

3. To develop the software in such a way that the software is easy to use, understand and work with.

This thesis aims to describe the proposed software in 5 chapters.

Chapter 2 gives information about the literature and contemporary applications of simulation tools to serve performance enhancement and also gives brief information about room acoustics to determine the limits of the literature and applications.

Chapter 3 gives detailed information about the theory of room acoustics, method chosen for the construction of the program algorithm, namely method of image sources, parameters to be calculated with the program within the scope of thesis.

Chapter 4 is focuses on goals regarding the usage of the program, interface development process, and tests conducted to validate and verify the goals regarding the usage of the program.

Chapter 5 describes tests conducted to determine the numerical and computational limitations and the convergence of calculated results with theoretical, measured and other simulation software results.

In chapter 6, a brief summary is made and the thesis is concluded with the recommendations for the future work.

CHAPTER 2

STATE OF ART

In this chapter, previous studies and applications relating to the design and optimization of architectural acoustics via software simulations and analysis is to be summarized. Since architectural acoustics involving in the optimization process as well, is an interdisciplinary subject, this chapter is divided into two parts. In the first part, computational technologies mainly simulation software used in the room acoustics, existing approaches, their advantages and disadvantages are to be discussed. Secondly, relevant room acoustics knowledge and applications will be outlined summarizing the major parameters evaluating the acoustical performance of the enclosed spaces.

2.1 ACOUSTICAL SIMULATION AS A TOOL FOR PERFORMANCE MEASUREMENT

2.1.1 Importance of Simulations in Improving Design Performance

Performance based design approach enabling to explore experience and evaluate the response of the design to several internal and external forces have been given more consideration with advents in computational technologies. In this respect, computer simulations permitting to evaluate the performance of the design regarding the objectives or criteria set have become an integral part of the design process as Sorguc, Selçuk and Çakıcı explain as:

> *” Simulation begins with the creation of mathematical ‘models’ that imitates the behavior/performance /response of phenomena/cases with a certain level of precision either set by the model itself or by the present state of the knowledge.”* [Sorguç, Selçuk, Çakıcı, 2011]

Performance of a building or a space has always been a topic of interest and consists some subjective (state of art, visual comfort, etc) and objective (energy efficiency, sustainability, acoustical comfort, etc.) criteria. Simulation tools serve for the evaluation of both criteria. Firstly, experiencing the buildings by visualization, auralization and other simulations give information about how the building will look, sound or feel like when it is built and enables designer and audience to evaluate the building subjectively. Secondly, with the calculations and simulations made throughout the designing process, qualitative and quantitative information enlightens the evaluation of building performance as objective criteria [Fasoulaki, 2008]. The objective criteria of performance are mostly measurable and related to different domains of science; thus performance based design and simulations requires incorporation of inter disciplinary approaches requiring the user have knowledge literacy related with field of interest.

Although the performance of a design continuously changes throughout the design process, the initial design decisions determining the principal design decisions have crucial roles on the final performance and achievement of design goals. Hence, starting from the very early phases of the design process, simulation tools (from representation to evaluation) provide various feedbacks helping designer to improve the design without destroying the integrity of the design process. As the preliminary analysis of performance is made, the data gathered are used to evaluate and improve/optimize the design towards the desired criteria of performance. [Fasoulaki, 2008]

Today there exists several simulation tools used for visualization and evaluation of performance of buildings regarding their structural, acoustics, lighting, material, heat and etc responses.

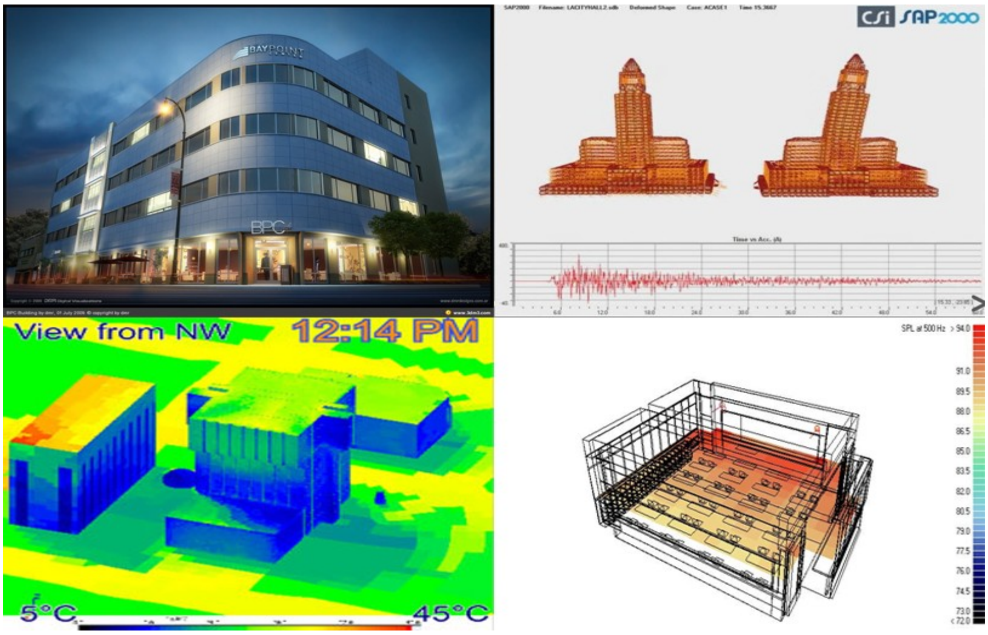


Figure 1. Examples of simulation tools developed for different field of interests

2.1.2 Software Development Process – Fitting to Users' Needs

The efficiency of the performance analysis and simulation is highly dependent on computational technologies, and on the software used in the process. However, software and their interfaces which have been based on similar architectures and generic in their nature requiring some expertise on the related field of knowledge can also be considered as an obstacle in the integration to the design process if the software is hard to be adapted to the field or the user is not familiar to that domain and have not adequate skill to adopt it to his or her field. Software may be developed regarding a need or may be developed specifically for a client/user but whatever the reason is, every software has a target group and profile of user. There are several software architectures employed in the their development process such as code and fix model, basic waterfall, evolutionary, incremental, spiral, agile. [CMS, 2008] In each of the model, there is a different feedback mechanism and output progression in each step of the model. The software development model is chosen based on the several factors such as complexity of the software to be developed, number of people to work in the project team and has to be chosen carefully because inappropriate choice of software development model may result in failure of corresponding the requirements and budget overflows.

Regardless of the software architecture used in the development phase, validation and verification processes of the software development is essential to evaluate the accuracy of the results, convergence rate, and limitations of the software. Verification of the software product, questions the precision and accuracy of the outputs of the software. There are several methods to measure both verification and validation of the software products.

Verification can be further classified into two categories as static and dynamic verification. In the static verification, the software is observed without operating the system and focused on syntax and structure bugs mainly. Dynamic verification focuses on operational behavior of the software and can be conducted by operating critical test cases. [Sommerville, 2004]. Usually, both static and dynamic verification is conducted throughout the design process whereas validation of the software is conducted after the completion of the software. Usability of the product developed is one of the major aspects while evaluating the validation of software. Usability is defined by Jeff Rubin and Dana Chisnell as:

> "…when a product or service is truly usable, *the user can do what he or she wants to do the way he or she expects to be able to do it, without hindrance, hesitation, or questions."* [Rubin, Chisnell, 2008]

As having such a broad definition, every product has its own usability criteria and measures depending on the target user profile needs such as usefulness, efficiency, effectiveness, etc. The concerned usability measures can be one or more of the mentioned criteria including the ones determined by the software developers. [Rubin, Chisnell, 2008] Another issue for the measurement of usability is the determination of usability test. There are several methods each having different focuses and the way conduct the test depends on the software requirements. In general, potential users are subjected to complete possible tasks throughout possible scenarios and recorded in the process. Then the session recordings are inspected by focusing on the desired criteria. [Rubin, Chisnell, 2008] One of the popular methods used in the validity check is known as think aloud protocol which is conducted by monitoring the users by observing and having verbal communications to determine the usability of the product. This method is effective especially for the software products for which the usability of the interface is crucial.

2.1.3 Acoustical Analysis and Simulation Tools: Advantages and Drawbacks

Starting from the mid 70's the number of simulation tools allowing handling large data sets and experiencing response of various systems to internal and external inputs have been increasing continuously in any discipline. Although a similar increase is observed in acoustics, the number of commercially available acoustic simulation tools is still very few. [http://www.acoustics.org/software.html] Among these acknowledged software, ODEON, EASE, CATT are the most popular ones and used extensively both in education and practice, yet their interface and the required input data imposes difficulties in using these tools as an integrated part of the design process and decision making tools. Hence, more research on the development of new acoustic design tools and the precision of the available ones and the expected precisions should be discussed.

The aforementioned acoustic simulation tools are mainly based on so called hybrid method, which is the combination of two statistical room acoustics methods namely, image source method and ray tracing method.

Image source method, which is based on the generation of virtual image sources at each reflection, is a more precise algorithm in cases which diffuse sound field is attained but computational cost of the algorithm is highly dependent on the complexity of the subjected geometry. For geometries with less complexity image source method is a much faster algorithm than the ray tracing, with some limitations. Image source method provide relatively less precise results for rooms where diffuse field is not achieved or impulse length is very long i.e. room is very reverberant. Computational cost of ray tracing algorithms is independent from complexity of the geometry subjected and relatively slower in simpler geometries but their sensitivity to diffuse field assumption is less. In ray tracing method, finite number of rays are generated from the source and traced until the rays hits a volume specified the resemble sound receiver. The drawback of the ray tracing method is that as the number of generated rays increase accuracy increases but also the computational cost does; so as the computational time is taken into account the results provided by both algorithms are comparable. With the hybrid method, fewer rays are generated and image source method is employed for the early reflections so the accuracy is improved while computational cost is decreased. It is also possible to employ image source method or ray tracing method only if the option is enabled. [ODEON, EASE, CATT]

Contemporary room acoustics simulation tools operate aiming high precision. Even though considerable discrepancies are observed between the results of the mentioned tools caused by employing different algorithms and lack of agreement on some calculation methods such as scattering, main focus of their orientation is to simulate the design in question with the highest convergence possible to obtain precise results. Thus, specific inputs are required for complex calculations such as precise design geometry and certain information about the sound source and sound receiver. The analysis results obtained through the simulations are mostly presented as graphical distributions of energy changes in the rooms and the qualitative evaluation parameters used in the room acoustics. However, requirement of precision and detailed information may form an obstacle for the integration of the mentioned tools to the whole design process in terms of both user interaction of the software interface and accessibility of the information required for the detailed analysis of the geometry especially in the early stages of design process.

Contemporary acoustical simulation and analysis tools are developed aiming to evaluate a given design, hence they are mostly used as post design tools rather than in design ones requiring complex solid models and detailed specifications from material to source and receiver positions. The required complexity of the model and detailed specifications for the acoustical analysis avoids the use of these tools in the pre-design and design phases and the use of them by any user profile which may not be competent in the acoustics. Thus the use of these simulation tools and their integration to the design process at any phase of the process to improve the performance is still a research question and needs to be improved.

Apart from the requirement of complexity of models and detailed specifications of several parameters, another problem faced while integrating mentioned software in design phases, is the usability of design interfaces of these software. These simulation tools are developed with the aim of analysis and simulation not for design. Hence, their integrated computer aided design (CAD) interfaces are relatively hard to use compared to commonly used CAD software used by designers. This is the reason why acoustical simulation tool companies provide plug-ins to CAD software to enable data import to simulation tools. Most of the acoustical simulation and analysis software focus on development of such data transfer plug-ins rather than improving design interface present within the software. Usage of the import/export plug-ins makes analysis of the design geometry simpler as the design process can be conducted within CAD software; however, continuous transition between two tools is required for continuous feedback about the acoustical performance of design.

2.2 APPLICABLE ROOM ACOUSTICS KNOWLEDGE TO PERFORMANCE MEASUREMENT AND OPTIMIZATION

Room acoustics theory is evolved parallel with the physics of wave up to the late 19th century when Sabine defined reverberation time as 60dB drop of the energy to define the sound characteristics in an enclosure in time. Since then, evaluation parameters defining the performance of the enclosed spaces have been and still are defined and proposed for further evaluation of acoustics.

In any enclosed space when an impulse is generated, a disturbance in the sound field is created which can be analyzed as the disturbance created by the source itself as direct sound and the disturbance provided by the reflections from the boundaries named as reverberant sound which superposes with the direct sound and the reflections themselves. As the sound propagates and reflects from the boundaries, sound rays lose energy which results in damping of the sound pressure/energy created by the sound source. After a while, sound field returns to its steady state. This alteration in the pressure in time is represented by impulse response graph. Impulse response, as being self explanatory, shows the response of the enclosure to a determined impulse created within the room and contains valuable information for the extraction of evaluation parameters in room acoustics. A typical measured impulse response is shown below:

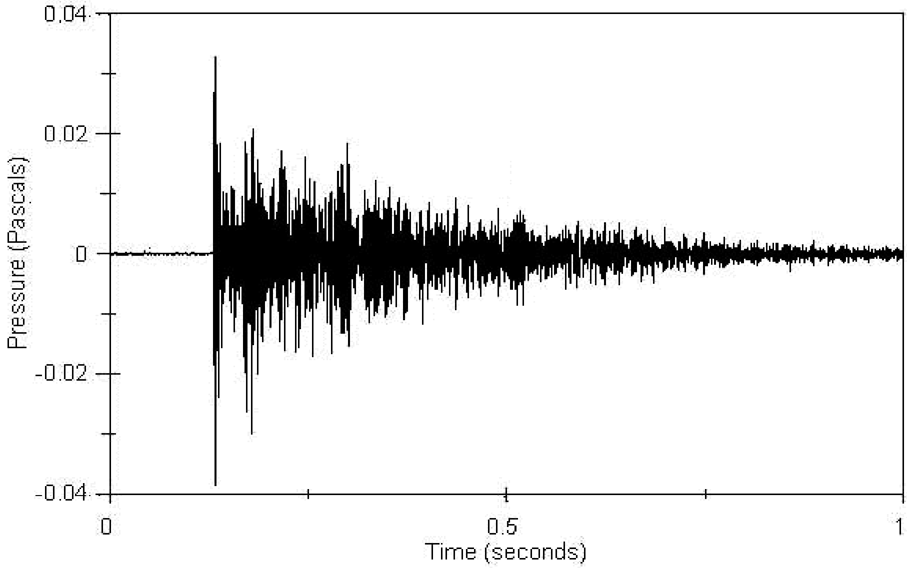


Figure 2. Measured impulse response

Measured impulse response in Pascals has positive and negative values caused by the waveform. However, when converted into dB scale the values become positive. It is possible to only obtain response of the room for an instantaneous impulse. Calculated impulse response diagram showing only the reflections and direct sound is shown below:

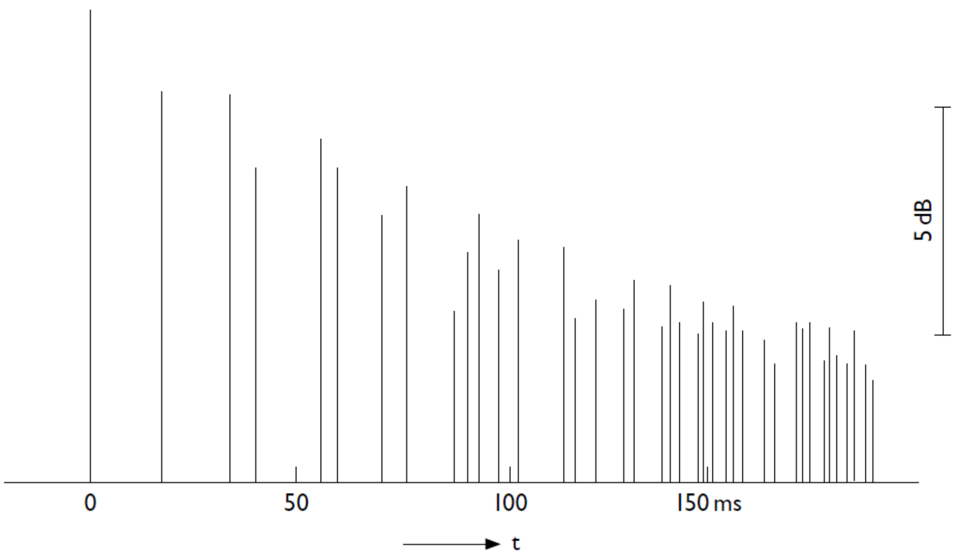


Figure 3. Calculated impulse response diagram [Kuttruff, 2006]

Geometrical room acoustics is a commonly used approach for the simulation of the sound field and the analysis in an enclosure to gather impulse response of the room. There are certain assumptions made for the analysis of sound field and the creation of impulse response diagram. In geometrical room acoustics, sound sources are treated as point sources generating a collection of rays and reflection of these rays from the boundaries are explained with the optical laws of reflection [Sorguç ,1990].

Several methods are developed to analyze the sound field in time following the geometrical room acoustics approach. Ray tracing method and image source method can be given as examples to these methods. With the advancements of the technology, a hybrid method comprising two methods to provide both fast and accurate results is also developed.

Both of the methods have certain advantages and drawbacks compared to their counterparts. In ray tracing method, the source is assumed to generate finite number of rays to all directions and the rays are traced until the pressure of the ray decreases under the level of threshold of hearing or a predetermined level or passes through a volume resembling the sound receiver. The rays passing through that volume are taken into account while calculating the pressure. When the rays hit a boundary, angle of reflection is calculated by the angle of incidence and energy of the ray is decreased by a proportion depending on the specifications of the surface material. To calculate impulse response of the room, pressures of the rays passing through the receiver volume are calculated from the boundaries they are reflected and they are marked according to their arrival times in the impulse response diagram. Since each ray is traced and the phenomena in the reflections are inspected, ray tracing is an accurate and powerful tool also considering diffraction. However, to gather very accurate results, the number of rays generated from the source must be increased to a considerable level which results in computational cost. This is the advantage of the counterpart of ray tracing method, image source method.

In image source method, all reflecting boundaries are assumed to be planar and if the boundaries have any curvature, they are segmented into planar surfaces. Then, image sources are generated from these surfaces until the desired order of reflection is reached. At each generation of image, the energy of the new image source is decreased with a proportion depending on the reflecting surface. Then the boundaries are removed and sound field is analyzed as free field. The method proved to be faster than ray tracing method but fails to take diffraction into consideration. Allen and Berkeley can be stated as the pioneers of the image source method used in the form of today's structure. [Allen, Berkeley, 1979] A figure resembling both methods is shown below. Straight lines indicate the ray traces and circles denote the image sources.

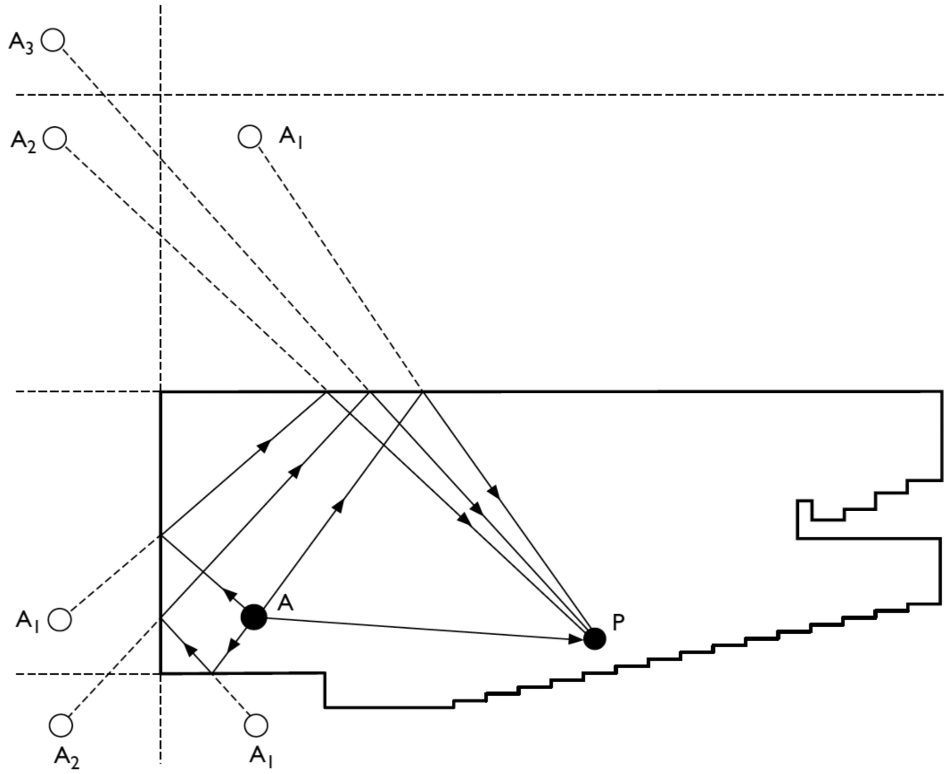


Figure 4. Ray paths and image sources [Kuttruff, 2006]

Once the impulse response of the room in time is found, many parameters can be calculated. Most of the parameters depend on the energy decay in the room and for the calculation impulse response has to be converted in order to obtain energy decay curve. Even though there are valuable works on optimization of the algorithm, the milestone is the Schroeder's backwards integration or tone-burst method formulation stated in 1964. [Schroder, 1964] Even though the method has been used for more than 50 years, it still conserves its validity and employed for its simple behavior. In this method, energy is calculated by adding the pressures from the latest to first. Then the energy has a linear damping curve and energy decay curve can be obtained by a curve fitting operation. Works of Lehmann and Johansson can be given as an example for one of the latest works for the application of Schroder's method of energy decay curve to image source method while constructing a closed formulation for the room impulse response. [Lehmann, Johansson, 2008] An impulse response and calculated Schroeder Curve is shown in the figure below:

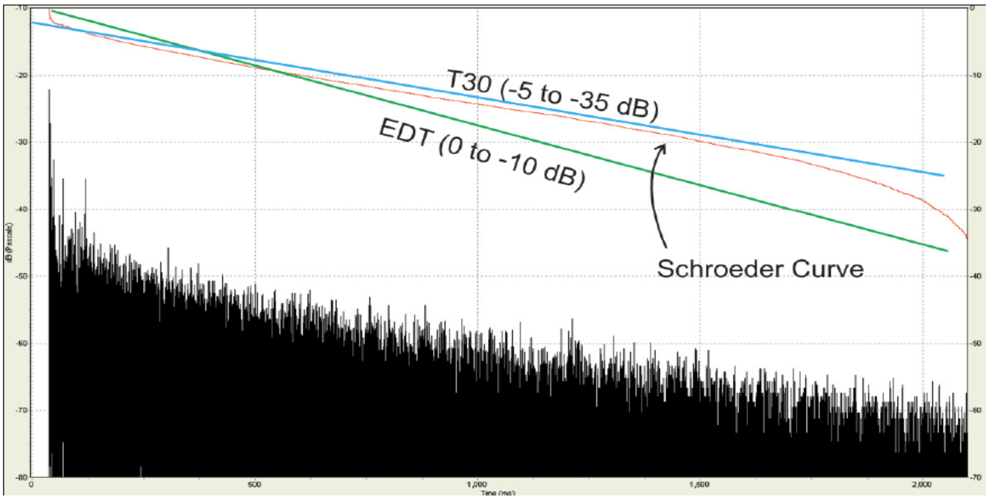


Figure 5. Impulse response and Schroeder curve

Even though, Schroeder's method is the most common method used and valid for the calculation of energy decay curve from measurement data or from calculated impulse response data with sufficient length to observe full energy decay, additional steps must be followed while applying Schroeder's method in cases which the impulse response length is not sufficient for the detection of full energy decay. While using image source method, it is not always possible to obtain an impulse response diagram with a time interval sufficient to observe 60dB drop of the energy curve. It is possible to calculate the energy decay curve with the well known Schroeder's backwards integration but in the case of insufficient impulse response length, a sudden drop caused by the absence of reflections obtained by higher orders occurs and this point of sudden drop has to be detected and the curve before that point is evaluated while calculating reverberation time. [Sorguç, 1990]

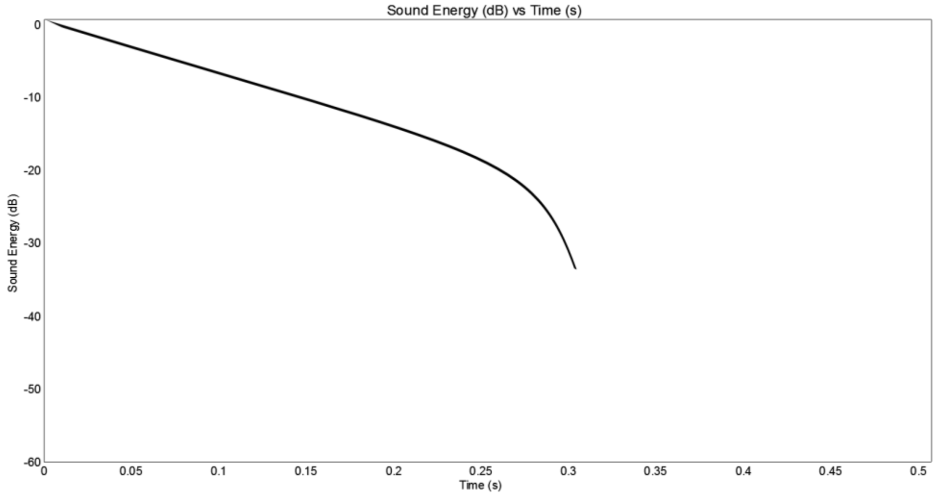


Figure 6. A typical Schroeder's curve with insufficient length to observe 60 dB energy drop

This breaking point showing the sudden drop in the energy is caused by the absence of late reflections which are to be obtained with higher order reflections. The selection of the breaking point of the energy decay curve is manually done and may be biased resulting in the manipulation of the results. Selection of the sudden drop point affects the slope of the energy decay. Conventional software facing these results either does not provide results warning users to change analysis setting or employ statistical methods such as extrapolation. However, there is not a standard which is agreed on.

