Acoustic Enhancement of Proposed Grand Lecture Hall using Computer Simulation

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ABSTRACT

The presented research deals with the acoustical performance of a proposed grand lecture hall using experimental and modeling techniques. The primary challenge for the senior undergraduate engineering group was that the room has yet to be fully designed or constructed. The secondary goal was to optimize the design of the room using the computer software ODEON in the early design stage rather than after it has been built as is often the case. Reverberation time, early decay time, clarity and STI were the four acoustical parameters considered. The modeling software was also validated using test measurements conducted in a similar lecture room. The results of the present room design demonstrated less than ideal reverberation time and early decay times for the proposed room use but above average clarity and STI values. Design suggestions are given to increase the acoustical performance of the proposed lecture hall.

RÉSUMÉ

La recherche présentée est une étude des conceptions pour optimiser les propriétés acoustiques d'un amphithéâtre par méthodes expérimentales et avec les modèles informatiques. Le principal défi pour le groupe d'étudiantes de quatrième année en génie était que la salle n'a pas été encore complètement conçue ou construit. L'objectif secondaire était l'optimisation de l'amphithéâtre en utilisant le logiciel ODEON au stade de la conception, plutôt qu'après que la salle a été construit, comme c'est souvent le cas. Les quatre paramètres du son en considération étaient: le temps de réverbération, le temps de décroissance, la clarté et le STI. Plusieurs expérimentes ont été mené dans un amphithéâtre similaire pour corroborer le modèle en ODEON. Les résultats du présent amphithéâtre conceptuel ont démontré des niveaux de temps de réverbération et temps de décroissance moins que ceux qui seraient idéales pour ce type de salle de classe, mais ils ont aussi indiqué des valeurs de la clarté et de STI au dessus de la moyenne. Les suggestions sont données pour augmenter la performance acoustique des paramètres sous-performants.

1. INTRODUCTION

The primary purpose of this undergraduate research project was to evaluate the University of Windsor's Centre for Engineering Innovation (CEI) grand lecture hall. The challenge associated with this was that the CEI building has not yet been constructed which eliminates the possibility of using conventional evaluation methods. For this reason, a computer modeling program was used to analyze the lecture hall. The software chosen for this task was ODEON and the metrics analyzed were: reverberation time, early decay time (EDT), clarity (C80), and speech transmission index (STI) [1-4]. These four acoustical parameters were chosen to provide a thorough room evaluation.

The secondary goal was to acoustically optimize the design of this proposed lecture hall. Since construction had already begun, it was impossible to make drastic changes. However, new acoustical technologies can be implemented into a completed room such as better wall materials and sound traps. The results were used to gauge the necessity of the design upgrades.

ODEON is simulation software used to evaluate the acoustical properties of spaces. This investigation was unique because the room which was evaluated is the size of a concert theatre, but must have the acoustics of a classroom. To ensure the results were accurate, a few different room sets were evaluated. Simple and detailed room models were used with the original and upgraded materials. This diversity of test conditions helped validate the results received from ODEON. The results of the investigation confirmed the importance of evaluating the acoustics of a room during the design phase. The results of the current undergraduate group project are presented in this paper.

Section 2 presents the results of the acoustical investigation of an existing lecture theatre. The simulation process and preliminary results of the simulation are described in Section 3. The modeling details as well as the details of the design upgrades are shown in Section 4. Section 5 contains the results of the simulation. Potential errors of the simulation are described in Section 6. Design recommendations are discussed in Section 7 and the conclusions of the current investigation are presented in Section 8.

2. VALIDATION OF SIMULATIONS

Prior to evaluating the acoustics of the grand lecture hall based on design drawings alone, a validation exercise of the software's ability to predict reverberation time and STI was carried out. To do this, a simulation model of an existing 155 seat lecture hall was created and the results were compared to physical measurements for these metrics.

The measurements of reverberation time and STI for the existing hall were performed using DIRAC software, a PC program designed for determining various acoustical parameters based on the measurement and analysis of the impulse response.