Most of the evaluation parameters measuring the acoustical performance of a room is derived from impulse response diagram or energy decay curve which is also calculated from impulse response diagram. When impulse response of a room is obtained, objective room acoustics evaluation parameters can be extracted. Even though the debates of the usage of parameters still continues and new evaluation parameters are derived, there are certain accepted evaluation parameters which the acceptable ranges, calculation methods and definitions are determined. The formulations and acceptable ranges of accepted parameters are defined in international standards. [ISO3382, 2008] Also, a recent comprehensive work of Gonca Yıldırım, summarizes commonly used room evaluation parameters such as reverberation time, clarity, definition, etc by their definition and acceptable ranges.

CHAPTER 3

THEORETICAL BACKGROUND OF THE SOFTWARE: ROOM ACOUSTICS & IMAGE SOURCE METHOD

3.1 INTRODUCTION

In chapter 3, necessary information about the theoretical background of the acoustical simulation tool which is one of the main goals of the thesis will be discussed with the definitions and necessary formulation.

Since one of the focuses of the thesis is to provide an acoustical simulation tool, which can be integrated into the designing process from the preliminary and early design phases, goal brings some restrictions to be considered while implementing the tool. The mentioned tool has to be fast to provide feedback to user, accurate to provide information about the acoustical performance of the room and comprehensive enough to embrace both the users who do have and does not have advanced room acoustics knowledge by providing relevant outputs. Image source method is employed for the fulfillment of the requirements of the software program since it operates faster than ray tracing method when early reflections considered which provides information about the sound field accurately enough.

3.2 IMAGE SOURCE METHOD

Image source method, as a method for application of geometrical room acoustics, is based on the analogy of optics of physics which explains the phenomena of reflection from a source (light, sound, etc.) by generating a virtual image of the source generated by each surrounding boundary to find the impulse response of the enclosure. After the generation of the image sources, the reflecting boundaries are removed and the effects of the image source are investigated as there are no obstacles or boundaries, as a free field. There are certain assumptions of geometrical room acoustics approach generally and image source method specifically, which have been briefly described in the preceding section. These assumptions and restrictions will be dealt in detail to enlighten the applicable cases where the results remain valid.

First limitation of the image source method or geometrical room acoustics emerges at the relatively small rooms where the wavelength of the rays emitted by the sound source is comparable to the room dimensions. In optics, since the wavelengths of lights are never comparable to the dimensions of world of classical physics, this phenomenon is never a problem. However, in room acoustics, rays at low frequencies may have wavelengths large enough to be comparable to the dimensions of the room and at this case, a different phenomenon called room modes emerges and geometrical room acoustics begin to fail. For the application of the method, relatively large enclosures are the topic of interest. Hence, frequencies below 63 Hz, where room modes may emerge, are not investigated.

Also, in image sources, source is assumed to be a point source emitting spherical rays since generally source dimension is negligible compared to the room dimensions and most of the sources act as point sources at the range of room dimensions.

Diffraction, even though can be dealt with ray tracing method, is a phenomenon that cannot be considered while using method of image sources. Diffraction can be explained as the ability of a ray to go behind an obstacle. It is explained by Huygen's principle as "each wavefront acts as a sound source". In method of image sources, it is assumed that the sound cannot reach the acoustical shadow zone and regarded as invisible area from the point of source view. However, it is not the real phenomena but can be neglected for the calculations made for only gathering an idea about the sound field.

This drawback can be regarded as a sacrifice for computational speed since image source method has a considerable speed advantage against its counterparts. Also for the analysis of complex concave geometries such as L-shaped rooms, ray tracing method requires generation of considerably high number of rays since some of the rays are fades away by going under multiple reflections. For method of image sources, the operation is handled with the same computational cost regardless of the concaveness or convexness of the geometry. This are the main reasons that the image source method is employed for the software to be developed as a result of the thesis, since rapid feedbacks enough to give an idea are more important than the working slowly but with high precision.

3.2.1 Generation of Image Sources

Image sources are generated up to some pre-set order limited with the computational capacity of the computer which the algorithm is implemented. However, order of 5 and more gives an idea with the trend of pressure and energy decay within a room and full phenomena can be evaluated by statistical methods, such as curve fitting.

Generation of image sources is a geometrical problem and dealt with analytical geometry equations. In the image source methods, all surfaces are assumed to be planar and the surfaces with curvature are regarded as the combination of numerous plane surfaces in accordance with the required precision of the calculation. Since all the boundaries are assumed to be planar, the distance between the source and the surface can be calculated with the formula:

$$d = \frac{Ax_s + By_s + Cz_s + D}{\sqrt{A^2 + B^2 + C^2}} \tag{3.1}$$

Where the surface is defined as $Ax + By + Cz + D = 0$ and source which the images to be generated is defined as a point with coordinates (x_s, y_s, z_s).

Image coordinate can be calculated by the formula:

$$p' = p_0 - 2d\hat{n} \tag{3.2}$$

Where $\hat{n}$ is the unit normal vector of the surface and can be calculated from the three edge points p_1, p_2 and p_3 of the surface by:

$$\hat{n} = \frac{(p_2 - p_1) \times (p_3 - p_2)}{norm((p_2 - p_1) \times (p_3 - p_2))} \tag{3.3}$$

$\hat{n}$ always points inside the enclosure and points must be selected in that order.

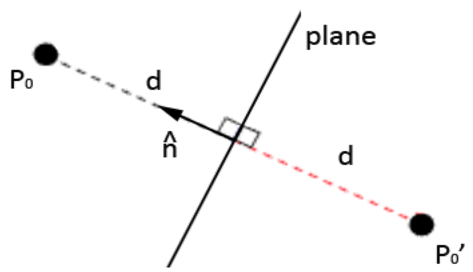


Figure 7. Reflection

After generating images from all of the surfaces, each image source acts as a real source and 2nd order image sources are generated from the 1st order image sources. Image source distribution for a rectangular enclosure is shown in the figure below:

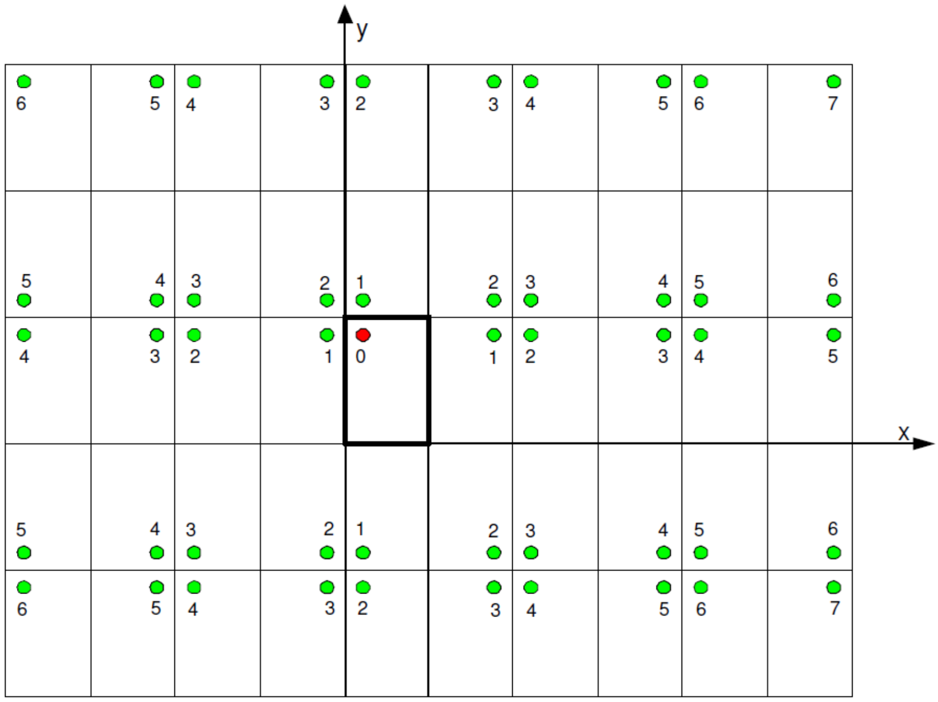


Figure 8. Two dimensional image source distribution [Collins, 2004]

Ideally number of images generated is

$$Number\ of\ images\ in\ i^{th} order = n^i \qquad (3.4)$$

Where *n* is the number of surfaces and *i* is the order of reflection. But this is never the case since sound rays propagate though a straight path and cannot be reflected from the latest surface they are reflected before hitting to another boundary surface or obstacle. So certain tests are applied to generated images to validate the existence of the images. In this thesis, two test regarding the validity and visibility of the images are conducted.

Validity Test

Image generation process is conducted with the boundaries / surfaces facing inside the enclosure. Hence, an image cannot be created from the back of a mirror. Validity test checks whether the images are generated from the front or back of the surfaces.

In the figure below, second order images generated from two surfaces by a source are shown. Even though three of the images are valid, one of four remains invalid since it is generated from the back of the reflecting surface. While checking the validity of an image, a perpendicular line is drawn from image to reflecting surface and the angle between this line and normal vector of the reflecting surface is compared. If the angle exceeds 90^0, the image is said to be invalid.

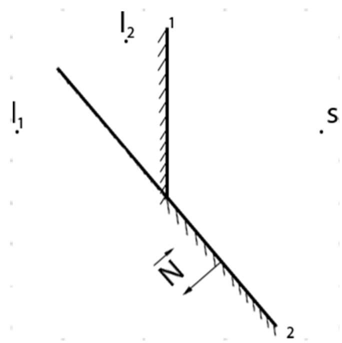


Figure 9. Validity test – I_1 visible image source, I_2, which is the second order reflection derived from I_1, is an invisible source

Another control mechanism can be stated from the definition of method of image sources. In the method of image sources, after generating all of the images the boundaries are removed and the sound field is analyzed as free field which means that sound rays are propagating continuously in the direction of emission. If an invalid image is generated from an image source (from the back of a reflecting plane) the distance from that image source to original source is smaller than the distance from the parent image source to original source. This approach is shown in the figure below:

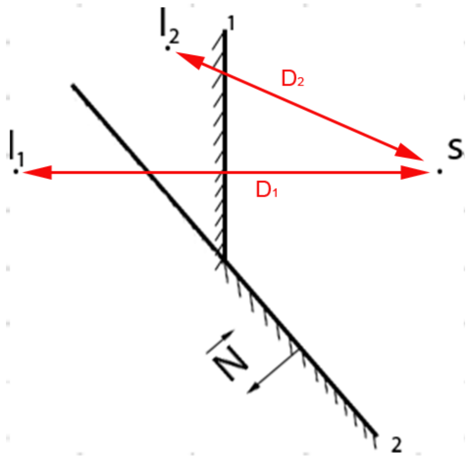


Figure 10. Validity Test – Visibility test by comparing distances of parent and child image sources to receiver

If an image source fails to be valid in any order, it is omitted from the calculation and the possible child image sources generated from that image source are not investigated.

Visibility Test

Image sources being valid do not necessarily qualify to participate in the sound field for a specific receiver location. Even though the image is generated from the fronts of the reflecting boundaries and being valid, they may reside in a volume which is blocked by an obstacle or another boundary which means that sound rays emitted from that image source fails to reach the receiver. Hence, the images are said to be invisible from the location of the receiver and are not taken into account while making the calculations. Visibility test is conducted as follows. A straight line is drawn from the image source to receiver point. If this line passes from the area occupied by the reflecting boundary, which the subjected image source is generated from, the image source is said to be valid. The test procedure is shown in the figure below.

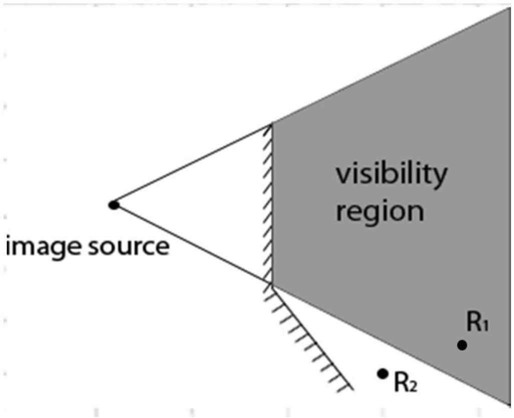


Figure 11. Visibility test, R_2 invisible, R_1 visible

Even though an image source can be invisible from the receiver location, it may generate child images which may be visible. So visibility test is applied after all the images are generated and validity test is applied. The ones which fail the visibility test are omitted from the calculation.

One of the most important things is to conduct validity test before the visibility test; since the image sources which fail the validity test cannot pass the visibility test. By this way in a rectangular room, more than 1500 image sources are omitted in an analysis of 5th degree image generation. There are also other tests that may be applied for the enhancement of computational speed. Termination criterion is an example of these tests which examines whether the image source has a pressure lower than the threshold of hearing or not. Since we cannot hear sound from these sources and they have a value lower than $2x10^{-5}$ Pa or 0 dB, they also do not contribute to the calculations. This test is mostly useful when absorption coefficients of the surfaces of the room are relatively high to damp the sound before the specified order of reflection is reached.

3.2.2 Processing The Images: Pressure Of The Generated Images

Generation of image sources is a matter of analytical geometry and up to this point nothing about the pressure or the energy of these image sources is explained. However, in order the make analysis of the subjected room, pressure and/or the energy of the image sources must be found.

Impulse response diagram is a graph showing the pressure damping in time which provides very important information about the changes in the sound field and the response of the enclosure as a measure of the acoustical performance. A closed space can be dealt like a system. In a case of disturbance in the system, space reacts with a response to this input. In the case of sound in enclosed spaces, this response can be evaluated in time scale. When impulse response of the room is investigated, first arriving sound is the direct sound emitted from the source. Then sound rays, reflected from a single surface will reach to the receiver, which are followed by sound rays reflected from two and three surfaces. Needless to say, some sound rays reflected from more surfaces may reach before the one reflected from fever surfaces. With each reflection some amount of the energy that sound ray contains is absorbed with a factor which is a property of the material that forms the surface, is called absorption coefficient and denoted with α.

As the result of the calculations of the pressures of arriving sound rays, an impulse response diagram is obtained.

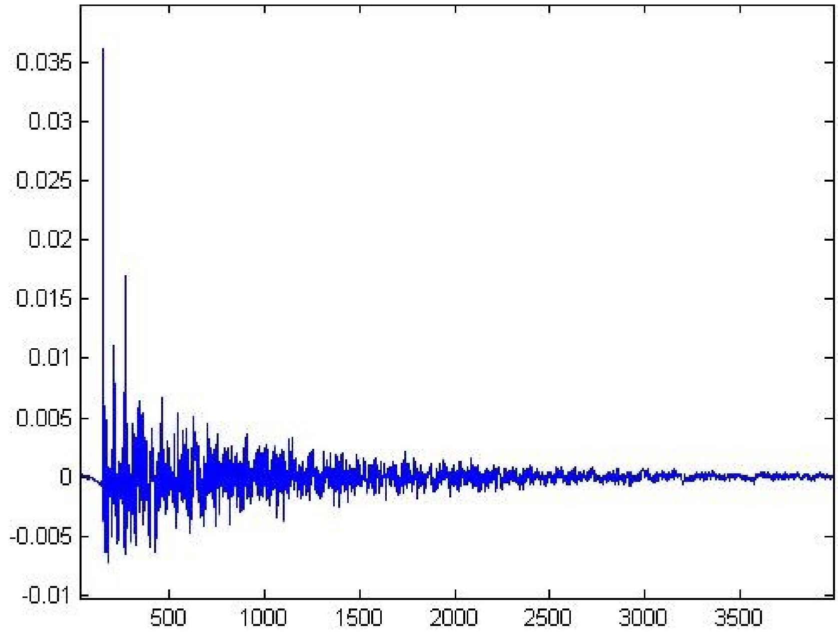


Figure 12. A typical impulse response graph (pressure vs time)

Most of the parameters interested while evaluating the sound field in an enclosure is derived from the change in energy in time which can be calculated from the pressure time graph or impulse response graph.

While conducting application of image source method, as after the generation of all image sources field is assumed to be free field; thus every image source is at a different distance from the receiver resulting in discrete arrival times of responses. Each unique arrival time is marked by a single line in the impulse response diagram at the corresponding time value. This application is shown by dirac delta function as:

$$p(t) = \delta[t - d/c]p_{image\ source} \tag{3.5}$$

In order to get rid of excessive number of image sources sampling rate of the echogram can be specified. In that case image sources residing at a distance with Δt separation are calculated as they are at the same distance. Specifying sampling rate brings a condition of $0 \leq t - d/c \leq \Delta t$.It is evident that, multiple rays may arrive within the specified time interval and this situation is reflected to the impulse response diagram by taking the RMS value of the incident rays.

While evaluating the sound field in an enclosure, images of the sound source are generated and the loop is followed up to the order desired by generating child image sources from the previous order images. After each reflection sound pressure is absorbed with a ratio of $(1-\alpha)^{1/2}$ where α is the absorption coefficient of the reflecting boundary which absorbs α of the incident sound power. Generally α has a value between 0 and 1. For each reflection a coefficient of $(1-\alpha)^{1/2}$ is integrated to the formula of sound pressure depending on the absorption coefficient of the boundary. Also, sound pressure has a dependency of distance since the pressure is inversely proportional to the distance. Summing up all above, sound pressure formula used in method of image sources become:

$$p(t) = (1-\alpha_1)^{1/2}(1-\alpha_2)^{1/2} \ldots (1-\alpha_i)^{1/2} \frac{\delta[t-d/c]}{4\pi d} \qquad (3.6)$$

For an image source which goes through *i* reflections and residing at a distance *d* and the pressure of the image source residing at a distance of *d* is reflected into the impulse response diagram at a time of *d/c* where *c* is the speed of sound. Then equation 3.6 becomes:

$$p(t) = \sum_{t=0}^{\infty} (1-\alpha_1)^{1/2}(1-\alpha_2)^{1/2} \ldots (1-\alpha_i)^{1/2} \frac{\delta[t-d/c]}{4\pi d} \qquad (3.7)$$

Once the image sources are generated and pressures are calculated in Pa scale, the values are converted to dB scale by taking the logarithm.

$$L_p = 20\log\left(\frac{P_{rms}}{P_{ref}}\right) \tag{3.8}$$

where $P_{ref} = 2x10^{-5}$ which is assumed to be threshold of hearing.

3.2.3 Room Acoustics Equation as a Test Function

Room acoustics equation gives the pressure level at a distance r if the sound power level at any frequency is known. It has two parts showing free field response and the participation of room itself as reverberant term. Well known room acoustics equation is shown below:

$$L_p = L_w + 10log\left(\frac{Q}{4\pi r^2} + \frac{MFP}{r}\frac{4}{S\left(\bar{\alpha}+\frac{4mV}{S}\right)}\right) \tag{3.9}$$

Where *Q* is the directivity factor of the sound source, *MFP* is the mean free path, *S* is the surface area, $\bar{\alpha}$ is the room average absorption coefficient, m is the air absorption and *V* is the volume of the enclosure. Definitions of $\bar{\alpha}$ and *MFP* can be stated as:

$$\bar{\alpha} = \frac{\sum_i \alpha_i S_i}{\sum_i S_i} \tag{3.10}$$

$$MFP = \frac{4V}{S} \tag{3.11}$$

Room acoustics equation enables the analysis of effect of air absorption which has a strong effect on the room response at high frequencies. From 2000Hz and above air absorption becomes more important since the wavelength (and the energy) gets smaller and easily affected from any absorbing material such as air.

For the application of image source method, reverberant term in equation 3.9 is since the first assumption of image source method is that the sound field is assumed to be free field after generation of the images. Also, directivity factor, Q, is taken as 1 since the source is assumed to be omnidirectional sound source in free field conditions. Then, room acoustics equation can be written as:

$$L_p = L_w + 10log\left(\frac{1}{4\pi r^2}\right) \tag{3.12}$$

While applying the room acoustics equation for image source method, sound power level of the image source can be found by multiplying with the reflecting surface as:

$$W_i = W(1-\alpha) \tag{3.13}$$

$$L_w = 10log\left(\frac{W_i}{10^{-12}}\right) \tag{3.14}$$

It is important to note that, while applying the equation is that the room acoustics equation can only be used for single source. However, while conducting image source method, numerous image sources are generated thus, some of the image sources arrive to the receiver point at the same time interval and had to be summed up according to superposition rules.

$$L_p = 20log\left[\sum_{i=0}^{N} 10^{(L_{p_i}/20)}\right] \tag{3.15}$$

3.3 ENERGY DECAY CURVE AND RELATED EVALUATION PARAMETERS

3.3.1 Schroder's Decay Curve

Energy decay curve is an important analysis as being a medium providing most of the objective evaluation used in room acoustics. Schroeder's decay curve is a result of Schroeder's method which is used to obtain energy decay curve from the response of the room.

While finding Schroeder's decay curve, backward integral of the impulse response is taken and converted into dB scale as:

$$E(t) = \frac{\int_t^{\infty} p^2 dt}{\int_0^{\infty} p^2 dt} \tag{3.16}$$

Then a curve fitting is done to calculate average energy decay in the room. By this way, response of the system is transferred from discrete time domain to continuous time domain which is the real case in an enclosure.

Reverberation time is an important objective criterion for the evaluation of room acoustics which resembles the 60dB decay of the energy from impulse energy. It is possible to calculate the reverberation time by calculating global estimated values as well as calculating from the energy decay curve for a specific receiver position. Three methods are commonly used for the calculation global estimates of reverberation, which are Sabine's Formula, Eyring Formula and Millington-Sette Formula. Sabine's formula, forming the base of the other two equations, gives results in agreement with the measurement especially for reverberant rooms. For less reverberant rooms Norris Eyring Formula gives better results and Millington-Sette Formula focuses on the rooms with materials with wide variety of absorption coefficients. These formulas are shown below:

$$RT = \frac{0{,}161V}{\sum_i \alpha_i S_i} \tag{3.17}$$

Sabine's Formula

where α is the absorption coefficient of a surface, *S* is the surface area and *V* is the volume of the enclosure.

$$RT = \frac{0,161V}{-Sln(1-\overline{\alpha_{av}})} \tag{3.18}$$

Eyring's Formula

where $\overline{\alpha_{av}}$ is the average absorption coefficient.

$$RT = \frac{0,161V}{-\sum_i S_i \ln{(1-\overline{\overline{\alpha_{av}}})}} \tag{3.19}$$

Millington-Sette Formula

3.3.2 Application of Schroeder's Method to Impulse Responses with Insufficient Length

It is known that computational cost exponentially increases as the order of reflection increases while using image source method. Caused by this exponentially increasing computational cost, image source method is either regarded as a method to calculate early reflections only or a valid method only for simple geometries such as rectangular prisms. [Chen, 2007, Christensen, 2011] Number of image sources with respect to order of reflection and plane number is given in Kuttruff's Room Acoustics book [Kuttruff, 2001] and is:

$$N(i) = N\frac{(N-1)^i-1}{N-2} \tag{1}$$

where $N(i)$ is the number of reflections, N is the number of planes and i is the order of reflection to be calculated.

While using image source method, it is not always possible to obtain an impulse response diagram with a time interval sufficient to observe 60dB drop of the energy curve. In such cases, a sudden drop caused by the absence of reflections obtained by higher orders occurs and this point of sudden drop has to be detected and the curve before that point is evaluated while calculating reverberation time as stated in chapter 2. [Sorguç, 1990] However, detection of sudden drop is rather a manual operation and thus may be biased and is subjective. A mid step modification is proposed to eliminate the possibility of biased selection of sudden drop and to construct a method to estimate reverberation time algorithmically. There are several propositions constructed in order to apply proposed method.

Firstly, expected reverberation time has to be known. The expected reverberation time can be calculated with the well known Sabine's, Eyring's or Millington-Sette's reverberation time formulae or can be determined with proposed measurement data if provided. In Schroeder's method of backwards integration, it is assumed that energy has a linear decay which has a 60dB drop at reverberation time. Thus, one can draw the ideal energy decay curve by simply calculating the line equation from two points.

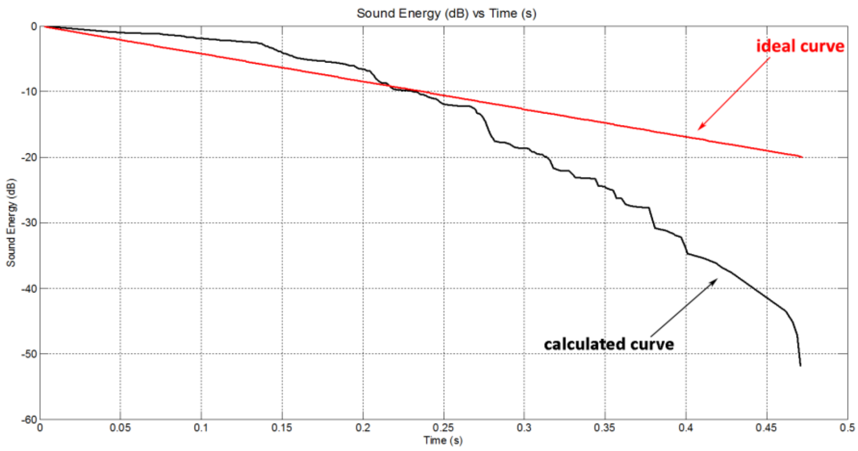


Figure 13. Ideal energy drop curve calculated from RT Sabine value and calculated energy decay curve

Secondly, as Schroeder's backwards integration method prescribes, the data values are calculated by adding sound pressures. Maximum effect of adding two sound pressure levels is observed in the case of two equal sound pressure addition and results in 6 dB increase which is reflected to energy decay curve as a 6dB drop. It is a known fact that sound pressure level (and also sound energy level) fluctuates until the room reaches its steady state. However, a fluctuation exceeding 6 dB level can be interpreted as an indicator of sudden energy drop which is sought with the proposed method. Hence, a 6dB lower barrier is drawn to detect the sudden energy drop and the values below the barrier are omitted in the subsequent calculations. 6 dB barrier, omitted and valid data are as shown below:

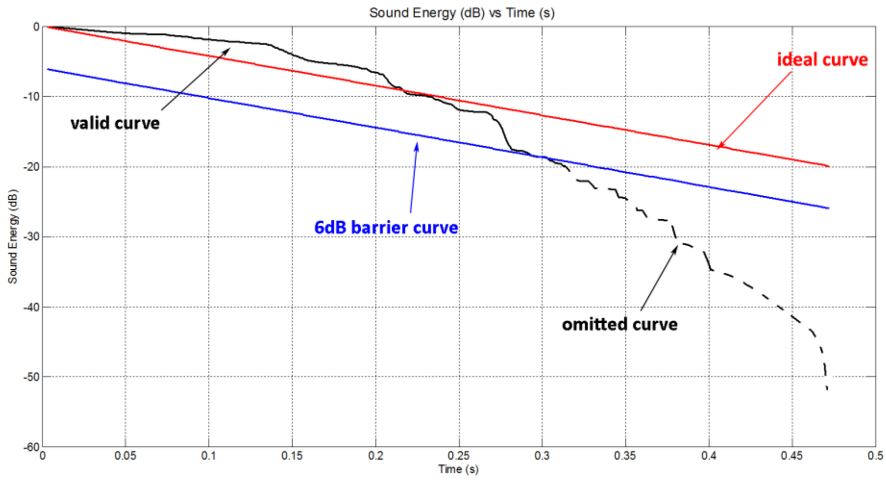


Figure 14. Extracting valid sound energy decay data using 6dB barrier

Sudden energy drop point does not necessarily have to be the intersection point of the calculated energy decay curve and the 6dB barrier curve. Sudden drop may begin before the intersection time but still may consist data points before reaching the barrier which results in underestimated results of reverberation time. In order to avoid this situation, data points are extrapolated with the expected reverberation time with equal weights with any data point. Then linear curve fitting is applied to estimate the reverberation time. By this way, remaining data from the sudden drop is compensated and yet calculated energy decay curve data is the dominant factor influencing the fitted energy decay curve and thus reverberation time.

With the proposed mid step modification to Schroeder's backwards integration method, it is possible to estimate reverberation time even if the impulse response length is not sufficient or the concerned design is more complex than a rectangular prism. With the increasing impulse response length, the results converges to conventional method results, thus as more the impulse response data is gathered by means of simulations, accuracy of the estimates will be higher. An important factor to consider is determining the quick/global estimates. This step is prone to be biased since determining the estimate is done with the initiative of the user. Also, Sabine's, Eyring's and other estimation methods have their own limitations in terms of average absorption coefficients and thus the estimate shall be selected carefully by considering these limitations. However, it is seen that with the presence of an estimate which is known to be valid, proposed modification provides accurate reverberation time estimates.

3.3.3 Room Acoustics Evaluation Parameters Derived from the Energy Curve

Although it is possible to obtain numerous evaluation parameters which can be derived from the energy decay curve, there are parameters that should be taken into accounted which are determined by international standards. (ISO3382, 2008) The major evaluation parameters that will be taken into account within the scope of the thesis are explained in the table below together with the acceptable ranges and how they are derived from impulse response or energy decay curve:

Table 1. Acoustical evaluation parameters, definitions, reference values and corresponding subjective quality [Yıldırım, 2011]

Acoustical Evaluation Parameter	Definition	Reference Value	Corresponding Subjective quality
RT in s	Reverberation Time, is the time required for the reverberant sound level to decay 60 dB below the maximum. It is measured between -5 and -35 dB. and then doubled. (Long, 2006) RT varies little throughout a well-designed auditorium. (Barron, 2006) It tends to be constant throughout the hall. (Barron, 2009)	Concert Halls 1.8 ≤ RT ≤ 2.2 (Barron, 2005) Speech 0.7-1.0 (Barron,1993 for 500 Hz) Opera 1.3-1.8 (Barron,1993 for 500 Hz)	Clarity Liveness Brilliance
D50 in %	Definition/ The distinctness of the speech. The ratio of early reflections energy to total energy within 50 miliseconds.	0.34 (Cremer,1982) 0.56 (Bradley,1986) 0.4 - 0.6 (Gimenez, 1988) 0.45-0.55 (Hilbert,1982) Conference ≥65 (Riberio, 2002) Music 45<D≤ 60 (Riberio, 2002)	Intelligibility
C80 in dB	Clarity/Early to late sound index is the difference of the sound energy received at a listener in the first 80 milliseconds minus the (late) reverberant energy (all remaining sound energy)	-4<C80<4 (???) 0 (Cremer, 1982) -4 - 0 (Beranek, 1996) -2 - +2 (Barron, 1993) -1 - +1 (Hyde, 1994) Symphony -1-+2 (Hyde, 2006) -2- +4 (Çalışkan, 2002)	Clarity
Ts in ms	Central Time is the time of the centre of gravity of the squared impulse response	<140 (Cremer, 1988) Ts=RT/0.0138 (Kurtulan,2009)	Clarity Liveness
ITDG in ms	Initial Time Delay Gap is the interval between the arrival of the direct sound and the first reflection at the listener	<25 (Beranek,1996) ≤ 20 (Hidaka,2004) Lack of intimacy if >35ms (Beranek, 2008)	Intimacy Clarity

The parameters are selected to give relevant information throughout to design process and highly dependent on volume and geometry of the design. ITDG parameter is omitted in the algorithm of the program later since ITDG requires more information about the design such as seating area. In general, while calculating ITDG, first reflection is created by ceiling, lateral walls or back of the stage. Floor surface generally does not participate for the first reflections since floor surface is generally occupied with seating areas which is highly scattering. It may not be feasible to identify to seating area in the early stages of design, ITDG parameter is omitted and parameters involved with volume, material and geometry are included in the program.

3.4 AURALIZATION

Auralization is a word developed with the analogous to visualization. It is the simulation of sound field in a virtual medium. It can be perceived as a possible output derived from the impulse response of an enclosure which may also be easily understood by the people who are not very familiar with the theory of room acoustics.

Auralization is a signal processing process where the original signal is convolved with any given impulse response. In many applications, for the sake of simplicity, original sound can be taken as an instantaneous impulse signal. Energy decay curve reflects the energy damping of the system which the impulse is given, but as the convolution of a continuous function requires excessive computational cost, impulse response is used instead. Auralization process is demonstrated in the figure below:

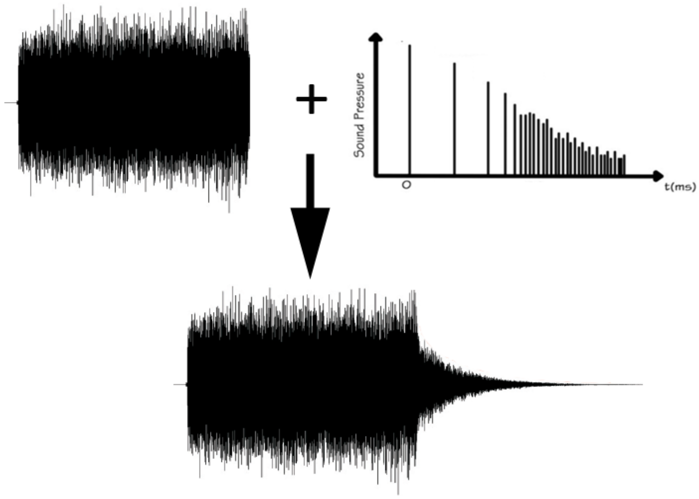


Figure 15. Auralization process

Convolution is denoted by an asterisk and the formula for continuous time domain is shown below:

$$(f * g)(t) = \int f(\tau) g(t - \tau) d\tau \tag{3.23}$$

When working on discrete time domain, integral is replaced by summation sign. Expansion of the formula can be stated as:

$f(1) = f(1) * g(1)$
$f(2) = f(1) * g(2) + f(2) * g(1)$
$f(3) = f(1) * g(3) + f(2) * g(2) + f(3) * g(1)$
…
$f(n) = f(1) * g(n) + f(2) * g(n-1) + \cdots + f(n) * g(1)$
…
$f(2n - 1) = f(n) * g(n)$

As absorption is frequency dependent parameter, thus impulse response should be obtained in the frequency band of interest. Hence, in order to apply convolution process must be converted into frequency domain by taking Fourier transformation and the resulting signals after convolution is collected back together with inverse Fourier transformation.

CHAPTER 4

INTERFACE DEVELOPMENT – PROCESS AND VERIFICATION

4.1 OBJECTIVES OF THE COMPUTER PROGRAM

Motivated by the absence of an acoustical simulation and analysis software which is integrable to pre design and design phases, a computer program is proposed to be developed. As having such a specific goal, several objectives are determined to accomplish which are listed below:

1. Program shall provide comprehensible information about the acoustical performance both as numerical analysis results of room acoustics evaluation parameters and as aural experience,

2. Program shall be easy to use and it shall provide rapid feedback about the acoustical performance of the room subjected to be an integral part of the designing process,

3. Program shall require simple and procurable inputs about the design at any level of the design process,

4. The program shall provide comprehensible and enlightening feedbacks as outputs to contribute the optimization of the acoustical performance of the subjected room to any user having room acoustics knowledge at any level.

The room acoustics program developed in this study which is named Room Acoustics Tool (RAT) and is capable of computing any acoustic parameter used in the evaluation of rooms since it calculates the room parameters by means of simulating impulse response of the room, yet, since the objective is to create a pre-design and then recursive design tool for design optimization regardless of the user's experience, only highly acknowledged major evaluation parameters are included in this version. The program development environment has been chosen as, MATLAB which is a versatile programming language, having easy data management and several toolboxes and built-in allowing constructing the image source method at ease. MATLAB also provides interface and compiling support to construct standalone programs. Furthermore, another reason of choosing MATLAB as the programming language is the efficiency of construction of algorithms based on mathematics operations. Complex functions are provided as built-in functions within MATLAB as well as algorithms which can be shared among MATLAB users as being an open source platform. For the sake of simplicity, only the algorithm structure is given in this chapter since processes followed in the algorithm is explained in detail in the previous chapter. Main focus of this chapter is to explain the interface elements, development process, and verification of the interface developed by means of usability test. Algorithm structure is shown below:

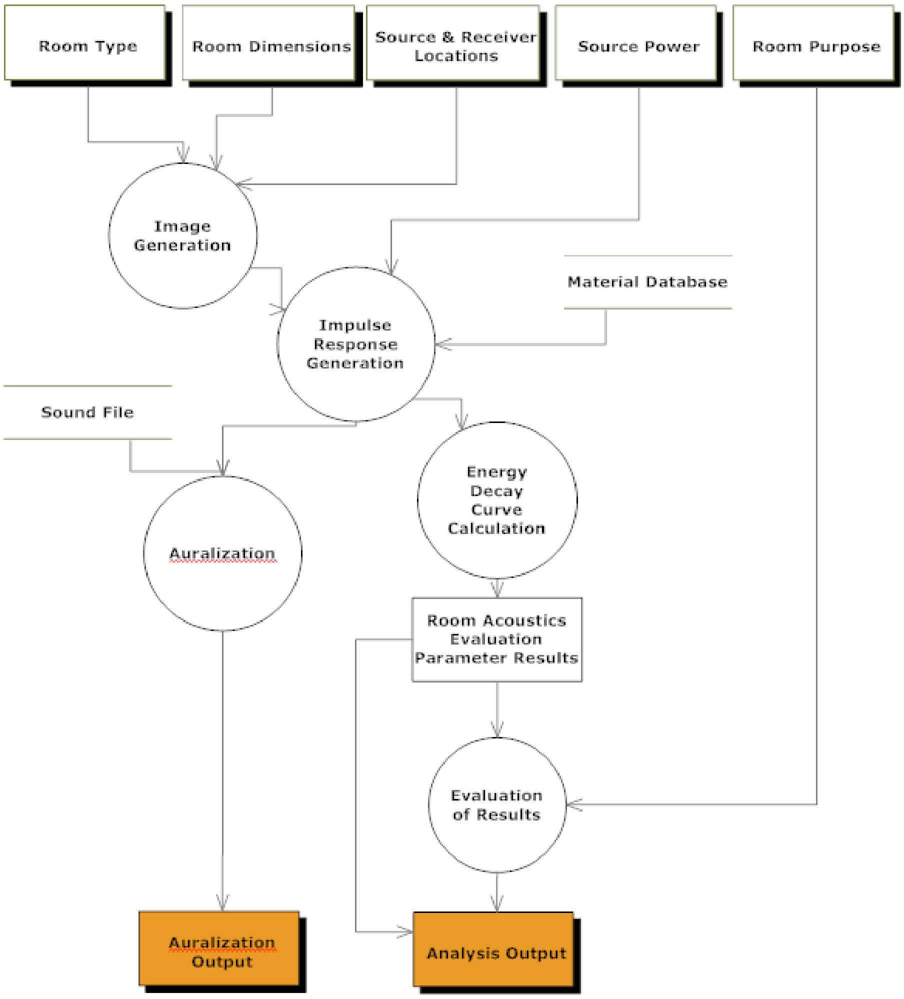


Figure 16. Data flow diagram showing program structure

4.2 INTERFACE : INPUTS

Since the main objective of the development of the acoustical simulation program in this study is the integration of the "tool" and thus the knowledge to the design process (especially early design phase), the input output relations on the interface and the results are designed to provide feedbacks, guiding the user to enhance the acoustical qualities. The complexity of the interface is minimized to encourage any user even the inexperienced ones to be able to employ in the design process. Hence an outmost care has to be given to optimize the ease of use and usability test has been carried on to improve the interface.

The required parameters for the conduction of image source method to enable acoustical simulation are: the main form of the hall, sound source and receiver positions, sound source pressure/power and the materials and their absorption coefficients in full octave band to be used in the surfaces of the design.

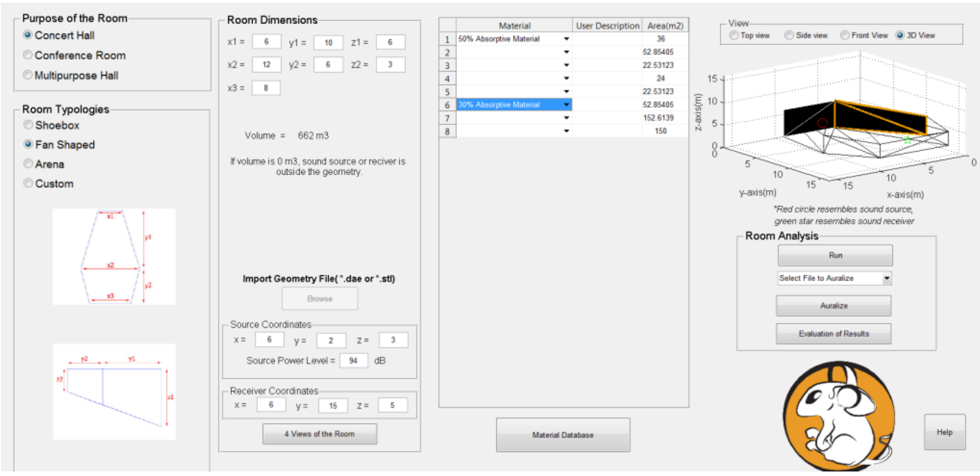


Figure 17. Main interface

Firstly room type and room purpose are specified in the ‘Room Purpose’ and ‘Room Typologies’ panels. Room purpose selection does not have any effect on main interface but determines the acceptable ranges of the room acoustics evaluation parameters which are shown in ‘Evaluation of Results’ output window. In the ‘Room Typologies’ panel, there are four options present. First three options are basic auditorium types to provide possible options for the users who may not have any expertise in acoustics. Exploring typologies for the forthcoming design, three room types as shoebox, fan shaped and arena are provided since in this choice, no curvilinear forms which require more advanced expertise are offered and these forms can be described simply with x, y and z parameters. If one of the three options is selected, required room dimensions are entered from the ‘Room Dimensions’ panel and the changes are reflected to the perspective view of the design shown in the right top of the interface. What these parameters refer to is shown by legends at the bottom of the ‘Room Type’ panel. In this way, it is easy to change the dimensions and thus the volume of the room of the choice.

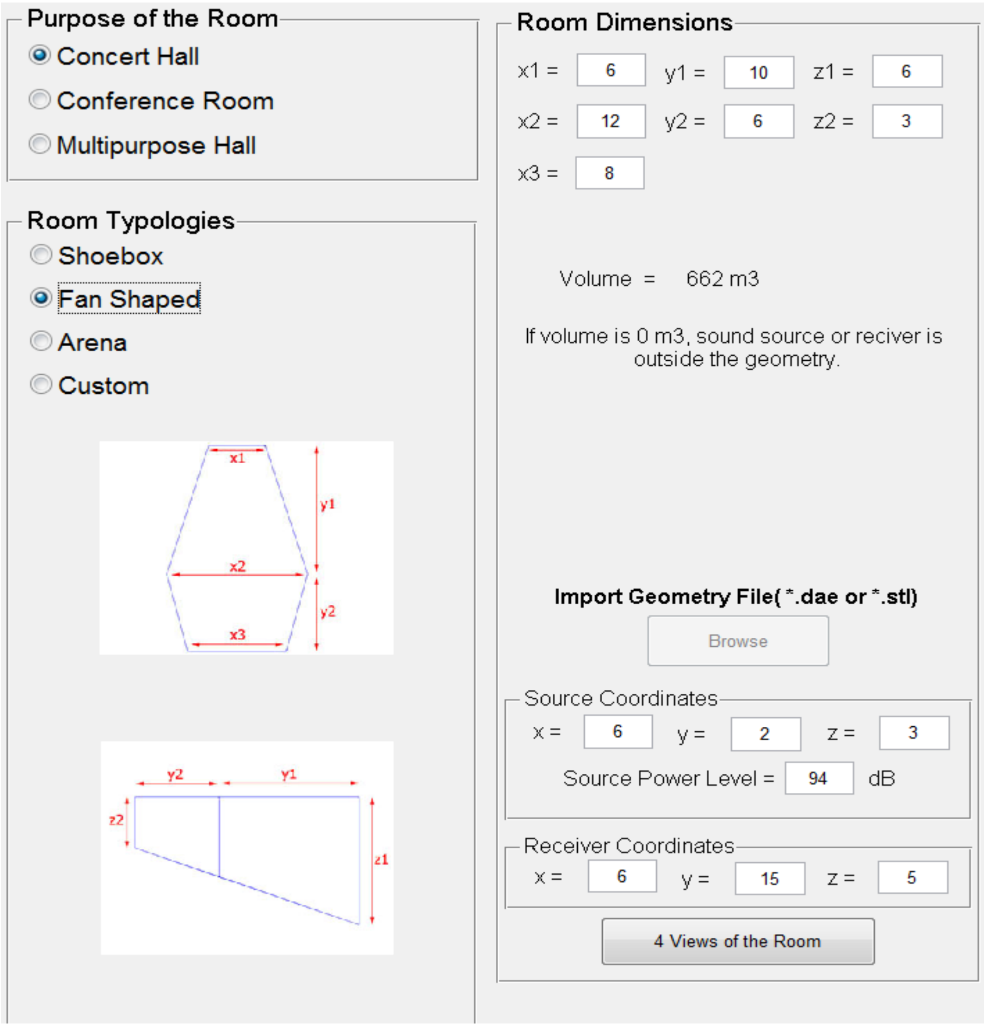


Figure 18. ‘Room Purpose’, ‘Room Typologies’ and ‘Room Dimensions’ panels

Curvilinear room types with curvatures are not included in this part requiring more parameters such as sweep angle, center of the curvature and number of segments but it is much easier to import designs to the program from any CAD software which the user is familiar with. If user desires to analyze customized form, ‘Custom’ option is selected and a dialog box appears to request the location of the design file. Program supports *.stl and *dae formats. Stl format is used for stereolithography and supported by almost all CAD software and Dae format is the acronym for digital asset exchange and supported by Google SketchUp software. Designs from almost all CAD software can be imported to the developed program. Also, in ‘Custom’ option, the design is visualized after locating the design file by clicking ‘Browse button’. When customized forms are imported, CAD software automatically divides curvatures into planar segments as specified while saving as stl or dae file.

When room type and dimensions are specified, receiver and source positions have to be entered in the relevant fields. In order to carry the analysis both the source and the receiver have to be inside the enclosure. If sound source or receiver is outside the geometry or the geometry imported is not a closed room, volume is shown as 0 to warn the users that the computation cannot be done. The locations of sound source and receiver can be checked from the pop up window for visualizing the design by clicking the ‘4 Views of the Room’ button. The pop up window contains top, side, section and perspective views of the design including source and receiver.