Reverberation time of the lecture hall was measured following the procedure of ISO 3382 standard [5]. For this, the reverberation time was measured in 1/1 octave frequency bands and averaged at the most significant bands (500 Hz and 1000 Hz) at a receiver height of 1.2 meters which is representative of the height of a seated listener's ear and at a source height of 1.5 meters. A total of 20 reverberation times were measured in the lecture hall using alternating source and receiver positions around the room. To ensure that the reverberation times obtained were of good quality, the impulse to noise ratio (INR) values were verified to be within acceptable values over the measurement frequency range.

STI measurements were obtained by placing the source at the front and centre of the room to represents the position and source of a lecturer. A total of 15 receiver locations were situated at various positions throughout the hall at a height of 1.2 metres. An ESweep signal and a male filter using DIRAC were used to obtain the impulse response for the speech intelligibility metrics. The ESweeps signals are frequencies that increase exponentially over time and are often said to provide better quality results [6].

Next, the physical dimensions of the room were carefully measured, drawn into CAD software and imported into ODEON. Material surface properties including absorption and scattering coefficients were estimated using an extensive library of typical surface types. From this, a simulation model was created with source and receiver locations similar to those used in the experimental exercise. Predictions of the reverberation time and STI were then calculated using ODEON and compared to the experimental measurements.

Using ODEON, the unoccupied room had a predicted global reverberation time of 1.01s. This is comparable to the measured reverberation time of 1.03s. Upon closer examination, the results of the modeled and experimental measurements within the mid frequency band of 250Hz – 2000Hz were within a 5% agreement. The results at frequencies below 250Hz though did not agree as well which are assumed to be the result of poorly estimated absorption coefficients for some of the room surface materials.

The majority of the predicted STI values calculated at the 15 listener positions were within 5% of the measured STI results which is considered acceptable. However, there were very few STI values that were marginally outside of the 5% range.

Given the favourably comparative results from the validation exercise, it was concluded that the ODEON software is capable of predicting the common room acoustic metrics. This is conditional that the computer model is dimensionally and geometrically correct and that representative material surface properties are chosen.

3. SIMULATION PROCESS

The simulation process using ODEON began with the creation of geometrical representation of the space using AutoCAD software which is capable of exporting a drawing exchange format (dxf) file. While ODEON does have a drawing editor, this option should be used only for the creation of very simple structures. The importation of the geometry file requires the specification of key parameters including tolerance level, connection specification between surfaces and the position of the coordinate system. For this study, two models of the lecture hall were created. The first is referred to as the "detailed model" which is an accurate representation of the room geometry. A second "simplified model" was also created which had a more uniform representation of the surfaces with less architectural detail. The specific differences between the two models are described in Section 4.

The specification in the model of the surface connection type, in this case glued, is important to ensure that the enclosed space is without gaps where there should be none. The specified dimensions were given in millimetres with the tolerances selected to be medium to ensure efficient use of computational resources. A debugger option was used to ensure that no surface overlaps or unwanted irregularities were present. The software also allows the control of other conditions including temperature, humidity and background sound power levels. Standard values for these were used.

The next task in the modeling process was to assign material properties to the room surfaces based on the bill of material for the building design. These include absorption at select frequencies and scatter, or diffusion coefficient. The software has an extensive library of values which can be chosen by the user for these. While many of the room materials are common, such as tile and concrete floors, gypsum board, wooden desks and vinyl covered seats, other surfaces including the side walls and ceiling were made from newer and more innovative acoustic and thermal materials. Some information was found on the manufacturer's websites [7]. For others, the software did provide some guidance by providing a general range for these coefficients taken from similar applications and materials. These recommendations were used to estimate the unknown coefficients.

The next step in the process is to identify source and receiver locations representing where talkers and listeners would normally be located. For the sources, both position and directivity of the sources required specification. The analysis is done through the aid of specific jobs. This option allows the user to specify an analysis to a single job which can involve either one source-receiver combination or multiple source-receivers combination. The setting of the job entirely depends on the set of circumstances and the requirements of the user. The software requires that each job has only one active point source. In the end the user can set up multiple jobs so as to analyze different scenarios. Once the setup is complete and all the parameters are fixed, all the jobs are run simultaneously to complete the analysis which can take considerable time and processing power.