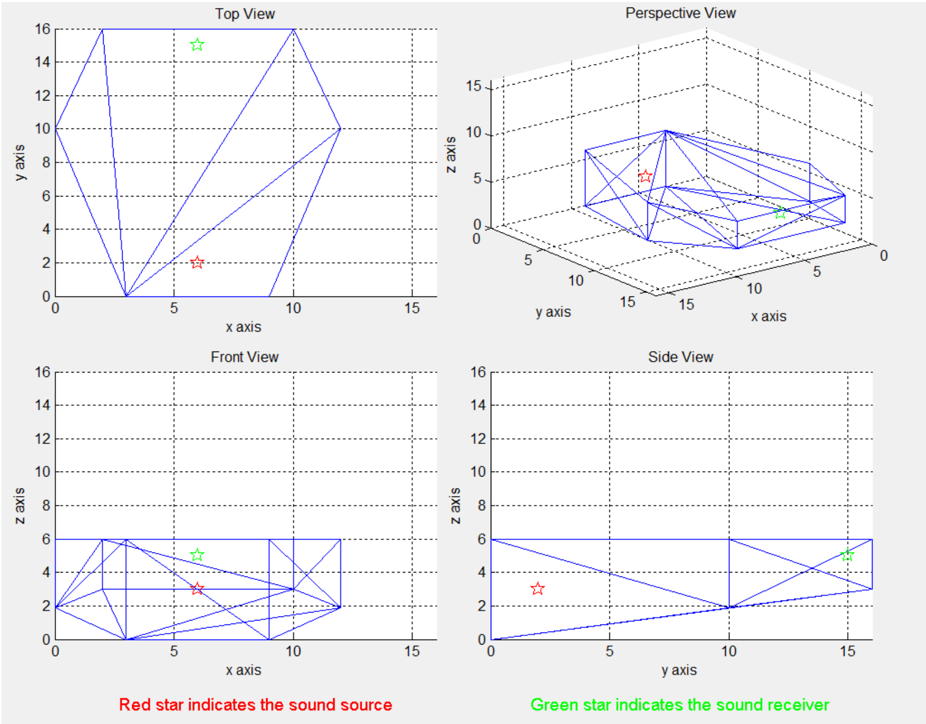


Figure 19. '4 Views of the Room' window

Source and receiver are also shown in the room view present in the main interface and it is possible to switch between View options.

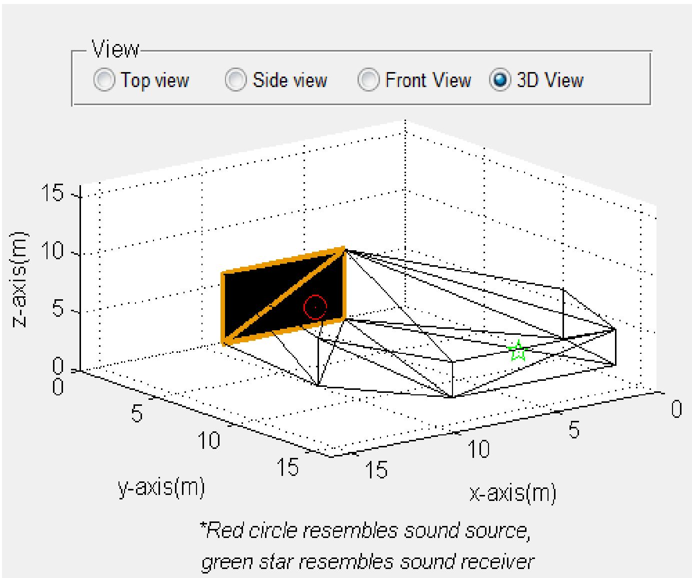


Figure 20. Room view in the main interface

Once the model is completely constructed, user specifies material information of the surfaces from the ‘Material’ table. As the rows are selected, the surface corresponding to the row is highlighted with orange and remains black when a material is assigned on. The perspective view is rotatable in 3d to ease allow the identification of surfaces which no material is assigned on. Also a space is provided in each row for users to take notes about the surfaces if necessary and surface areas are also provided for each surface.

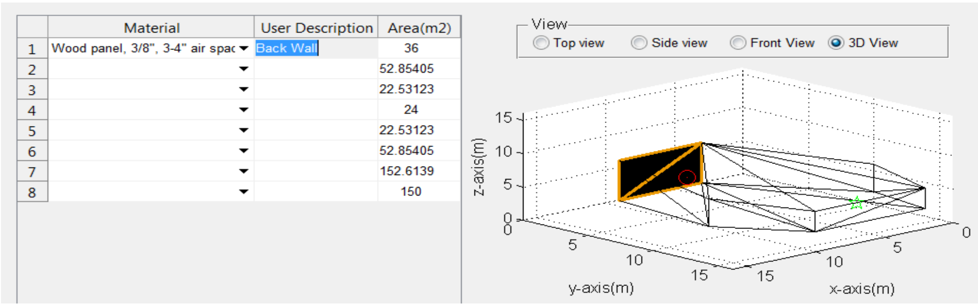


Figure 21. Surface table and corresponding room view

The user can further access the information about the sound absorption coefficients of the material by accessing the material database by clicking the ‘Material Database’ button. When the button is clicked, another pop up window showing the materials and their absorption coefficients is displayed. It is also possible to add new material to the material database. It is also possible to create a patched surface material if design contains an abstraction involving a surface formed by two or more types of material. In such a case, user determines the area and absorption coefficient of each material and program calculates average absorption coefficient for this surface. It is a useful tool especially for the pre and early phases of design. ‘Material Database’ window is shown below:

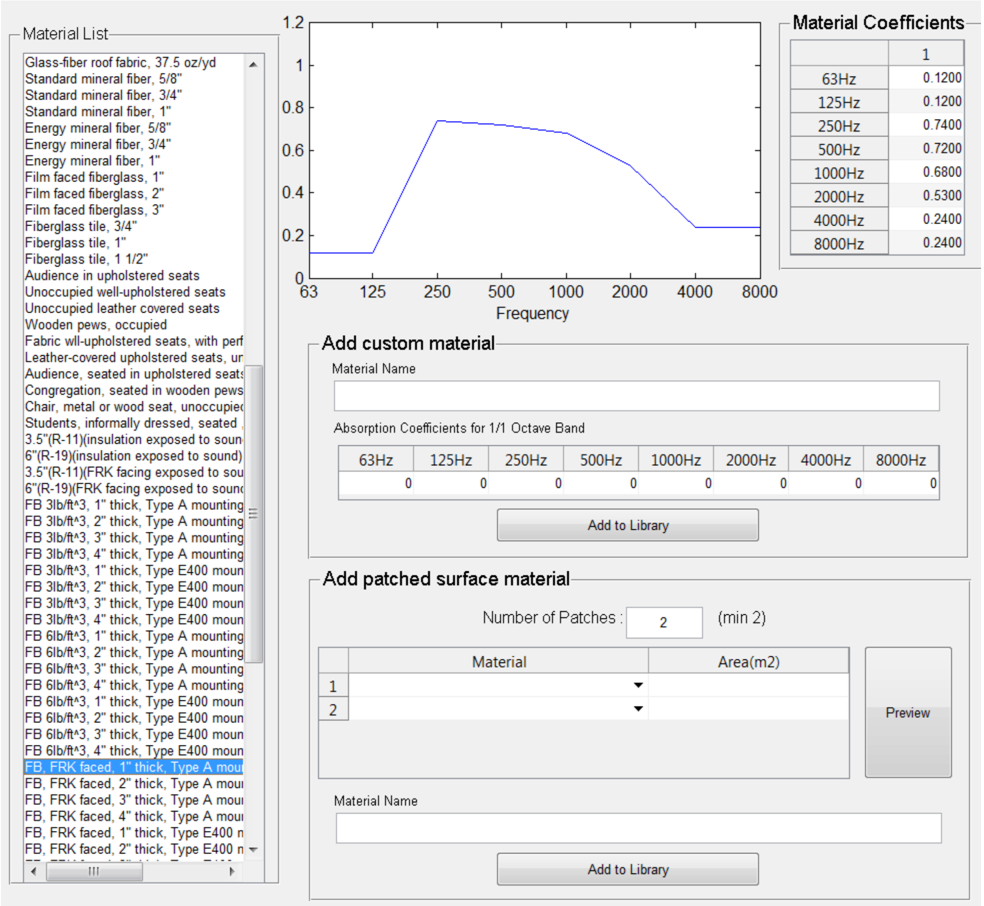


Figure 22. ‘Material Database’ window

Another parameter that has to be specified is the sound power level of the source in dB scale. With the specification of the sound power level all the inputs are specified and calculations are made by clicking ‘Run’ button.

If user desires to experience the room by means of listening the possible sound in the room, he or she specifies the sound file to be processed after the calculation is completed via a dropdown menu in the main interface. There are several sound files in the library of the program such as ‘Speech’, ‘Organ Music, ‘Jazz’, ‘Classical Music’, ‘Pop’. Also, it is possible to import any sound file with *.wav extension by selecting ‘Browse’ option.

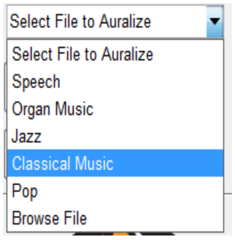


Figure 23. Dropdown menu for the selection of sound file for auralization

4.3 INTERFACE : PROVIDED OUTPUTS

In order to obtain easy to use program for all users regardless of their knowledge in room acoustics, outputs also have to be easily comprehensible. In this context, two types of output are considered to be provided.

First output is the auralization result as an audio file. Any designer even not experienced ones on room acoustics may use the auralization output, if s/he has an idea of how the room must sound like. If there are considerable design errors/deficiencies, they are reflected in the audio output as echoes, etc. If these defects are not present, the evaluation of the audio output becomes a subjective evaluation of the user and a method of design exploration.

When the computation is completed after clicking ‘Run’ button, sound file to be auralized is selected from the dropdown menu. When the sound file is specified, user can access to the aural output by clicking ‘Auralize’ button. When the auralization process is completed a window consisting a mini media player opens. Users have options such as ‘play’, ‘pause’, ‘stop’ and ‘save file’ for both the original sound file and auralization output. If user desires, he or she can save the file by specifying the target location and file name for the output file.

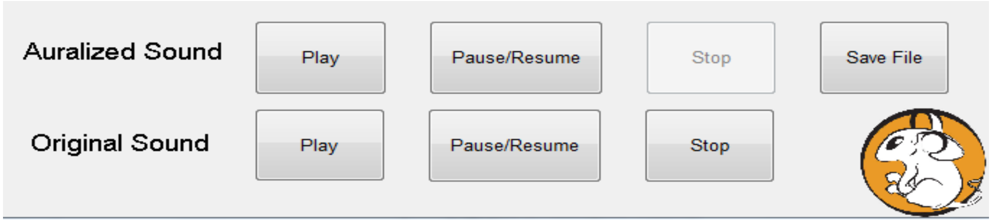
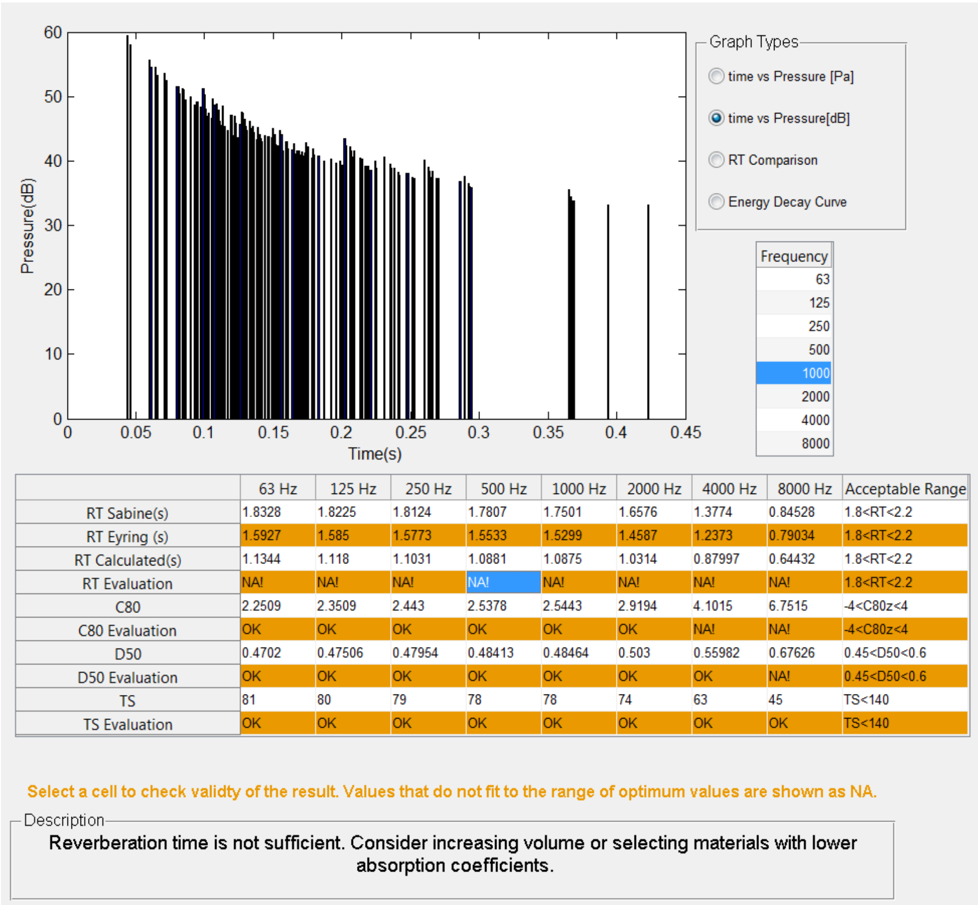


Figure 24. Auralization window

Second type of output in the program is the window which numerical results and their evaluations are present. This window automatically opens when the computation is completed after clicking the 'Run' button. It is also accessible by clicking 'Evaluation of the Results' button from the main interface.



	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz	Acceptable Range
RT Sabine(s)	1.8328	1.8225	1.8124	1.7807	1.7501	1.6576	1.3774	0.84528	1.8<RT<2.2
RT Eyring (s)	1.5927	1.585	1.5773	1.5533	1.5299	1.4587	1.2373	0.79034	1.8<RT<2.2
RT Calculated(s)	1.1344	1.118	1.1031	1.0881	1.0875	1.0314	0.87997	0.64432	1.8<RT<2.2
RT Evaluation	NA!	NA!	NA!	NA!	NA!	NA!	NA!	NA!	1.8<RT<2.2
C80	2.2509	2.3509	2.443	2.5378	2.5443	2.9194	4.1015	6.7515	-4<C80z<4
C80 Evaluation	OK	OK	OK	OK	OK	OK	NA!	NA!	-4<C80z<4
D50	0.4702	0.47506	0.47954	0.48413	0.48464	0.503	0.55982	0.67626	0.45<D50<0.6
D50 Evaluation	OK	OK	OK	OK	OK	OK	OK	NA!	0.45<D50<0.6
TS	81	80	79	78	78	74	63	45	TS<140
TS Evaluation	OK	OK	OK	OK	OK	OK	OK	OK	TS<140

Figure 25. Advanced analysis window

In the window, a graph and a table provides information about evaluation of the acoustical performance of the design. This window compromises several major evaluation parameters used in the room acoustics requiring some expertise in the field. In the provided graph, impulse response of the room can be viewed in dB or Pa scale, Reverberation Time calculated can be compared with the global estimate calculated by Sabine's and Eyring's reverberation time equation and Energy Decay Curve can also be viewed. Numerical results of the evaluation parameters are provided in the table below the graphs. In order to embrace inexperienced users in acoustics, evaluated parameters' results have been accompanied by the comments showing the acceptability of those parameters and thus the acoustics of the room. The values and ranges employed in checking the acoustics of the proposed design are highly acknowledged by the experts in this field as stated in the chapter 3. This feature is one of the major contributions of the present study to the acoustical design and design performance studies. Feedbacks guide designer to revise the design decisions, modify or in general can be considered as go-no-go. Hence it is expected designers to improve their design and thus the performance. In the table provided in the middle part of the window, numerical values of the parameters, reverberation time (both quick estimate and calculated), definition, clarity and central time are provided together with the acceptable ranges of the corresponding evaluation parameters for concert halls and the verbal evaluation of these parameters as "NA!" (Not Acceptable) and "OK". When one of the cells is clicked on, brief information on the evaluation parameters is given followed by the possible causes of the parameter to be outside the acceptable range and possible solutions.

The numerical information provided in the table may not be completely understood by the designer who has not experience in acoustics. Hence, the values shown in the table are processed by the program in order to evaluate the qualities of the present design with the recommended values in literature as a feedback. In this way, program can be used by any user profile and in any phase of the design as well.

4.4 STRUCTURE OF THE PROGRAM

The program is constructed to provide numerical results in a rapid and easy to understand way. The main aim of the construction of the software is to integrate room acoustics simulation and analysis throughout the designing process to optimize the acoustical performance of the design. The optimization can be done by constructing a closed loop control system with feedback mechanism.

The algorithm can be stated as a transfer function or a plant function since the algorithm requires definite inputs and provides definite outputs. Since it is not possible to formulate such a comprehensive algorithm with formulation, structure of the software is shown below:

If the software is symbolized as a plant function, the control loop can be defined as:

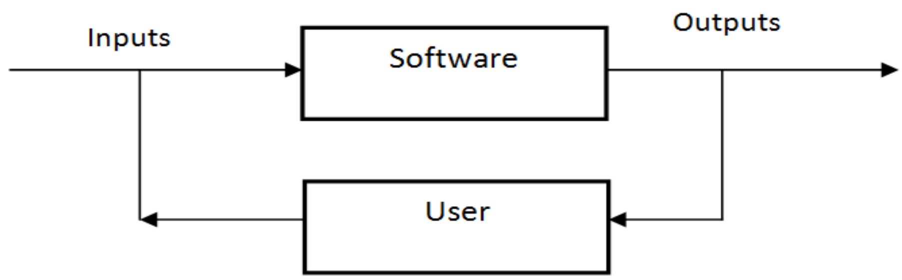


Figure 26. Closed control loop involving user

Since program does not provide artificial intelligence, aim of the program is to provide feedbacks to user who may or may not (depending on the designs acoustical performance) to provide inputs regarding the feedback gathered from the program.

4.5 VERIFICATION OF THE INTERFACE AND PROGRAM STRUCTURE: USABILITY TEST

One of the most crucial aspects of the program developed is the usability of the interface. Hence, the usability of the program is tested by means of usability test via a protocol after determining the usability criteria to be focused on.

Developed program is expected to be useful, efficient and learnable. Usefulness criteria refers to ability of the product to serve the users while users try to reach their goals, Efficiency is a measure of time and refers to how quick the product enables users to complete their goals whereas learnability refers to the competence of users to operate the product after some predetermined time is elapsed. [Rubin, Chisnell, 2008]

For the conduction of usability test, a think aloud protocol is built.5 participants are subjected to the protocol and requested to complete two tasks. These tasks are satisfying 3 acoustical parameters out of 4 for 1000Hz by deigning via a predetermined room type and via importing a custom design. The reason of choosing 1000Hz is for the sake of simplicity and to observe the usefulness of feedbacks and duration of these feedback loops. 5 participants are selected to represent different user profiles and include users who have acoustical knowledge and no knowledge at all. While conducting the protocol participants are requested to think aloud and follow their visual focus points by the mouse cursor. Sessions are recorded both by sound recordings and screen captures. Then the tasks are divided into ideal steps to be followed and both the durations of these steps and feedbacks used for the completion of the tasks are inspected. The results are shown below:

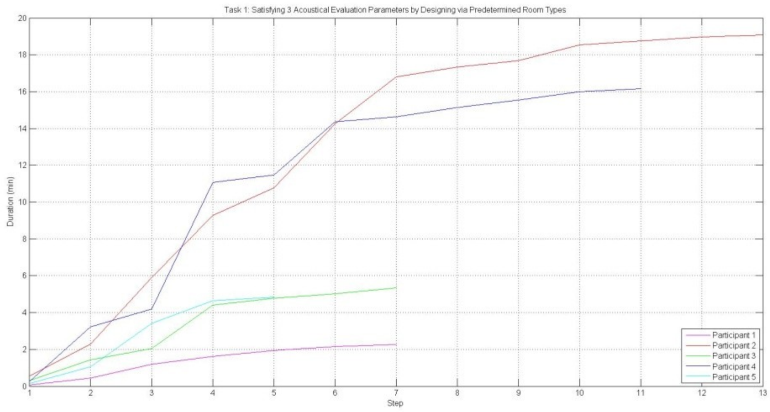


Figure 27. Time spent for each step versus step number (Task 1)

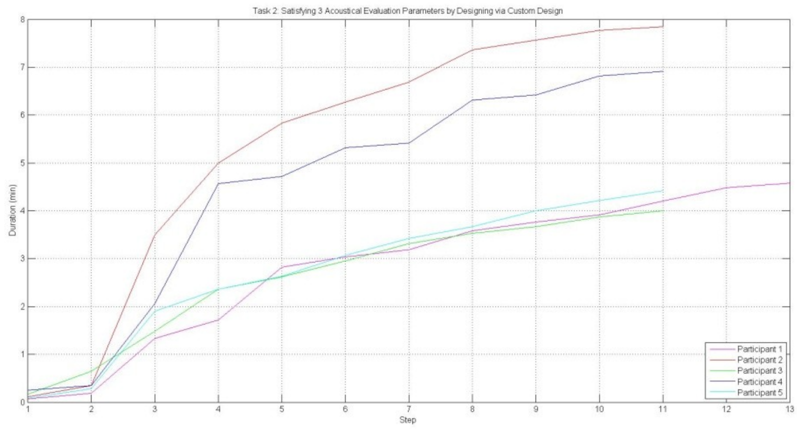


Figure 28. Time spent for each step versus step number (Task 2)

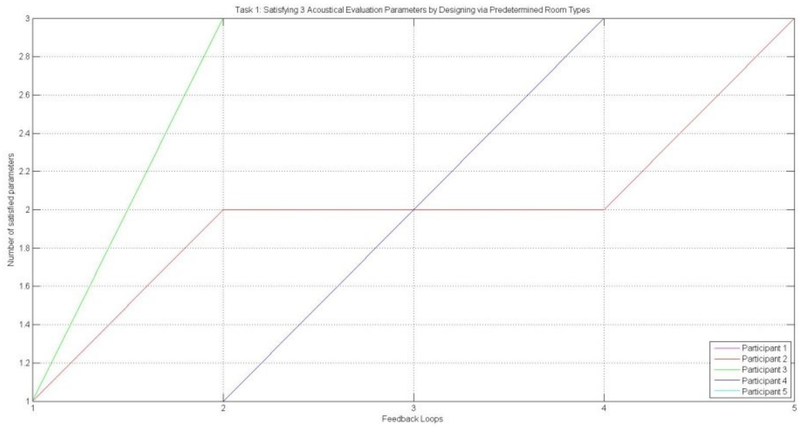


Figure 29. Satisfied parameter number versus feedback loops

(Task 1)

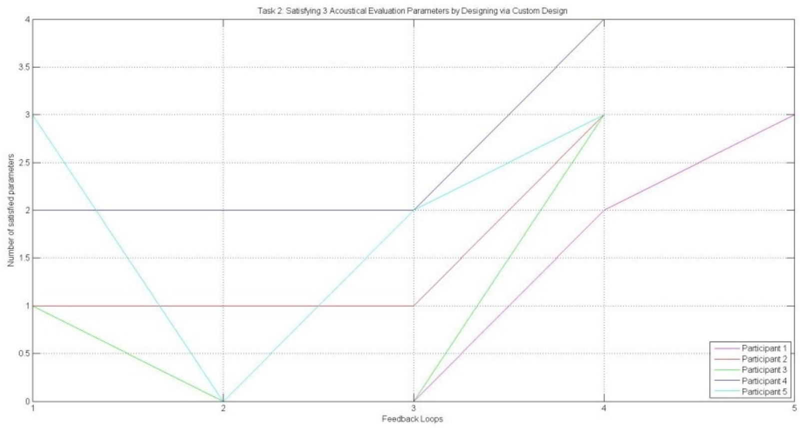


Figure 30. Satisfied parameter number versus feedback loops

(Task 2)

Steps are determined as follows:

Step 1: Selection of room type

Step 2: Determination of room dimensions / Importing custom design

Step 3: Locating sound source and receiver

Step 4: Determining surface materials

Step 5, 7, 9, 11, 13: Evaluation of computation results

Step 6, 8, 10, 12: Design changes

Also, a feedback is formed by a single couple of evaluation of computation results and design changes.

From the first two figures it is observed that, regardless of expertise level of users, every user managed to accomplish the task objective within 20 minutes with an average of 9.5 minutes for the first task which involves designing within the program. For the second task overall duration has an average of 5.3 minutes with a maximum of 8 minutes. The designs chosen by the users varied from 6 to 10 surfaces which can be regarded as pre or early design stage. It is evident that as the complexity of the geometry to be inspected increases, durations for the steps will also increase. However, average of 9.5 minutes is a bearable duration when compared to the time and effort required to optimize the acoustical performance in post design phase. Also, it is observed that the slope of the curve of durations decreases in each feedback loop which shows that the users learn how to use the program rapidly.

In the third and the forth figures, number of satisfied acoustical evaluation parameters in each feedback loop is inspected. It is observed that regardless of the expertise level of the user, every user managed to accomplish the task objective with 4 feedbacks at most which proves the usefulness of the provided feedbacks to optimize the acoustical performance of the subjected rooms. From the results gathered from the usability test, program has proven itself to be useful, efficient and learnable.

One of the most important outcomes of the usability test protocol is the feedbacks gathered from the participants about further needs of users in interface design. These feedbacks caused major influence in the final design of the interface.

4.6 INTERFACE DEVELOPMENT PROCESS

Throughout the program development process, continuous feedback is taken from the potential users. As a result of these feedbacks, interface is developed in time. Interface development is shown in the table below, together with the screenshots and necessary descriptions of the changes.

Table 2. Interface Development Stages

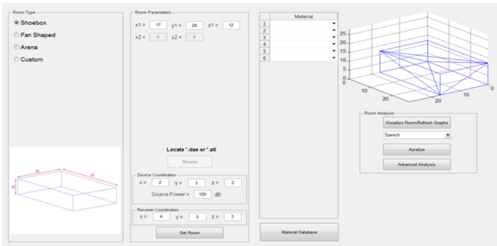
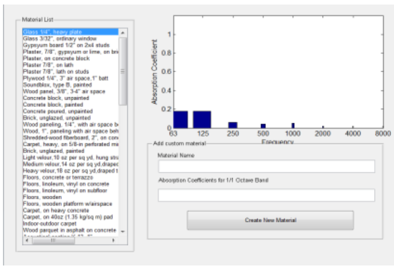
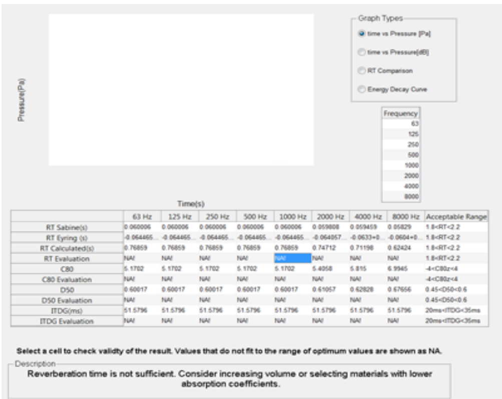
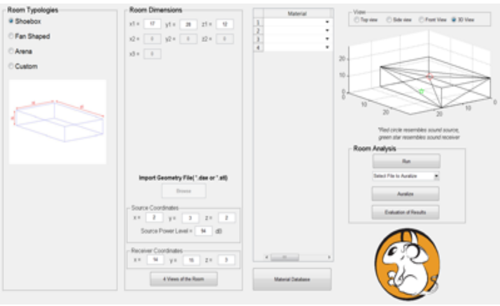
  	-Room geometry is viewed at the viewport in the main window after clicking 'Set Room' button. Room can be viewed in 4 views by 'Visualize Room/Refresh Graphs' button. Geometry is analyzed by clicking 'Advanced Analysis' button. As a material assigned to a surface, surface is NOT highlighted. 3d view is not rotatable. When any of the dimensions change user has to push 'Set Room' button to see the effect in the 3d view. -Material Database is only able to add new material. Material absorption coefficients are shown in bar graphs and numerical values are not provided.

Table 2. Interface Development Stages (continued)

<table>
<tr>
<td></td>
<td>Auralization does not play the output file, only saves the file.
Feedbacks are not highlighted.
For pressure vs time graphs, selection of frequency warning is not placed.</td>
</tr>
<tr>
<td>



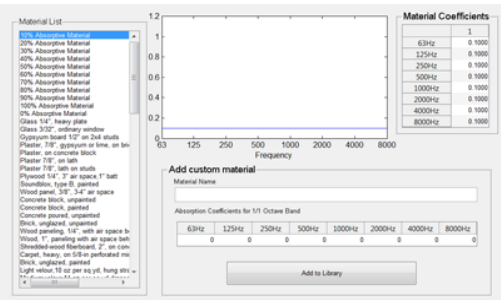
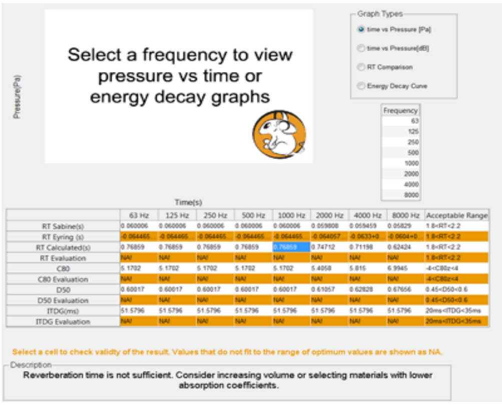
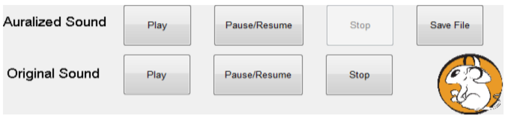
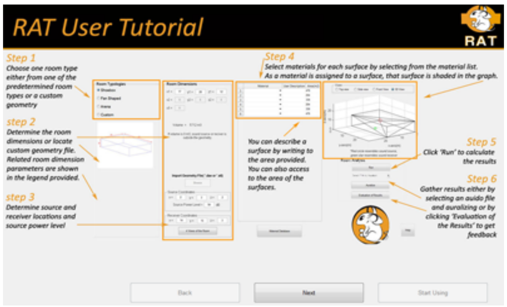

</td>
<td>-Version which the usability test is conducted.
-Loading screen is added.
-‘Visualize Room/Change Graphs’ button is replaced with ‘4 Views of the Room’ button. 4 views are also provided in the main window. Changes in the dimensions are reflected in the 3d viewport. Sound source and receiver are shown in the 3d view and the room shown is rotatable. Once a material is assigned to a surface, the material cannot be removed, but may be replaced by another material.
-Logo is added.
-‘Advanced Analysis’ button is replaced with ‘Evaluation of Results’. Advanced analysis window automatically opens when geometry is run.</td>
</tr>
</table>

Table 2. Interface Development Stages (continued)

<table>
<tr>
<td>






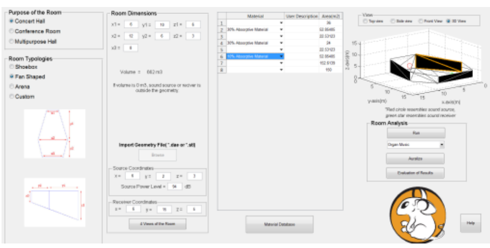
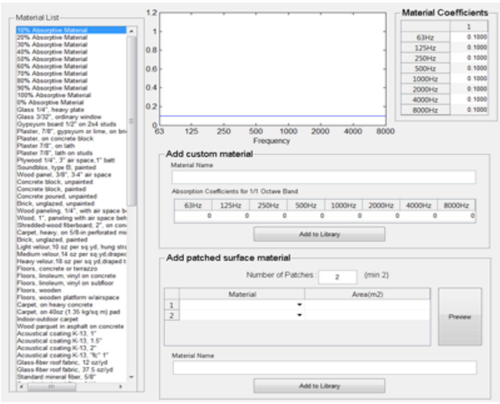
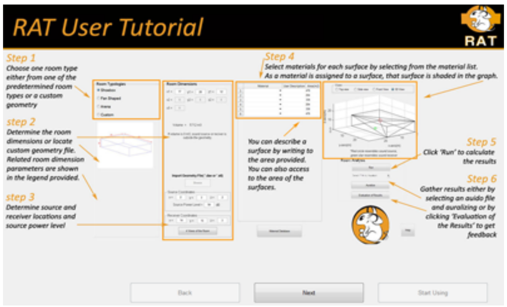
</td>
<td>
-Absorption coefficients are shown in line graph and also as numerical values.
- Selection of frequency for pressure vs time graph is added. Feedbacks in the Evaluation of the Results window are highlighted.
- Auralization output can be played paused, stopped and saved in a separate window.
-A user tutorial describing how to use the program and providing useful information on room acoustics is provided.
</td>
</tr>
<tr>
<td>

</td>
<td>
-The final interface developed with the influence of the feedbacks gathered from the participants of the usability test
-User Description rows and surface areas are added to the table which the users assign materials to surfaces. Room volume is shown in the 'Room Dimensions' Panel.
'Help' button is provided to open tutorial window. Materials assigned to a surface can be removed.
</td>
</tr>
</table>

Table 2. Interface Development Stages (continued)

<table>
<tr>
<td>




</td>
<td>
-Average absorption coefficient calculation option is enabled in the “Material Database” window. Surfaces composed of different materials as patches can be generated; absorption coefficients are previewed and added to the material database.
- User Tutorial is renewed.
</td>
</tr>
</table>

CHAPTER 5

VALIDATION AND VERIFICATION OF THE PROGRAM:

CASE STUDIES

5.1 INTRODUCTION

Every simulation and analysis software/program has certain limitations while providing results depending upon the methodology and algorithm structure used. As being an acoustical simulation and analysis program employing image source method, developed program also has limitations. In order to draw the lines of the validity/ correspondence of the program several case studies are conducted covering comparison with other commercial software in theoretical cases and comparison with measurements in real cases.

Within the scope of the thesis, four acoustical evaluation parameters, as reverberation time, clarity, definition and central time, are compared in four cases as; construction of convergence table consisting 14 cases of controlled theoretical cases, Astana Media Centre, two cases provided by Physikalisch-Technische Bundesanstalt (PTB) as Elmia Concert Hall and PTB Studio. In the case studies, acoustical evaluation parameters are inspected in mid frequencies since in low frequencies, contribution of room modes may occur which is neglected in the calculations and in high frequencies, contribution of air absorption increases and air absorption is highly dependent on room temperature and pressure and it is not possible to construct the same case caused by lack of information, especially while conducting the comparison between program results and real case measurements.

5.2 VALIDITY OF THE COMPUTATIONAL MODEL THROUGH CONTROLLED CASES

First case study conducted is the comparison of results of acoustical parameters (RT, C80, D50 and TS at 1000 Hz) for two receivers in four separate simple rooms for 14 cases. The comparison is divided into two parts. In the first part the materials of the surfaces of the rooms are homogenously distributed and regarded as even rooms as having the same absorption coefficients. For the first 9 cases, the absorption coefficients of the surfaces vary from 0.1 to 0.9. In the second part, absorption coefficients of the surfaces are selected to have variations to construct an inhomogeneous sound field and regarded as uneven rooms. By this way, limitations caused by the materials' absorption coefficients are observed while the room type, dimensions, sound and receiver locations are kept fixed. Also, room types, dimensions, sound source and receivers change as the cases varying with the materials' absorption coefficients are kept fixed.

Four rooms are determined for the first study dealing with the controlled case studies. These rooms enabling analytical solution of acoustics wave equation have been selected as the benchmarking of controlling the precision of the proposed computational model. Although high symmetries observed in these rooms create some overlapping images which require some additional steps in the analysis, they are still simple, scatter free enclosed spaces which can be modelled in any medium with the same level of solid model precision. By this way, any bias that may be caused by another software can be compensated and the results can be double checked when necessary. These rooms can be identified as a cube, two rectangular rooms with changing volumes and dimensions and a fan shaped room.

In all of the cases both the sound source and the receivers are located at the axis of symmetry and first receiver is at a 2 meters distance from the sound source whereas the second receiver is located 2 meters from the rear surface of the room investigated. The descriptions of the rooms and the cases are explained in the tables below:

Table 3. Rooms used in the convergence test

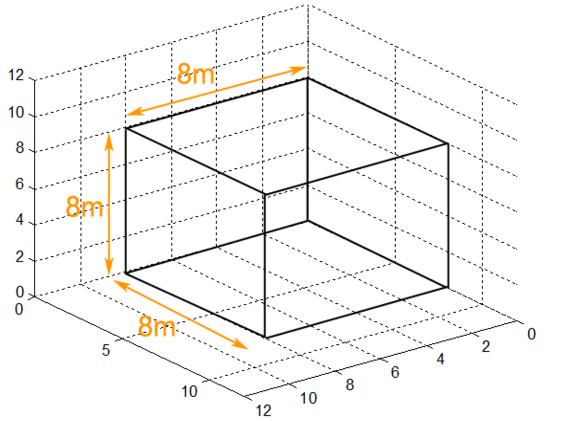
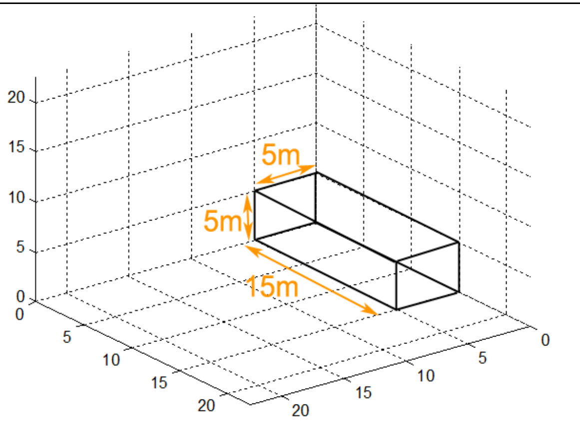
<table>
<tr><td>Square room
Dimensions: x=8m, y=8m, z=8m
Code: S1
Sound source: 2,4,2
Receiver 1: 4,4,2
Receiver 2: 6,4,2</td><td>
</td></tr>
<tr><td>Rectangular room
Dimensions: x=5m, y=15m, z=5m
Code: R1
Sound source: 2,2.5,2
Receiver 1: 4,2.5,2
Receiver 2: 13,2.5,2</td><td>
</td></tr>
</table>

Table 3. Rooms used in the convergence test (continued)

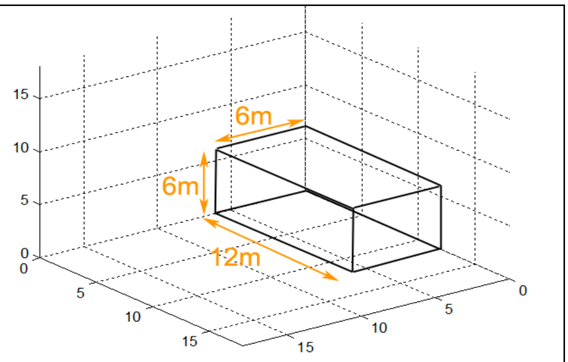
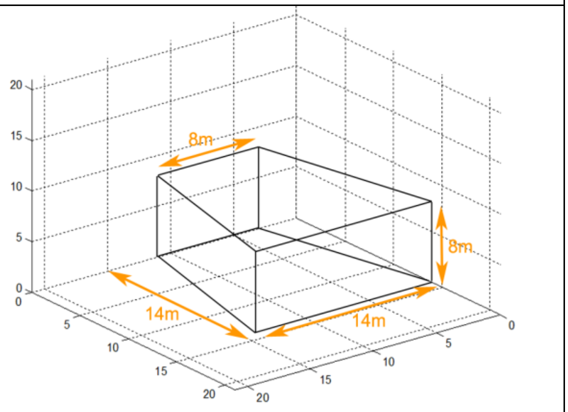
Rectangular room Dimensions: x=6m, y=12m, z=6m Code: R2 Sound source: 2,3,2 Receiver 1: 4,3,2 Receiver 2: 10,3,2	
Fan shaped room Dimensions: x=8m-14m, y=14m, z=8m Code:F1 Sound source: 2,7,2 Receiver 1: 4,7,2 Receiver 2: 12,7,2	

Table 4. Cases used in convergence test (As the surface colour is darker, more absorptive the material is)

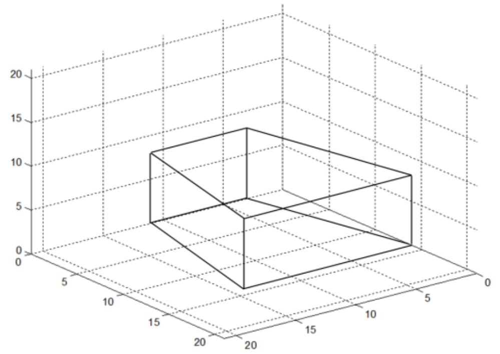
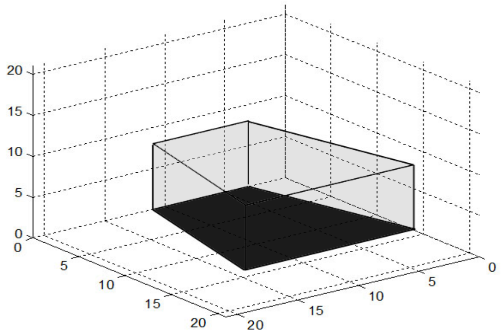
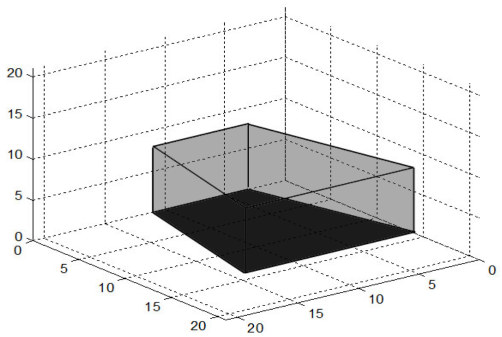
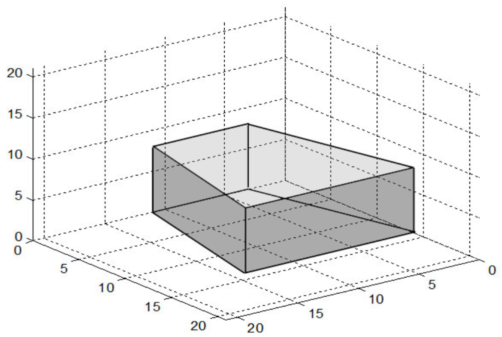
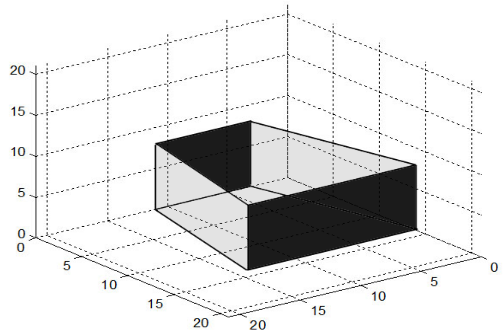
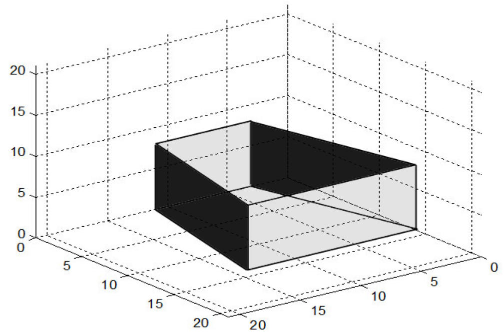
Cases 1-9: All of the surfaces are constructed with the same material with the same absorption coefficients varying from 0.1 to 0.9 for 9 cases respectively.	
Case 10: Floor material (shown with dark grey) has absorption coefficient of 0.9. The rest of the surfaces have absorption coefficient of 0.1.	
Case 11: Floor material (shown with dark grey) has absorption coefficient of 0.9. The rest of the surfaces have absorption coefficient of 0.3.	
Case 12: Ceiling material (shown with light grey) has absorption coefficient of 0.1. The rest of the surfaces have absorption coefficient of 0.3.	

Table 4. Cases used in convergence test (As the surface colour is darker, more absorptive the material is) (continued)

Case 13: Surfaces residing in y-z plane (shown with dark grey) has absorption coefficient of 0.9. The rest of the surfaces have absorption coefficient of 0.1.	
Case 14: Surfaces residing along symmetry axis (shown with dark grey) has absorption coefficient of 0.9. The rest of the surfaces have absorption coefficient of 0.1.	

In the first table below, reverberation times calculated by RAT, ODEON and global estimate calculated by Eyring's reverberation time formula (which RAT uses for the extrapolation and ideal energy decay curve) are compared as receiver locations, rooms are changed separately for the first 9 cases as controlled variable. In the next three tables, RAT and ODEON results for clarity, definition and central time are compared in the same formation. Since a global estimate formula is not present for such variables, the results obtained from the program are only compared with the ODEON results.

Table 5. Reverberation time comparison of RAT, ODEON and Eyring for first 9 (even) cases

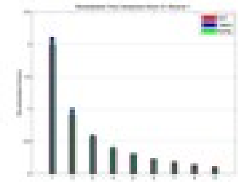
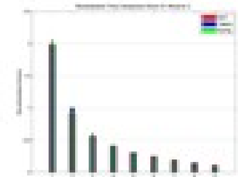
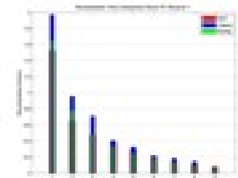
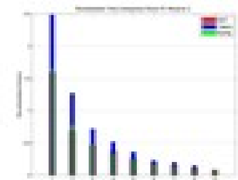
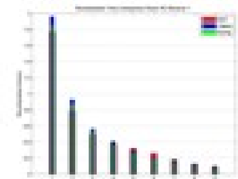
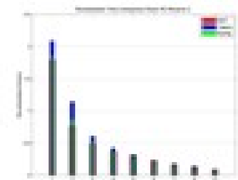
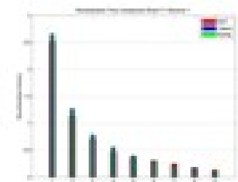
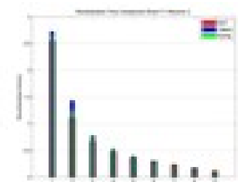
		$\bar{\alpha} = 0.1$ Case 1	$\bar{\alpha} = 0.2$ Case 2	$\bar{\alpha} = 0.3$ Case 3	$\bar{\alpha} = 0.4$ Case 4	$\bar{\alpha} = 0.5$ Case 5	$\bar{\alpha} = 0.6$ Case 6	$\bar{\alpha} = 0.7$ Case 7	$\bar{\alpha} = 0.8$ Case 9	$\bar{\alpha} = 0.9$ Case 9	Bar Graphs RT vs Case
S1 Receiver 1	RAT	1,99	0,91	0,56	0,40	0,30	0,23	0,19	0,14	0,11	
	ODEON	2,11	1,01	0,60	0,40	0,30	0,22	0,17	0,13	0,08	
	EYRING	2,06	0,97	0,61	0,42	0,31	0,23	0,17	0,12	0,09	
S1 Receiver 2	RAT	1,99	0,92	0,57	0,41	0,31	0,25	0,20	0,15	0,11	
	ODEON	1,97	1,00	0,55	0,40	0,29	0,22	0,18	0,14	0,09	
	EYRING	2,06	0,97	0,61	0,42	0,31	0,23	0,17	0,12	0,09	
R1 Receiver 1	RAT	1,53	0,65	0,48	0,40	0,30	0,22	0,16	0,11	0,08	
	ODEON	1,97	0,96	0,71	0,41	0,33	0,22	0,19	0,15	0,06	
	EYRING	1,66	0,78	0,49	0,34	0,25	0,19	0,14	0,10	0,08	
R1 Receiver 2	RAT	1,59	0,69	0,47	0,38	0,26	0,21	0,16	0,11	0,08	
	ODEON	2,49	1,27	0,72	0,52	0,36	0,23	0,20	0,15	0,05	
	EYRING	1,66	0,78	0,49	0,34	0,25	0,19	0,14	0,10	0,08	
R2 Receiver 1	RAT	1,77	0,79	0,50	0,38	0,32	0,27	0,18	0,13	0,10	
	ODEON	1,96	0,93	0,57	0,41	0,30	0,22	0,17	0,13	0,10	
	EYRING	1,86	0,87	0,55	0,38	0,28	0,21	0,16	0,11	0,08	
R2 Receiver 2	RAT	1,79	0,76	0,49	0,37	0,32	0,24	0,18	0,13	0,09	
	ODEON	2,09	1,14	0,61	0,42	0,31	0,21	0,17	0,14	0,07	
	EYRING	1,86	0,87	0,55	0,38	0,28	0,21	0,16	0,11	0,08	
F1 Receiver 1	RAT	2,52	1,14	0,70	0,46	0,37	0,32	0,25	0,18	0,14	
	ODEON	2,65	1,27	0,79	0,56	0,39	0,29	0,22	0,17	0,10	
	EYRING	2,67	1,26	0,79	0,55	0,40	0,30	0,22	0,16	0,12	
F1 Receiver 2	RAT	2,55	1,11	0,67	0,47	0,37	0,31	0,25	0,18	0,13	
	ODEON	2,73	1,43	0,78	0,52	0,39	0,30	0,22	0,18	0,09	
	EYRING	2,67	1,26	0,79	0,55	0,40	0,30	0,22	0,16	0,12	