The goal of a good design for the lecture hall is to have a space with uniform acoustic performance throughout the space. For this, an initial analysis was performed for which sound intensity maps were generated which are very similar to colour spectrograms. The sound source was a simulated lecturer at the front of the room and the seat represented the receivers. From these plots, location of low sound pressure levels can be identified. The initial analysis identified a problem with inadequate sound pressure levels at the rear third of the lecture hall. This result suggested that the decay times at some locations within the hall were too low. To solve this, an alternative design with alternative material selections having more diffuse properties [7] was evaluated to increase the decay times with the hope to also increase the sound pressure levels at the rear of the hall. Specifically, this revised model removed the presence of cloth covered architectural panels from the side walls and replaced them instead with smooth drywall. Further, the pyramidal shaped details in the ceiling were removed and again replaced with simple flat drywall surfaces. The seating in the auditorium in the first model incorporated cloth covered cushioned seats. To increase the diffusivity of the space these were replaced with a harder industrialized fiberglass chair. Other surfaces, such as linoleium flooring was replaced with painted concrete. The goal of these changes was to increase reverberation times in the space particularly in the hope of increasing sound levels at the rear of the auditorium.

It was also recognized that a simple increase in reverberation does not necessarily mean an overall improved soundscape within the space. Too much reverberation can result in poor speech recognition. One only needs to imagine listening to a lecture in an empty gymnasium to appreciate this. Because of this, other metrics were also predicted to evaluate the sound quality of the space including EDT, C80 and STI. An attempt to improve remaining problem areas was with the addition of sound traps [8].

4. DETAILS OF THE MODEL

It was stated in the previous section that a detailed and simplified model was generated to represent the space of the lecture hall. There were essentially four fundamental design simplifications which were incorporated into the two models.

The first major difference between the detailed and simplified model was the way that the ceiling surfaces were detailed. The ceiling, as it was designed by the architect, was very irregular in shape. The transition surfaces are not perpendicular to each other with some of these having pyramid shaped diffusers. These differences are illustrated in the plan view of the ceiling for both the detailed and simplified models as given in Figures 1 and 2 respectively.

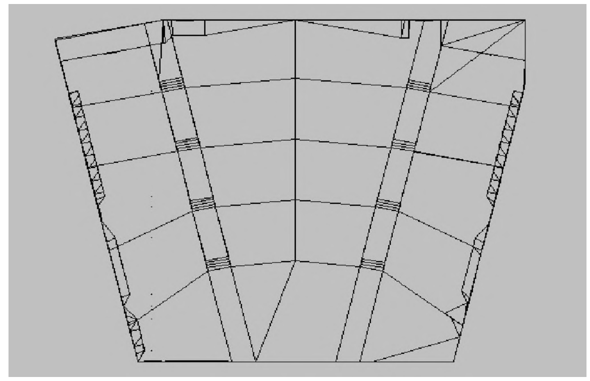

Figure 1: Plan view of Lecture Hall Ceiling for the Detailed Model

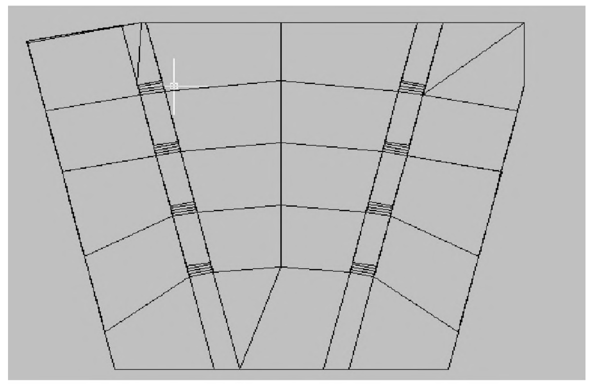

Figure 2: Plan view of Lecture Hall Ceiling for the Simplified Model

A second significant difference between the way that the detailed and simplified models were constructed is the position and shape of the lecture hall seating. The detailed model included shapes with relatively accurate dimensions and shape of the proposed seating for the hall. The simplified model instead represented the seating by box shapes having similar dimensions. The fundamental difference here is that the box shapes are totally enclosed compared to the more open style of the details seats. These differences are illustrated in Figures 3 and 4.