Table 6. C80 comparison of RAT and ODEON for first 9 (even) cases

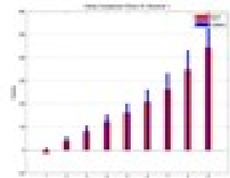
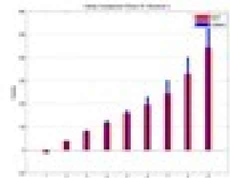
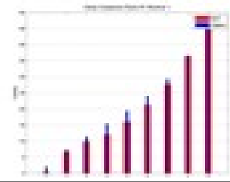
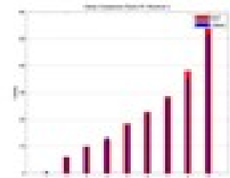
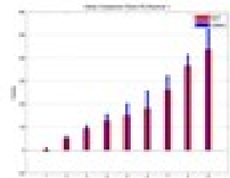
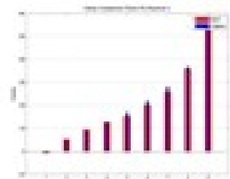
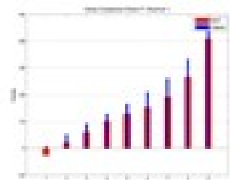
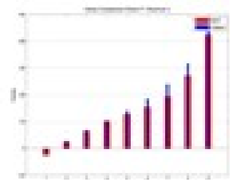
		$\bar{\alpha} = 0.1$ Case 1	$\bar{\alpha} = 0.2$ Case 2	$\bar{\alpha} = 0.3$ Case 3	$\bar{\alpha} = 0.4$ Case 4	$\bar{\alpha} = 0.5$ Case 5	$\bar{\alpha} = 0.6$ Case 6	$\bar{\alpha} = 0.7$ Case 7	$\bar{\alpha} = 0.8$ Case 9	$\bar{\alpha} = 0.9$ Case 9	Bar Graphs C80 vs Case
S1 Receiver 1	RAT	-1,24	3,90	8,19	12,25	16,16	20,95	26,33	34,78	44,40	
	ODEON	1,00	5,90	10,80	15,30	20,20	26,10	33,30	43,20	59,40	
S1 Receiver 2	RAT	-1,16	4,02	8,25	11,94	15,87	19,66	24,57	32,90	44,40	
	ODEON	-0,60	4,10	8,70	12,90	17,50	23,10	30,30	40,30	56,80	
R1 Receiver 1	RAT	0,31	6,70	9,85	12,06	16,03	21,35	27,51	36,34	48,20	
	ODEON	2,00	7,30	11,40	15,40	19,40	23,90	29,30	36,60	49,10	
R1 Receiver 2	RAT	0,04	6,09	10,01	12,49	18,57	22,84	28,48	38,08	54,30	
	ODEON	0,80	5,80	9,70	13,50	17,40	21,90	27,40	35,30	51,50	
R2 Receiver 1	RAT	-0,61	5,03	9,47	12,82	15,07	18,26	26,14	36,78	43,78	
	ODEON	1,30	6,40	11,10	15,60	20,40	25,90	32,50	41,50	57,20	
R2 Receiver 2	RAT	-0,65	5,29	9,62	12,91	15,29	20,31	25,98	36,08	52,80	
	ODEON	-0,30	4,50	8,90	12,90	17,10	22,00	28,10	36,70	52,40	
F1 Receiver 1	RAT	-2,57	2,27	6,06	10,17	12,88	15,30	19,24	26,71	40,78	
	ODEON	0,80	5,30	9,30	12,90	16,70	21,10	26,30	33,40	45,30	
F1 Receiver 2	RAT	-2,59	2,50	6,52	10,06	12,82	15,44	19,44	27,21	42,32	
	ODEON	-1,50	2,90	6,90	10,40	14,10	18,50	23,90	31,70	46,90	

Table 7. D50 comparison of RAT and ODEON for first 9 (even) cases

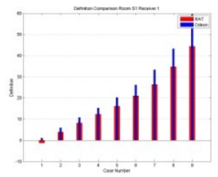
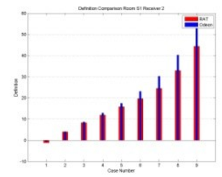
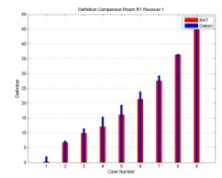
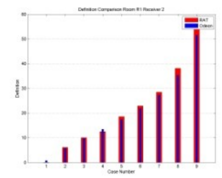
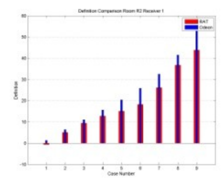
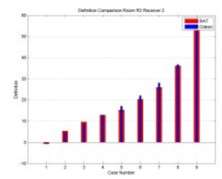
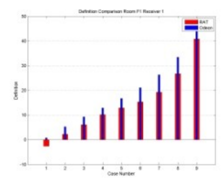
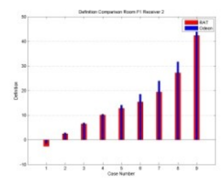
		$\bar{\alpha} = 0.1$ Case 1	$\bar{\alpha} = 0.2$ Case 2	$\bar{\alpha} = 0.3$ Case 3	$\bar{\alpha} = 0.4$ Case 4	$\bar{\alpha} = 0.5$ Case 5	$\bar{\alpha} = 0.6$ Case 6	$\bar{\alpha} = 0.7$ Case 7	$\bar{\alpha} = 0.8$ Case 9	$\bar{\alpha} = 0.9$ Case 9	Bar Graphs D50 vs Case
S1 Receiver 1	RAT	0,30	0,54	0,72	0,84	0,91	0,95	0,98	0,99	1,00	
	ODEON	0,45	0,69	0,84	0,92	0,96	0,99	1,00	1,00	1,00	
S1 Receiver 2	RAT	0,31	0,55	0,72	0,83	0,90	0,94	0,97	0,99	1,00	
	ODEON	0,34	0,57	0,75	0,86	0,93	0,97	0,99	1,00	1,00	
R1 Receiver 1	RAT	0,37	0,67	0,77	0,83	0,90	0,96	0,98	1,00	1,00	
	ODEON	0,53	0,76	0,89	0,95	0,97	0,99	1,00	1,00	1,00	
R1 Receiver 2	RAT	0,36	0,64	0,78	0,84	0,93	0,96	0,98	0,99	1,00	
	ODEON	0,43	0,68	0,85	0,93	0,97	0,99	1,00	1,00	1,00	
R2 Receiver 1	RAT	0,33	0,60	0,76	0,85	0,89	0,93	0,98	0,99	1,00	
	ODEON	0,47	0,71	0,85	0,93	0,96	0,98	0,99	1,00	1,00	
R2 Receiver 2	RAT	0,32	0,61	0,77	0,85	0,89	0,95	0,98	1,00	1,00	
	ODEON	0,36	0,61	0,79	0,90	0,95	0,98	1,00	1,00	1,00	
F1 Receiver 1	RAT	0,25	0,47	0,64	0,78	0,85	0,89	0,94	0,98	1,00	
	ODEON	0,49	0,72	0,85	0,92	0,96	0,98	0,99	1,00	1,00	
F1 Receiver 2	RAT	0,24	0,48	0,66	0,78	0,85	0,90	0,94	0,98	1,00	
	ODEON	0,32	0,54	0,72	0,83	0,91	0,96	0,99	1,00	1,00	

Table 8. TS comparison of RAT and ODEON for first 9 (even) cases

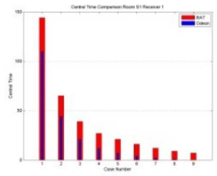
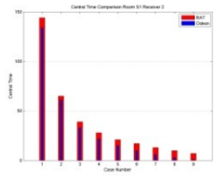
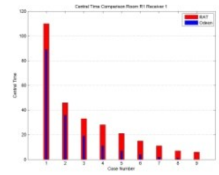
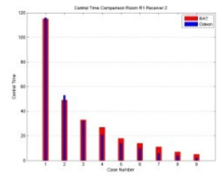
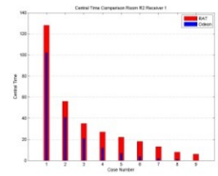
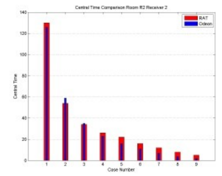
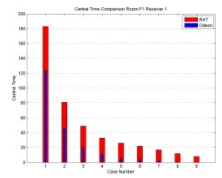
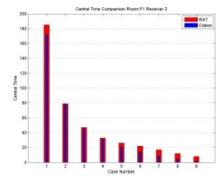
		$\bar{\alpha} = 0.1$ Case 1	$\bar{\alpha} = 0.2$ Case 2	$\bar{\alpha} = 0.3$ Case 3	$\bar{\alpha} = 0.4$ Case 4	$\bar{\alpha} = 0.5$ Case 5	$\bar{\alpha} = 0.6$ Case 6	$\bar{\alpha} = 0.7$ Case 7	$\bar{\alpha} = 0.8$ Case 9	$\bar{\alpha} = 0.9$ Case 9	Bar Graphs TS vs Case
S1 Receiver 1	RAT	144	65	39	27	21	16	12	9	7	
	ODEON	110	44	21	12	7	4	2	1	0	
S1 Receiver 2	RAT	144	65	39	28	21	17	13	10	7	
	ODEON	134	61	33	22	15	10	6	3	1	
R1 Receiver 1	RAT	110	46	33	28	21	15	11	7	6	
	ODEON	89	36	19	11	7	4	2	1	0	
R1 Receiver 2	RAT	115	49	33	27	18	14	11	7	5	
	ODEON	116	53	32	21	14	10	6	4	2	
R2 Receiver 1	RAT	128	56	35	27	22	18	13	8	6	
	ODEON	102	41	21	12	7	4	2	1	0	
R2 Receiver 2	RAT	130	54	34	26	22	16	12	8	5	
	ODEON	126	59	35	23	16	11	7	4	2	
F1 Receiver 1	RAT	183	81	49	33	26	22	17	12	8	
	ODEON	124	46	21	12	6	4	2	1	0	
F1 Receiver 2	RAT	185	79	47	33	26	22	17	12	8	
	ODEON	172	79	45	31	21	14	9	5	2	

Table 9. RT comparison of RAT, ODEON and Eyring for cases 10 to 14 (uneven)

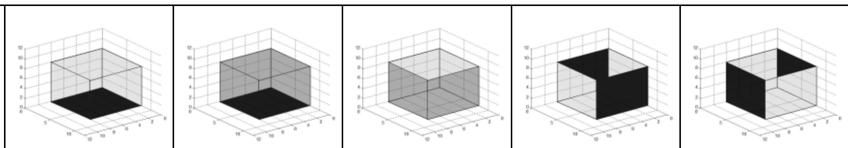
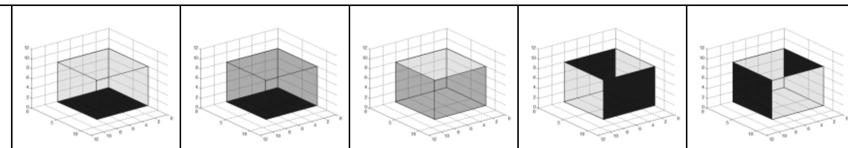
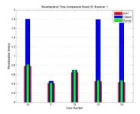
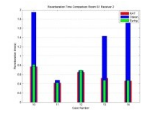
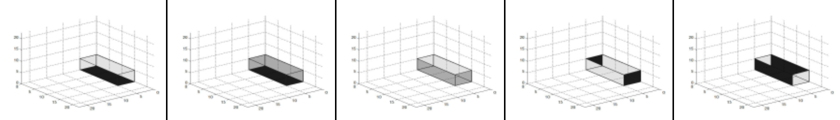
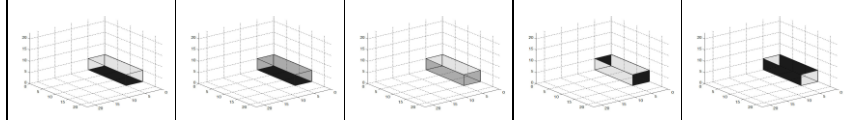
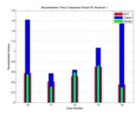
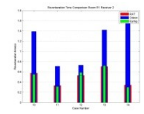
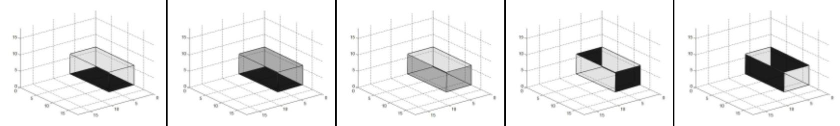
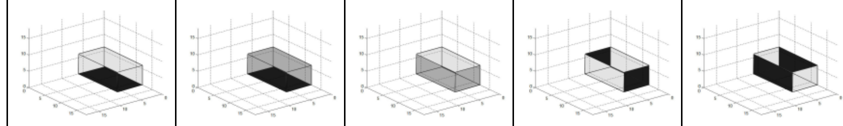
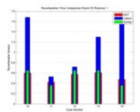
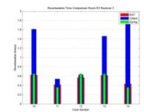
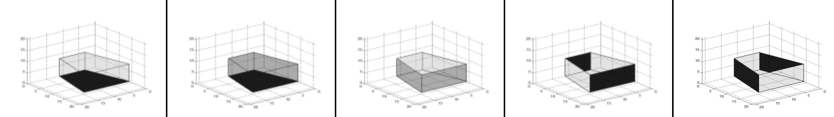
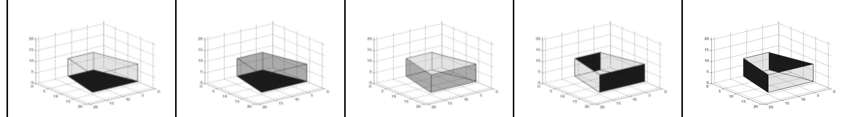
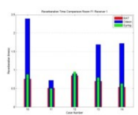
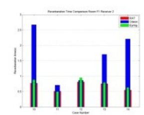
Cases							Bar Graphs Case vs RT	Cases							Bar Graphs Case vs RT
S1 Receiver 1	RAT	0,78	0,41	0,64	0,46	0,43		S1 Receiver 2	RAT	0,77	0,42	0,65	0,52	0,46	
	ODEON	1,80	0,46	0,70	1,79	1,82			ODEON	1,95	0,48	0,69	1,43	1,94	
	EYRING	0,82	0,43	0,70	0,48	0,48			EYRING	0,82	0,43	0,70	0,48	0,48	
Cases								Cases							
R1 Receiver 1	RAT	0,57	0,41	0,51	0,70	0,35		R1 Receiver 2	RAT	0,58	0,33	0,53	0,71	0,34	
	ODEON	1,62	0,57	0,64	1,07	1,58			ODEON	1,39	0,71	0,73	1,42	1,66	
	EYRING	0,55	0,31	0,59	0,72	0,30			EYRING	0,55	0,31	0,59	0,72	0,30	
Cases								Cases							
R2 Receiver 1	RAT	0,60	0,43	0,57	0,61	0,48		R2 Receiver 2	RAT	0,62	0,42	0,56	0,61	0,43	
	ODEON	1,68	0,53	0,72	1,30	1,61			ODEON	1,61	0,54	0,63	1,46	1,82	
	EYRING	0,65	0,36	0,65	0,65	0,36			EYRING	0,65	0,36	0,65	0,65	0,36	
Cases								Cases							
F1 Receiver 1	RAT	0,76	0,51	0,85	0,70	0,54		F1 Receiver 2	RAT	0,78	0,51	0,81	0,75	0,55	
	ODEON	2,39	0,72	0,90	1,69	1,72			ODEON	2,67	0,71	0,87	1,71	2,21	
	EYRING	0,88	0,50	0,95	0,80	0,64			EYRING	0,88	0,50	0,95	0,80	0,64	

Table 10. C80 comparison of RAT and ODEON for cases 10 to 14 (uneven)

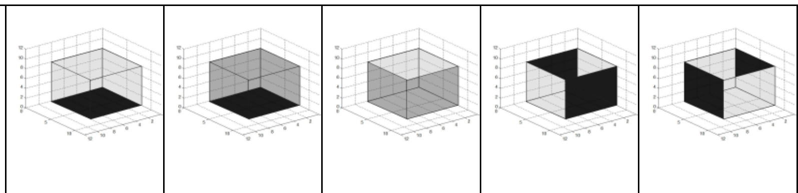
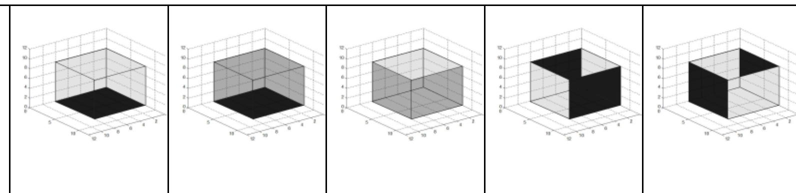
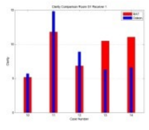
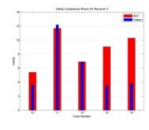
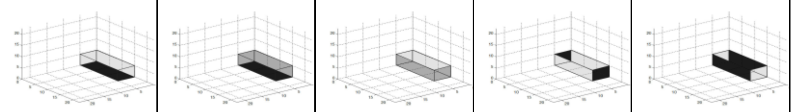
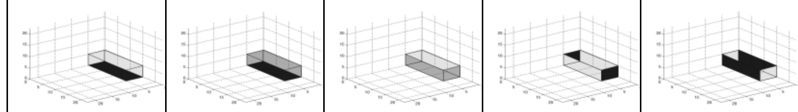
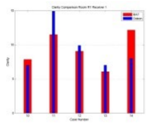
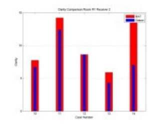
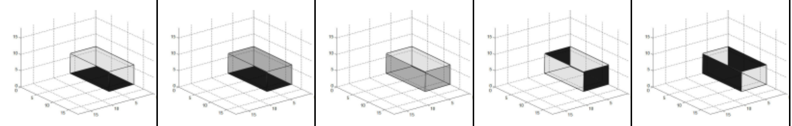
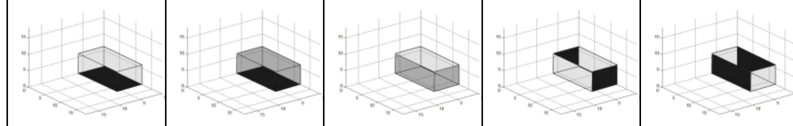
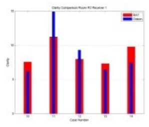
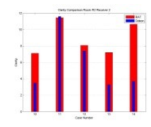
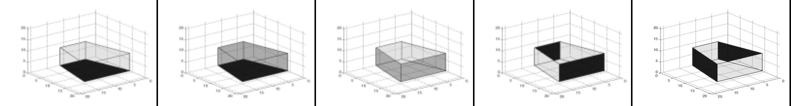
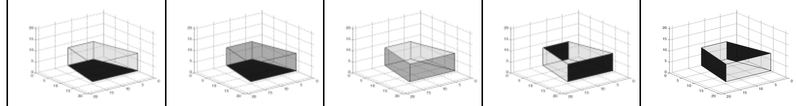
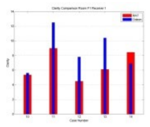
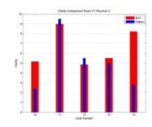
Cases							Bar Graphs Case vs RT	Cases							Bar Graphs Case vs RT
S1 Receiver 1	RAT	5,17	11,79	6,84	10,47	11,03		S1 Receiver 2	RAT	5,41	11,67	6,93	9,07	10,31	
	ODEON	5,70	14,80	8,90	6,30	6,60			ODEON	3,60	12,20	6,90	3,50	3,80	
Cases								Cases							
R1 Receiver 1	RAT	7,84	11,48	9,06	6,06	12,14		R1 Receiver 2	RAT	7,75	14,21	8,63	5,90	13,47	
	ODEON	7,00	14,90	9,90	7,00	8,00			ODEON	6,70	12,40	8,60	4,30	7,00	
Cases								Cases							
R2 Receiver 1	RAT	7,55	11,22	7,98	7,31	9,76		R2 Receiver 2	RAT	7,12	11,46	8,08	7,21	10,66	
	ODEON	6,20	14,90	9,30	6,40	7,40			ODEON	3,50	11,60	7,40	3,30	3,70	
Cases								Cases							
F1 Receiver 1	RAT	5,36	8,98	4,48	6,09	8,43		F1 Receiver 2	RAT	5,17	8,98	4,85	5,50	8,22	
	ODEON	5,60	12,50	7,80	10,40	6,90			ODEON	2,40	9,50	5,50	5,00	2,80	

Table 11. D50 comparison of RAT and ODEON for cases 10 to 14 (uneven)

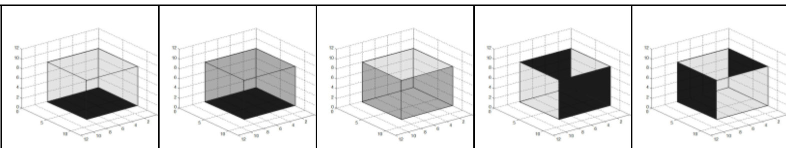
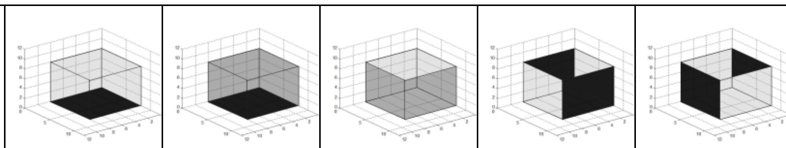
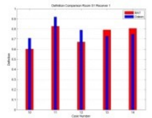
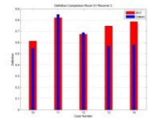
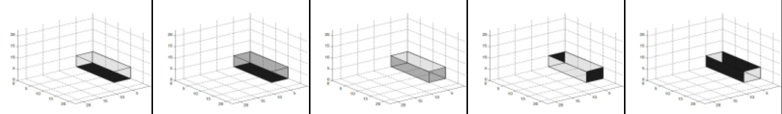
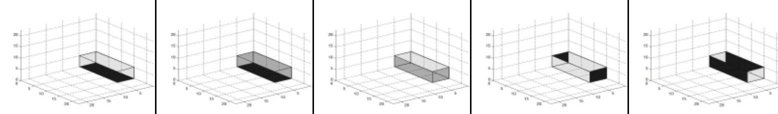
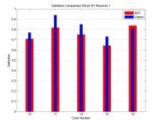
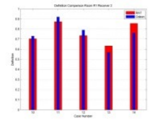
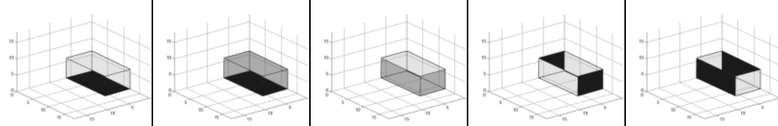
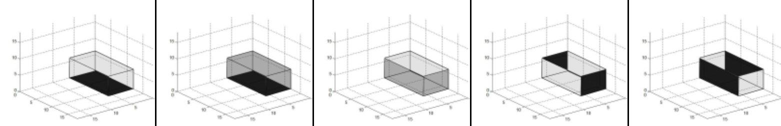
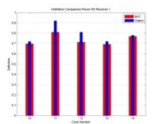
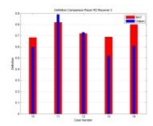
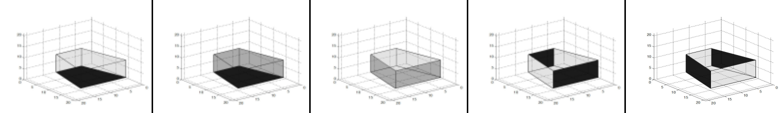
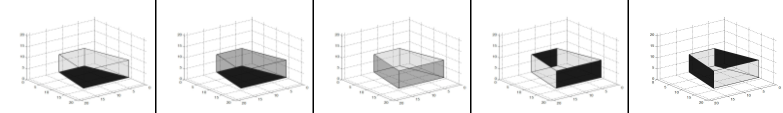
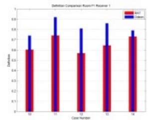
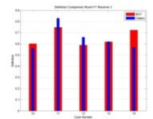
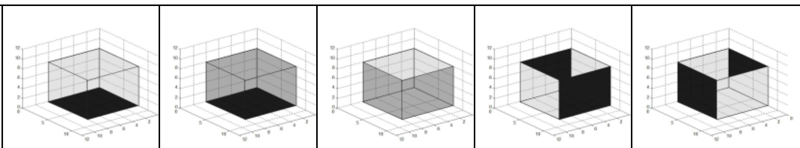
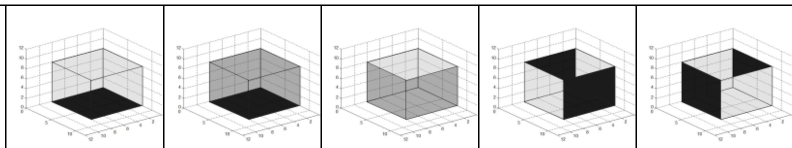
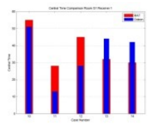
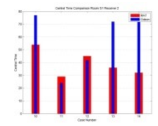
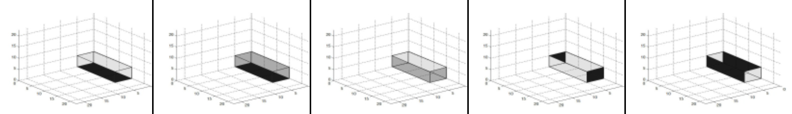
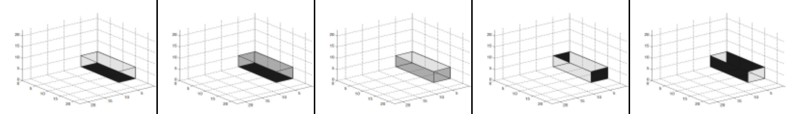
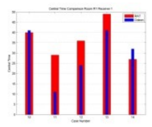
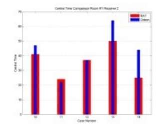
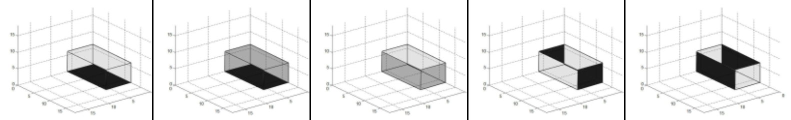
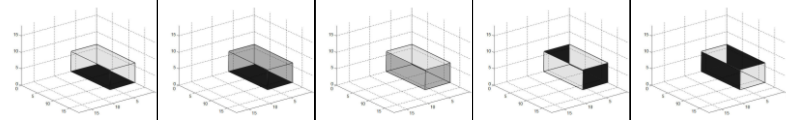
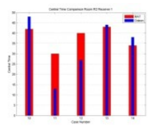
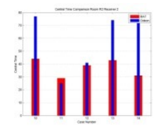
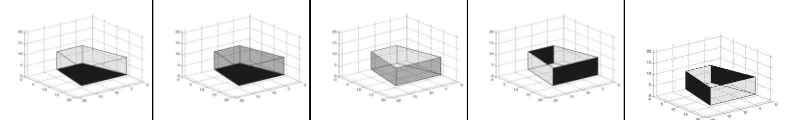
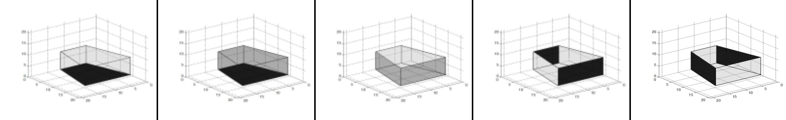
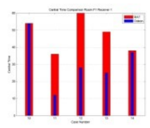
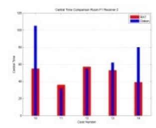
Cases							Bar Graphs Case vs RT	Cases							Bar Graphs Case vs RT
S1 Receiver 1	RAT	0,60	0,83	0,67	0,79	0,81		S1 Receiver 2	RAT	0,61	0,82	0,68	0,75	0,79	
	ODEON	0,71	0,92	0,79	0,73	0,75			ODEON	0,55	0,85	0,69	0,57	0,58	
Cases								Cases							
R1 Receiver 1	RAT	0,71	0,82	0,75	0,64	0,84		R1 Receiver 2	RAT	0,70	0,87	0,74	0,63	0,86	
	ODEON	0,77	0,94	0,85	0,73	0,81			ODEON	0,73	0,92	0,79	0,57	0,76	
Cases								Cases							
R2 Receiver 1	RAT	0,70	0,81	0,71	0,69	0,77		R2 Receiver 2	RAT	0,68	0,82	0,72	0,69	0,80	
	ODEON	0,72	0,92	0,81	0,72	0,78			ODEON	0,60	0,89	0,73	0,52	0,61	
Cases								Cases							
F1 Receiver 1	RAT	0,60	0,74	0,57	0,64	0,73		F1 Receiver 2	RAT	0,60	0,75	0,59	0,62	0,72	
	ODEON	0,74	0,92	0,81	0,86	0,79			ODEON	0,56	0,83	0,66	0,62	0,57	

Table 12. TS comparison of RAT and ODEON for cases 10 to 14 (uneven)

Cases							Bar Graphs Case vs RT	Cases							Bar Graphs Case vs RT
S1 Receiver 1	RAT	55	28	45	32	30		S1 Receiver 2	RAT	54	29	45	36	32	
	ODEON	51	13	28	44	42			ODEON	77	24	42	72	72	
Cases								Cases							
R1 Receiver 1	RAT	40	29	36	49	27		R1 Receiver 2	RAT	41	24	37	50	25	
	ODEON	41	11	24	41	32			ODEON	47	22	37	64	44	
Cases								Cases							
R2 Receiver 1	RAT	42	30	40	43	34		R2 Receiver 2	RAT	44	29	39	43	31	
	ODEON	48	13	27	44	38			ODEON	77	25	41	74	72	
Cases								Cases							
F1 Receiver 1	RAT	54	36	60	49	38		F1 Receiver 2	RAT	55	36	57	53	39	
	ODEON	54	12	28	25	37			ODEON	105	32	55	62	80	

In the first 9 cases as regarded as even cases, discrepancy between the results of RT is considerably low. As the average absorption in the room decreases, RT results increase thus the ratio of reverberation time and impulse response length also increases. Hence, as foreseen in the previous chapters, the results tend to remain underestimated because impulse response length remains insufficient compared to the “theoretical” measurement length.

As mentioned before parameters such as C80, D50 and TS are dependent upon the energy decay curve. In most cases, energy decay curve has linear decay behaviour. Thus if the reverberation time converges to the expected value, other parameters are expected to converge too as it is seen in the tables above.

However, major discrepancies between ODEON values and both RAT and Eyring values are observed for cases 10, 13 and 14. These cases deal with uneven cases having considerable differences between the absorption coefficients of the surfaces and causing the distortion of diffuse sound field. Image source method is based on the assumption of diffuse sound field and both the image source method and the global estimates of Sabine and Eyring fail at these situations. This is the reason of high discrepancy between ODEON and other results since ODEON is able to eliminate the assumption of diffuse sound field. However, RT values obtained by Eyring and RAT have a high convergence rate. Also, same discrepancies occur for the C80, D50 and TS results because different energy decay curves are calculated by RAT and ODEON. In cases 11 and 12 as the differences between the absorption coefficients of the surface materials decrease, convergence increases.

For an overall evaluation of the convergence table results, it is observed that RAT is giving satisfactory results as long as diffuse field conditions are satisfied. The convergence rate is not affected by the room dimension ratios or the inclination of the surfaces, by the average absorption coefficient or by the source receiver positions. From the convergence table it can be concluded that provided program works in almost every case which Eyring or Sabine formulation is valid.

5.3 CASE STUDY 2: ASTANA MEDIA CENTRE (AMC)

Astana Media Centre (AMC) is a case study base on an existing concert hall. In the case study, computational performance of program and convergence of the mid design results to final results of acoustical evaluation parameters are observed.

Original design of AMC consists a lot more surfaces that can be analyzed by image source method so the design is abstracted to a geometry which can be a mid design step under the supervision of the acoustical designer of AMC, Arzu Gönenç Sorguç. Abstracted form of AMC consists 14 surfaces and the materials facing inside are used neglecting the volumes residing between exterior walls and panels used in the original design. Original design and abstracted form are shown below:

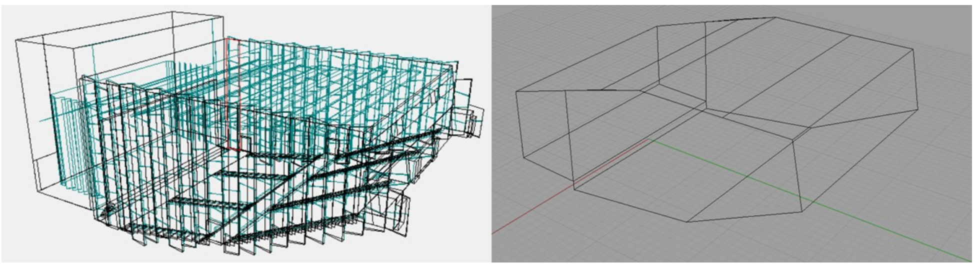


Figure 31. Original design and abstracted form of AMC

Complexity of the abstracted form is selected to be a target complexity level within the scope of the thesis. Thus, computational time of analysis ought to be regarded as quick response to give feedback to users. Computational time needed to analyze AMC and give feedback is 45 seconds and rated as convenient for the analysis of a room with 14 surfaces.

There are two main seating areas provided in AMC. Two receiver locations are selected in each of the seating areas. The location of sound source and receivers are shown below:

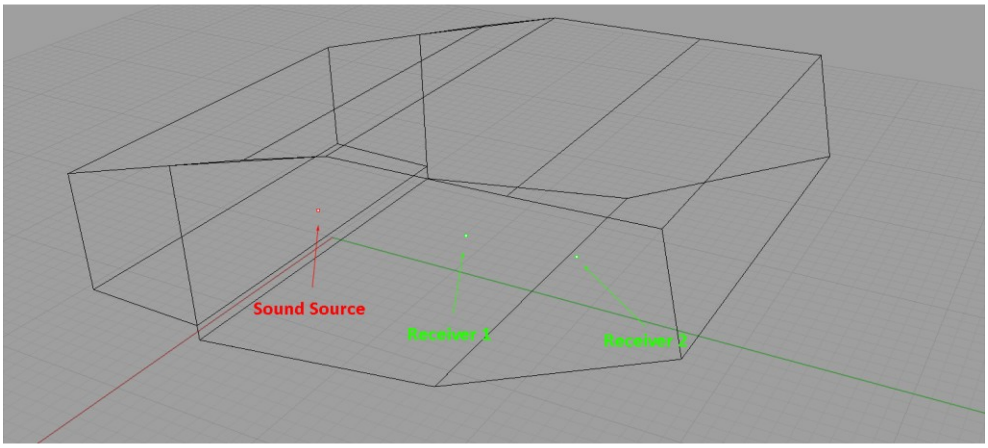
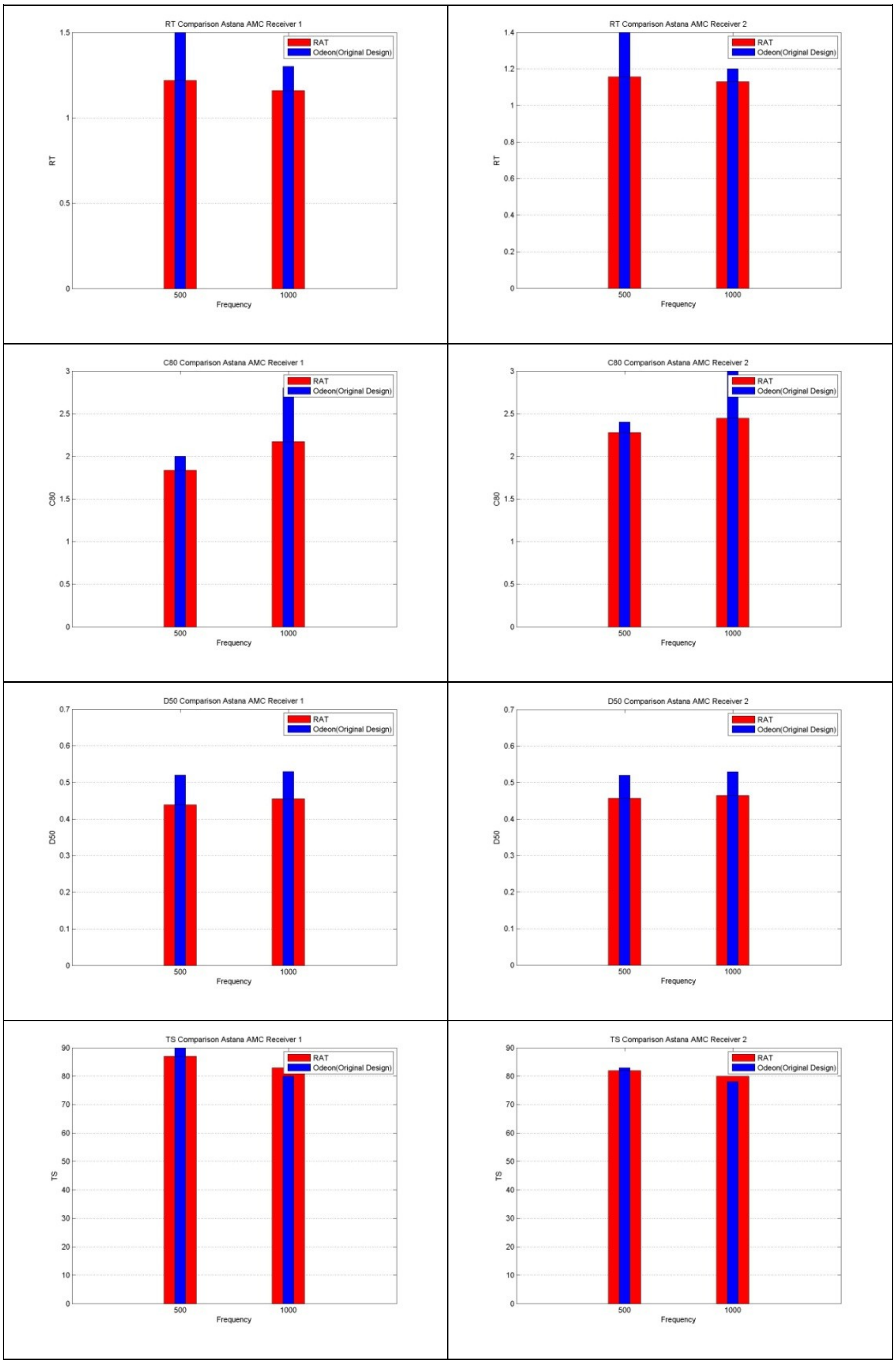


Figure 32. Sound source and receiver locations

The analysis has been made for two receiver locations and for RT, C80, D50 and TS at 500 Hz and 1000 Hz. The results are shown below:

Table 13. RT, C80, D50 and TS comparisons of RAT and ODEON (Original Design) of AMC



For this case, impulse response length is not sufficient for exact estimation of reverberation time and thus energy decay curve and acoustical valuation parameters are expected to be underestimated. However, even though being underestimated, results of all the acoustical evaluation parameters are observed to be in an agreement with the expected results. The discrepancy between the results varies between %2 to %15 with respect to ODEON's results which is a suitable range.

5.4 CASE STUDY 3: ELMIA CONCERT HALL

In the third case study, Elmia Concert Hall is inspected. Elmia Concert Hall in Jönköping/Sweden is the subject of international round robin 2 organized by Physikalisch-Technische Bundesanstalt (PTB) providing analysis results of 13 participant acoustics software for the model provided by PTB and also measurement results.

Figure 32. Elmia Concert Hall [Retrieved from http://www.ptb.de/en/org/1/16/163/roundrobin/roundrob2_1.htm, Last visited: 22.05.2012]

Elmia Hall model provided by PTB is a complex model consisting many surfaces which builds up a computational cost what cannot be handled by image source method. The complexity issues are also issued by PTB. For this reason the model provided by PTB is abstracted conserving the main model geometry to a model consisting 31 surfaces. The comparison of original model provided and abstracted model are shown below:

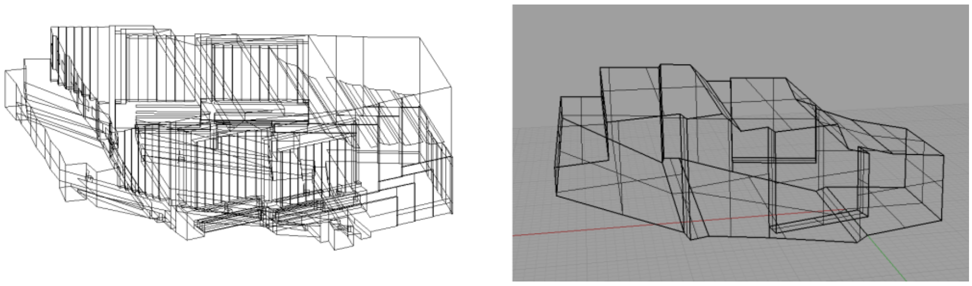


Figure 33. Original model and abstracted model of Elmia Hall

Abstraction is done to conserve the geometrical considerations as much as possible. Panels are modelled as one surface and the gaps within the panels are neglected together with the exterior walls. With 31 surfaces, computational time required 8,5 hours. Because of the computational difficulties only one source and three receiver points are analyzed. Locations of the sound source and receivers are shown below:

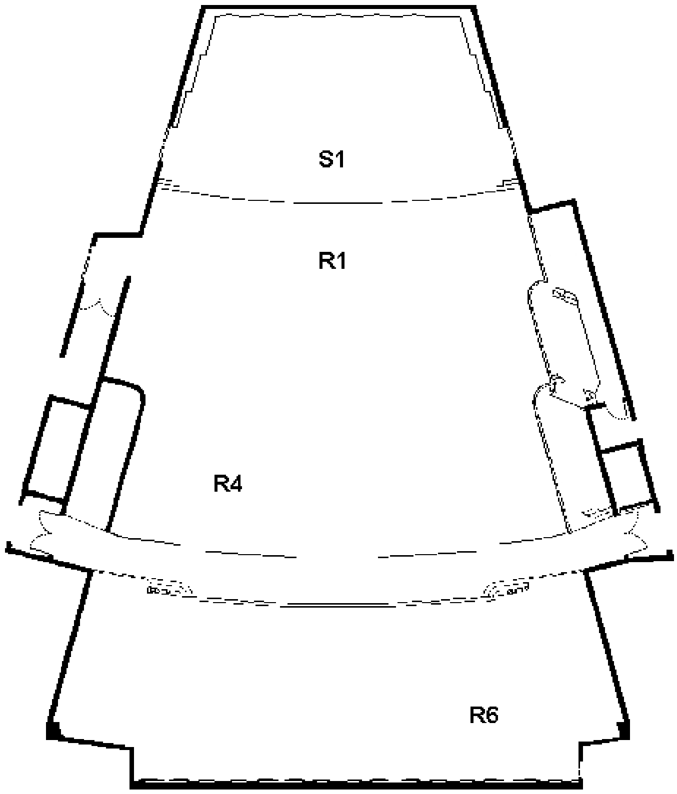
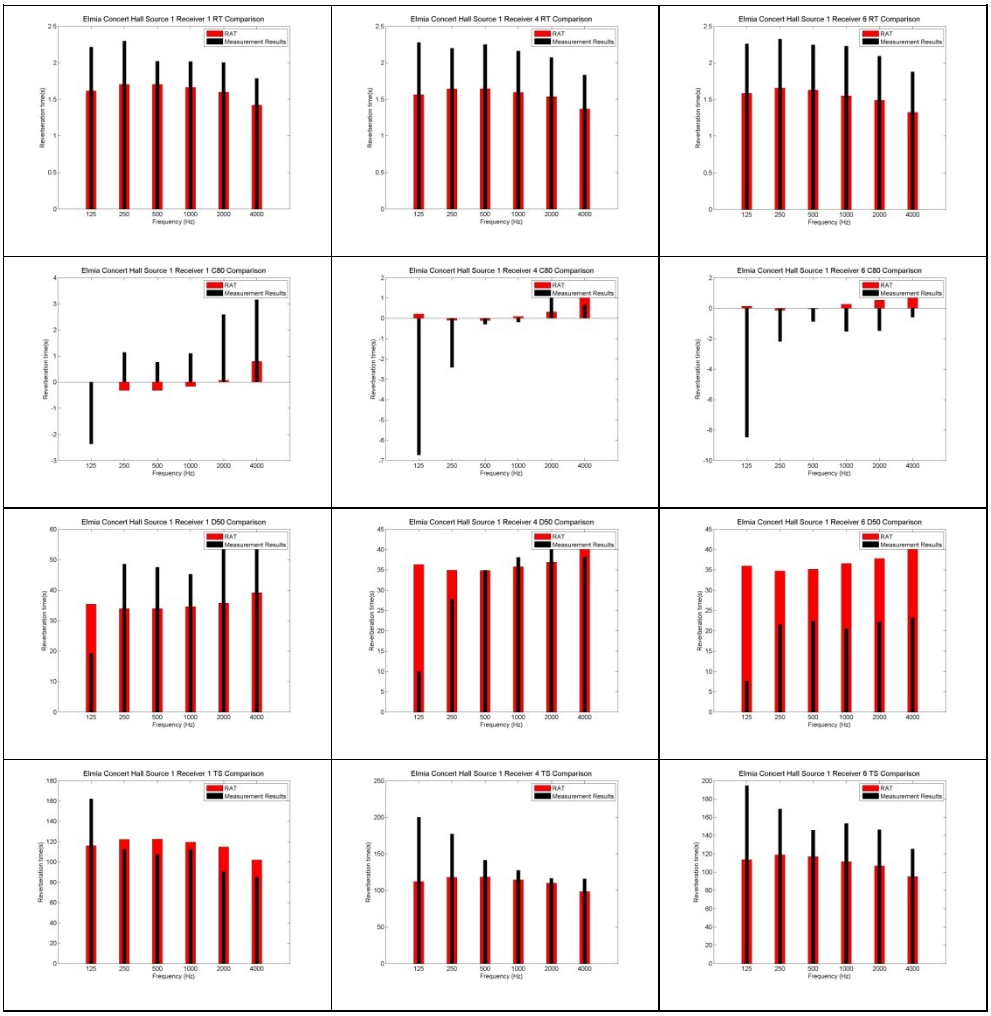


Figure 34. Source and receiver locations in Elmia Hall

Surface absorption coefficients are selected due to the data provided by PTB. Also, surface scattering is an inevitable phenomenon for the geometrical models with this complexity level. Surface scattering coefficients are also selected due to the data verified by PTB. Comparison of results obtained by RAT and measurement results are shown in the table below:

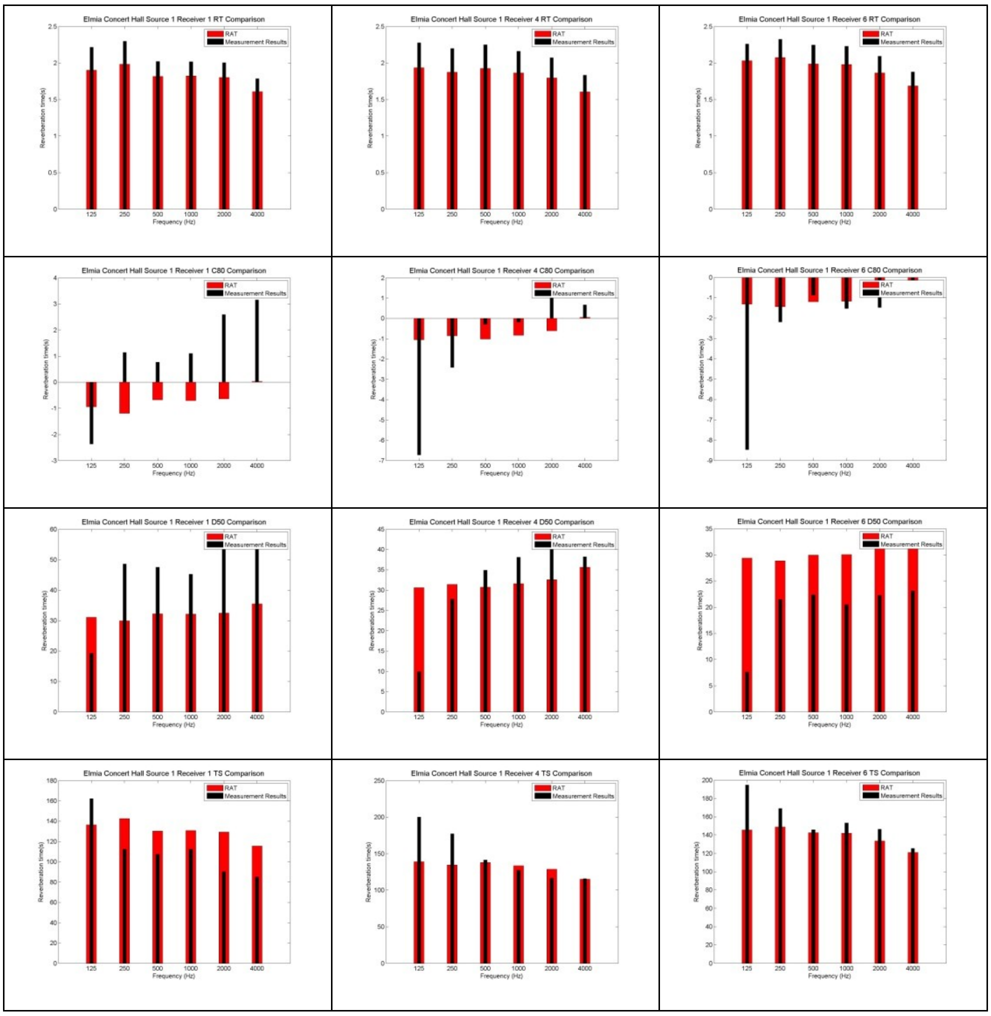
Table 14. Comparison of RAT results and measurement results



It is observed that the discrepancy between the results and measurement between the RT values of calculated and measured data goes up to %30 which is considerably high. However, Sabine and Eyring values are also have discrepancies about the same level because of the fact that global estimates of Sabine and Eyring does not involve the effects of scattering which mostly causes higher reverberation time. Since data obtained by RAT is extrapolated with the expected values (In the case of Elmia Hall, data is extrapolated by Eyring RT), resulting analysis results have discrepancies with the same level of Eyring and Sabine. It is also observed that, RAT results reside within a range determined by the participant results and have more converging results with respect to most of the participants' results.