The last major difference between the detailed and simplified model was the way that the wall surfaces and internal

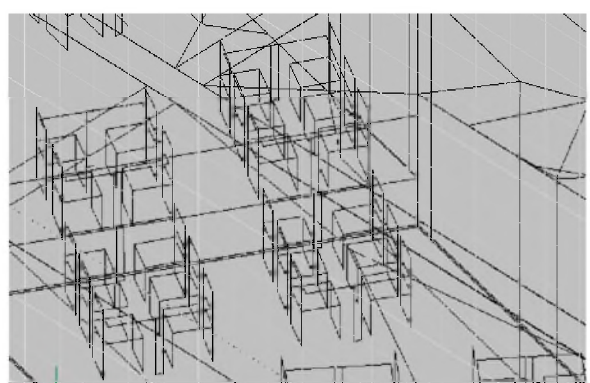

Figure 3: Seating for the Detailed Model

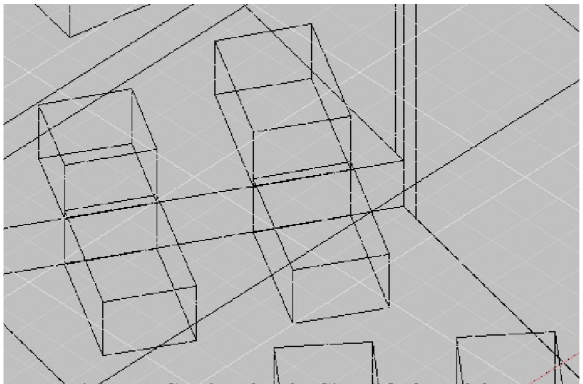

Figure 4: Seating for the Simplified Model

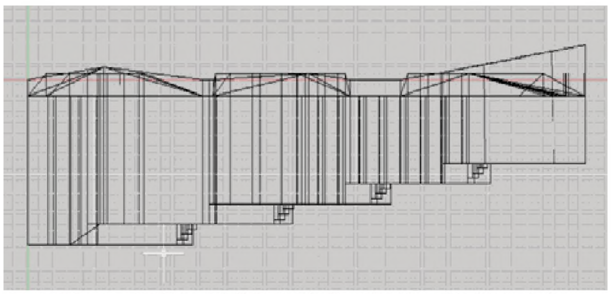

Figure 5: Side Wall Details for the Detailed Model

Figure 6: Side Wall Details for the Simplified Model

structures were modeled. Similar to the case of the ceiling, the architects design of the wall surfaces were very irregular with much surface detail. The internal structures were also hollow at some locations and solid at others. The simplified model had much smother surfaces without the detail and was created without any hollow spaces behind the walls. These are illustrated in Figures 5 and 6 for the detailed and simplified models.

5. RESULTS AND DISCUSSION

The primary purpose of this research was to evaluate the acoustics for the yet to be constructed grand lecture hall to be located in the University of Windsor's new engineering building. The secondary goal was to acoustically optimize the design of this proposed lecture hall. The modeling included the use of both the proposed building surface materials as well as upgraded materials. The results of both a detailed and simplified geometry were also examined. For each of these, the metrics of reverberation time, early decay time (EDT), clarity (C80), and speech transmission index (STI) were predicted. The predicted results for each of these are detailed below.

The results for the original materials showed low values for the reverberation time and EDT but higher than average clarity and STI values. The simple room design performed better than the detailed in all parameters except STI. The upgraded materials increased the reverberation time and EDT, but lowered the clarity and STI.