For this particular case, while evaluating the results, expected values of reverberation time can be manually entered by providing measurement results for post design analysis of the hall. In such a case, the values still remain underestimated but discrepancy is reduced to convenient level. The results are shown in the table below:

Table 15. Comparison of measurement results and RAT results calculated by extrapolation with measurement results



5.5 CASE STUDY 4: PTB STUDIO

The last case study is conducted with the data provided by PTB for PTB Studio. The case study is denoted as round robin 3 by PTB and contains three phases. Only the first one is dealt within this case study which an abstracted form of PTB Studio is subjected. The other phases deal with complicated designs of the PTB Studio. The reason of choosing only the abstracted form of the studio is to show the discrepancies between the participants of the round robin and determine the convergence of the program results among other acoustical analysis and simulation software. In Round Robin Phase 3, two sound sources and 3 sound receivers are inspected. The room geometry and locations of sound source and receiver are shown below:

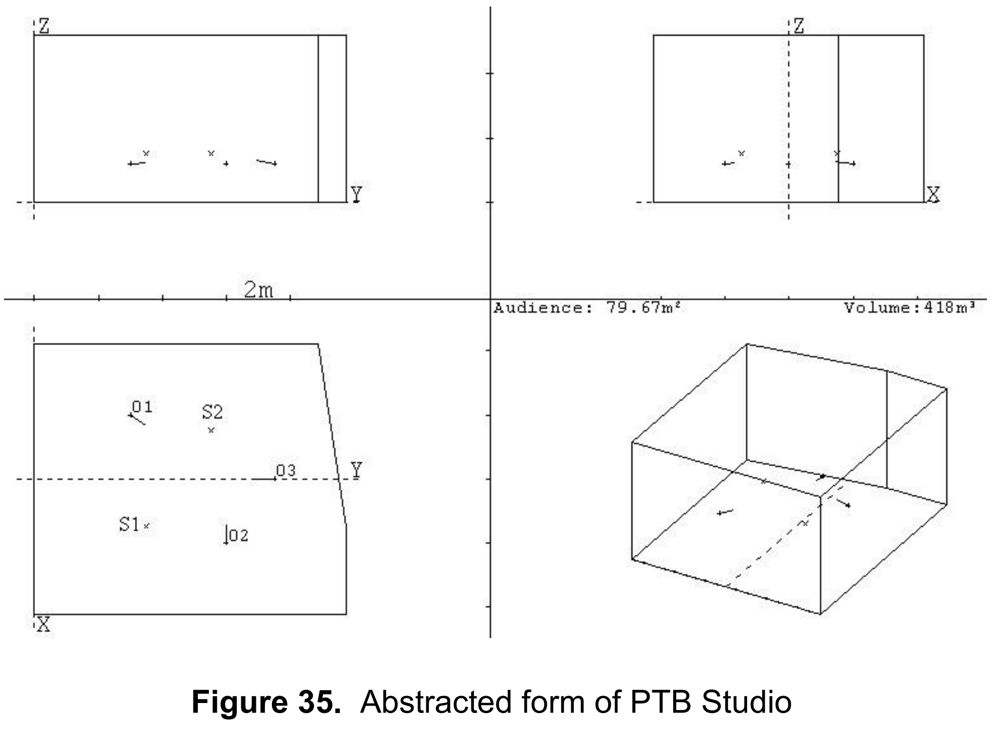


Figure 35. Abstracted form of PTB Studio

In order to avoid excessive and unnecessary information RT(T30) , C80, D50 and TS comparisons for 1000 Hz for only sound source 1 and sound receiver 1 are inspected and results are shown below:

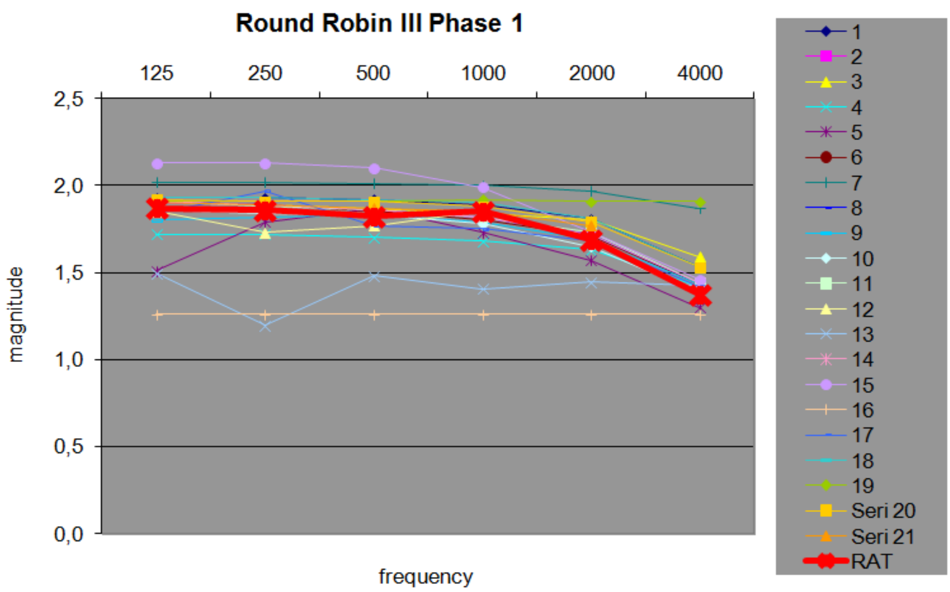


Figure 36. RT comparison for 21 participants and RAT

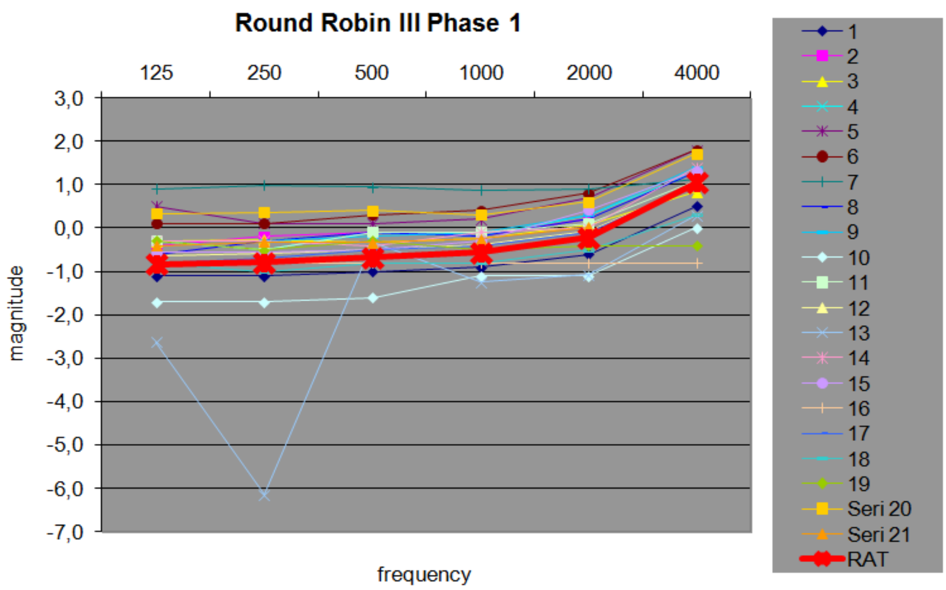


Figure 37. C80 comparison for 21 participants and RAT

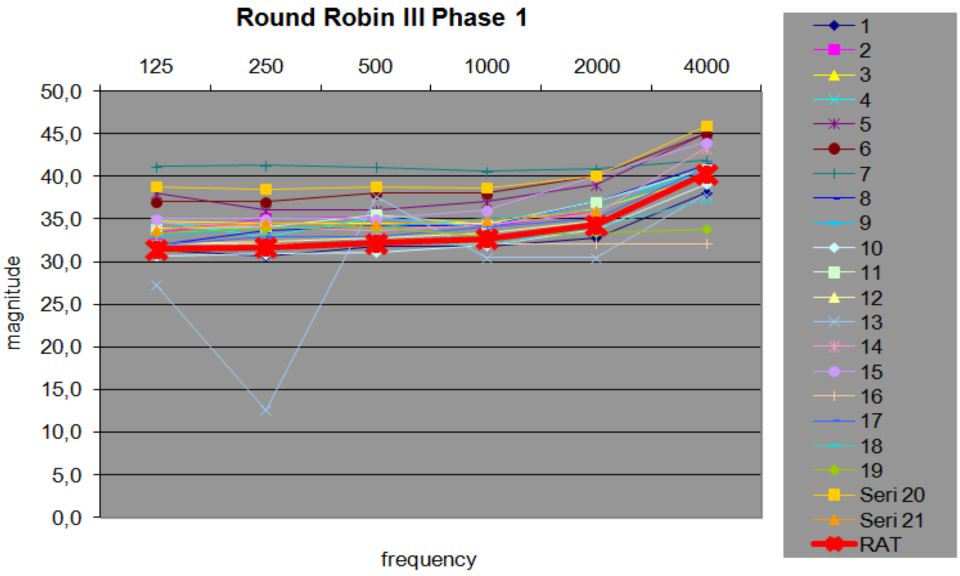


Figure 38. D50 comparison for 21 participants and RAT

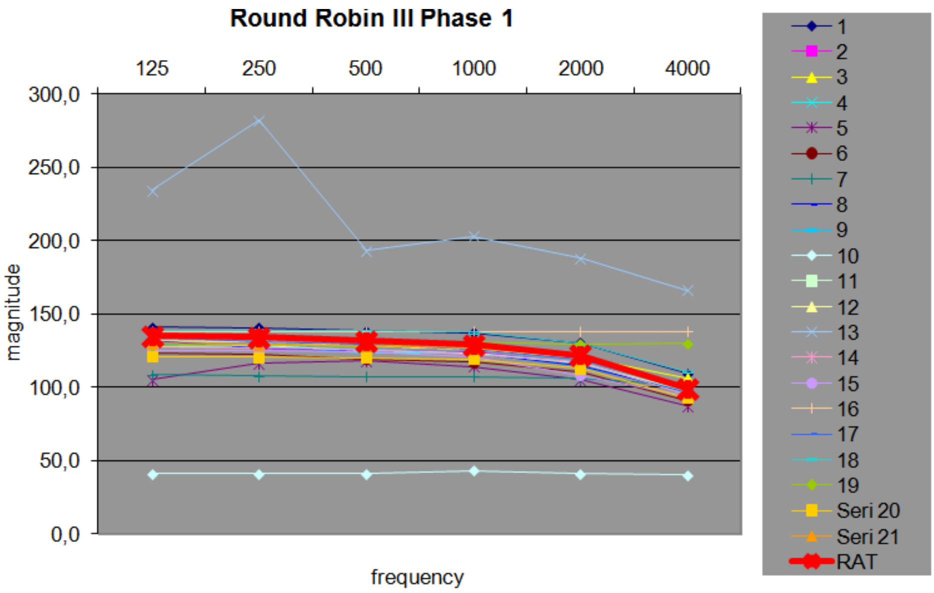


Figure 39. TS comparison for 21 participants and RAT

It is observed that the developed program outputs results with appropriate precision to lay in a range defined by the participant results. However, it is also observed that, even though a range of values are determined from the results of the participants, there is an observable discrepancy in the results of the participant software. For this particular case, measurement data is not provided by PTB since case is an abstracted imaginary case so it is not possible to determine which of the participant is closest to the measurement results.

To sum up, four cases are inspected to determine the limitations and check the validity and verification of the program developed. It is observed that most of the commercial acoustical analysis and simulation software lack to provide validity range of the software which is crucial for the users not to be misled by the provided results. Provided program has proven itself to be valid for the diffuse field cases for both theoretical and real case studies and remain underestimated in uneven cases.

CHAPTER 6

CONCLUSION

6.1 CONCLUSION

Within the scope of the thesis an acoustical analysis and simulation program with easy to use interface embracing all users without a requirement of advanced knowledge on room acoustics is developed. The program has some advantages as well as several disadvantages when compared to commercial acoustical simulation tools. These drawbacks and advantages are shown in the table below:

Table 16. Advantages and disadvantages of RAT

Advantages	Disadvantages
- Provides **numerical, verbal and aural feedbacks** about the design performance of acoustics - **Useful, easy to use** and **learn** - Has **simple interface** - Does not require **experience** in room acoustics - Provides **reliability range of operation** and gives warnings for the cases outside the range	- Cannot operate for **highly complex geometries** because of both image source method and computational limitations - Cannot operate in **non-diffuse field conditions**

Three main outcomes are achieved in the development and during the use of the program which can be regarded as the contributions of the thesis to the field.

First contribution is the use of the program itself as being a successful proposition for the integration of acoustical design to the whole design process. As described in chapter 4, the usability tests proved that the program developed is usable, useful, efficient and learnable and also with the correct and accurate feedbacks, even the non expert users can design acoustically pleasant spaces. Usability test conducted to verify to usefulness and usability of the program showed that the feedbacks provided by the program are easily comprehended by the users and users succeeded to make the necessary changes to enhance the acoustical performance of the design. In this manner, developed program can be regarded as being a design support mechanism enhancing acoustical performance of the design in the early stages of design. The developed program is no doubtfully is not an alternate to acousticians but shall be regarded as a promising useful tool for both architects and acousticians to be used throughout the design process to optimize the acoustics of the concerned room. It is not possible to verify the usefulness of the program throughout the whole design process because of computational issues both caused by image source method and the programming skills and programming environment; however, the program has proven itself to be useful and usable for the intended phases of design. Also with the easy to use behavior and not requiring experience on room acoustics, program has an educative role for inexperienced users by providing useful and relevant information about acoustical design parameters and room acoustics concepts.

Second important contribution can be regarded as the provided information during the usage of the program. It is known that auralization and numerical outputs are also provided with the commercial acoustical simulation software. However, most of these software lack information about the reliability range of the software which brings the possibility of misinterpretation of the results by the users. This situation is especially dangerous for users with limited or no knowledge as users tend to take the results provided by the software as gospel which may mislead the users. As being aware of the necessity of providing a validity range for the provided program, an extensive study is conducted to determine the operational limitations of the program to avoid such misinterpretations. It is seen that program results agree with the literature in diffuse field and nearly diffuse field conditions. Even though the program cannot provide precise results in extremely uneven conditions, the results provided by program remain underestimated and users are warned about the underestimated behavior of the results. Providing reliability range and necessary warnings, the program can be regarded as being more dependable compared to counterparts even though it fails to operate in a narrower range of cases.

Third important contribution of the thesis to literature is the modification made to the Schroeder's method. By this modification, computational issues caused by the image source method resulting in insufficient impulse response length are compensated in diffuse field conditions and it is possible to evaluate and simulate more complex spaces. With the modification, method chosen for the algorithm is challenged and as a result, applicability of image source method is extended up to a certain level. However, still the algorithm is limited by computational costs caused by the behavior of the image source method.

As a result, program proved itself to be a possible integral part of the early design process and can be regarded as a pioneer for a requirement in room acoustics simulation and analysis field.

6.2 RECOMMENDATITONS FOR FUTURE WORK

It is noted that, program developed cannot cover the whole design process. However, within the scope of thesis, program algorithm is developed using only image source method. Even though computational cost is compensated to work for more complex designs than rectangular prisms, program has still computational limits. In the future works, program algorithm can be either supported with or changed to another method, such as well known hybrid method, to lighten computational cost to evaluate design at every complexity level. By this way, the program can inspect whole design process and can be regarded as whole design acoustical support system. Also, in the recommended work, the design process shall be inspected as a whole and necessary adaptations observed within the usage shall be made.

Even though, the program has an easy to use interface, it still is a standalone program requiring data exchange for the custom designs. In the future works, the program can be redesigned to operate cooperatively with any commercial CAD program by automatically recognizing any design change, evaluating every design step and giving continuous feedbacks about the design changes throughout the design process without requiring extra work of data transfer or such. Another way of achieving the same goal can be the recognition of file formats supporting building information modeling. By this way, while importing design geometry, all material information can also be imported and user can get rapid feedbacks without spending time on the determination of materials and other input.

The program is providing results of only four major room acoustics evaluation parameters. The limitation of the provided evaluation parameters are caused by the requirement of additional information about the design which is not always feasible to provide at the early design stages and may lead to misinformation in the very beginning of the designing process. However, as the design is progresses, required information can be provided to calculate more parameters. In the future works, design stages can be determined and more evaluation parameters can be calculated as design progresses with proper feedbacks.

BIBLIOGRAPHY

- Allen, J.B., Berkeley, D. A. (1979). *Image Method for Efficiently Simulating Small Room Acoustics,* Journal of Acoustical Society of America, 65(4).
- Barron, M.,(2005) *Using the standard on objective measures for concert auditoria*, *ISO 3382, to give reliable results*, Acoustical Science and Technology, Vol. 26, No. 2. (2005), pp. 162-169.
- Beranek, L.(1996) *Concert and Opera Halls-How They Sound*, Acoustical Society of America, Woodbury, New York.
- Beranek, L.(2008) *Concert Hall Acoustics* J. Audio Eng. Soc., Vol. 56, No: 7/8, 2008 July/August, pp. 532-584
- Chen, Z.(2007)*. An Investigation Of Acoustic Impulse Response Measurement and Modelling For Small Rooms,* Unpublished Thesis, Department of Engineering, Montana State University.
- Christensen, C. L. (2011) *ODEON Room Acoustics Software Version 11 User's Manual*, ODEON A/S, Scion DTU, Lyngby, Denmark.
- Collins, C. M. (2004*), Development Of A Virtual Acoustic Showroom For Simulating Listening Environments And Audio Speakers* Unpublished Thesis, Department of Mechanical Engineering, Virginia Polytechnic Institute and State University.
- Egan, M. D.(1988), *Architectural Acoustics*, McGraw-Hill, New York.
- Fasoulaki, E. (2008). *Integrated design: A generative multi-performative design approach*. Cambridge, MA: MIT Press
- Funkhouser, T. & Tsingos, N. Et Al. (2004) *A Beam Tracing Method For Interactive Architectural Acoustics*, *Acoustical Society Of America* 115 (2), 739–756

- Gönenç Sorguç A. (2009), *Doğadaki Süreçleri Anlamak İçin Bir Arayüz: Sayısal Teknolojiler, Sayısal Düşünme Ve Tasarlama*, Arredamento Mayıs 2009.

- Gönenç Sorguç, A., Selçuk, S.A., Çakıcı, F.Z., (2001)*Computer Simulation as an Integral Part of Digital Design Education in Architecture, Education and Research in Computer Aided Architectural Design in Europe* (eCAADe 2011), University of Ljubljana, Faculty of Architecture, Ljubljana, Slovenia, September 21-24, 2011.

- ISO Standards, (2008) *ISO3382, Acoustics — Measurement of the reverberation time of rooms with reference to other acoustical parameters*, International Organization for Standardization, Geneva, Switzerland.

- Hyde, J. R.(2002)*, Acoustical Intimacy in Concert Halls: Does Visual Input Affect the Aurial Experience?,* Proceedings of the institute of Acoustics, Vol.24, Pt.4, July 2002

- Kolarevic, B. (2004), *Performative Architecture,* United Kingdom, Routledge.

- Kolarevic, B. (2005), *Architecture In The Digital Age Design And Manufacturing,* United Kingdom, Routledge.

- Kolarevic, B., Malkawi, A. (2004*), Performative Architecture: Beyond Instrumentality*, New York, Routledge.

- Kuttruff, H. (2001) *Room Acoustics,* Taylor & Francis, Spon Press, New York.

- Kuttruff, H. (2006) *Acoustics: An Introduction,* Taylor & Francis, New York.

- Lehmann E.A., Johansson, A.M. (2010) *Diffuse Reverberation Model for Efficient Image-Source Simulation of Room Impulse Responses*, IEEE Transactions on Audio, Speech and Language Processing, vol. 18, no. 6, pp. 1429-1439, August 2010.

- Mechel, F. P. (2002), *Improved Mirror Source Method In Room Acoustics*, Journal Of Sound And Vibration (2002) 256(5), 873-940

- Raghuvanshi, N. & Galoppo, N. & Ming C.L. (2008) *Accelerated Wave-Based Acoustics Simulation*, Stony Brook, New York.

- Rossing T,D.(Ed.)(2007) *Springer Handbook of Acoustics*, Springer Science + Business Media, LLC New York.

- Rubin J.,Chisnell, D. (2008) *Handbook of Usability Testing: How to Plan, Design, and Conduct Effecitve Tests, 2nd Edition,* Wiley Publishing, Inc. Indianapolis, Indiana, USA.

- Schroeder, M.J (1965), *New Method of Measuring Reverberation Time,* Journal of Acoustical Society of America 37(6).

- Sommerville, I. (2004), *Software Engineering 7th Edition,* University of Andrews, Addison-Wesly, United Kingdom.

- Sorguç, M. (1990), *Analysis Of Sound Field In Enclosed Spaces By Method Of Image Sources*, Unpublished Thesis, Department Of Mechanical Engineering, METU.

- Sumbatyan, M. A.& Pompei A. & Rigano M. A. (2000), *New Explicit Solutions In Acoustics Of Closed Spaces On The Basis Of Divergent Series*, Acoustical Society Of America. 107 (2), 709 -713

- Vorländer, M. (2008) *Auralization: Fundamentals Of Acoustics, Modeling, Simulation, Algorithms And Acoustic Virtual Reality*, Berlin Heidelberg, Springer, 2008.

- Yıldırım, G. (2001), *Performance Halls In Early Turkish Republic Period In Ankara And Their Acoustical Evaluations. 3 Cases: Küçük Tiyatro, Resim Heykel Müzesi (Türk Ocağı Binası) And Opera (Büyük Tiyatro),* Unpublished Thesis, Graduate School of Natual and Applied Sciences, METU.

- http://www.cms.gov/SystemLifecycleFramework/Downloads/SelectingDevelopmentApproach.pdf/ Centers of Medicare and Medicaid Services(CMS) (2005), *Selecting a Development Approach,* Webarticle, United States Department of Health and Human Services (HHS). (Last accessed: 07.02.2012)

- http://www.ada-acousticdesign.de/ Ada Ease Official Website (Last accessed: 07.02.2012)

- http://www.odeon.dk/ Odeon Official Website (Last accessed: 07.02.2012)

- http://www.catt.se/ Catt Acoustics Official Website (Last accessed: 07.02.2012)

- http://www.acoustics.org/software.html A Service of Acoustical Society of America (Last accessed: 07.02.2012)