Each graph shows the results for both the original and upgraded materials. Since there were two room models (detailed and simplified) evaluated, each sound parameter had two graphs. Therefore, there were four sets of results for each parameter. For all of the graphs except STI, the sound parameter was graphed against the frequency on a logarithmic range from 63 to 8000 Hz. Special notice was given to the 1000 to 4000 Hz range because this is where speech primarily resides. Performance in this frequency range was critically important since the room will be used as a lecture hall.

These sound metrics were all dependent on room size and shape, not sound loudness. For example, the results should be the same whether the room is tested with one speaker or 10. For this research, the results generated with 32 speakers in the room were active, were the same if just one source was active. This provides validity to the results. This issue is important because it will be discussed in depth for this room. Whether the lecturer will use the speaker system, or speak without amplification will affect the evaluation of the room.

5.1 Reverberation Time (RT60)

The desired reverberation time for a room of this size and intended use is between 1 and 1.2 seconds [9]. The predicted reverberation times for the detailed and simplified models are illustrated in Figures 7 and 8 respectively, each for the design and upgraded surface materials. The simple model with upgraded materials was the only room designed with reverberation times within the ideal range with all other models predicting lower times. The reverberation times between the original and upgraded materials for both models were fairly consistent over most of the frequency range with a decrease in the 1000 Hz to 4000 Hz range. The overall difference between the highest and lowest cases was approximately 40%. The low reverberation times may be due to the pyramid shaped ceiling details and absorptive materials. This assumption is reinforced by the results for the simplified room with upgraded materials which had neither pyramid ceilings nor absorptive materials and performed at a more desired re-

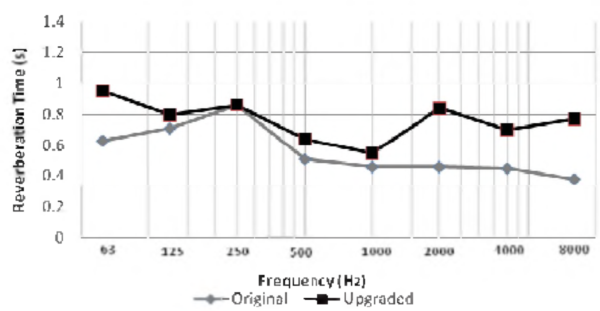

Figure 7: RT60 vs. Frequency for Detailed Model

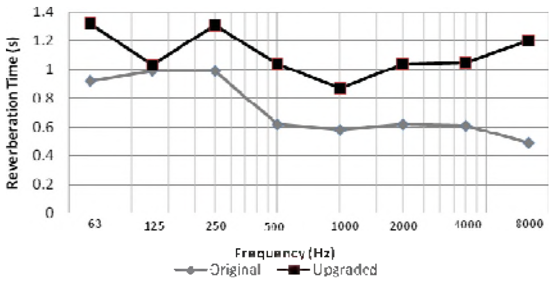

Figure 8: RT60 vs. Frequency for Simplified Model

verberation time.

5.2 Early Decay Time (EDT)

The results for the EDT are in Figures 9 and 10. The ideal early decay times should be similar to reverberation time, or 1 to 1.2 seconds. The EDT results should also correlate closely to the reverberation time results. In general, the results did correlate with 90% of the reverberation times. The EDT results gauge how diffusive the room was [10]. Similar to the results of the reverberation time, only the simple room with upgraded materials performed at the ideal range. However, this was the data set which least correlated with its respective reverberation time (78%).

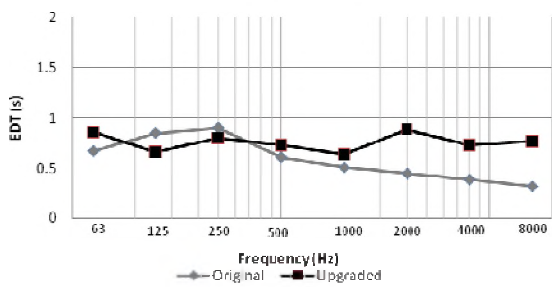

Figure 9: Early Decay Time vs. Frequency for Detailed Model

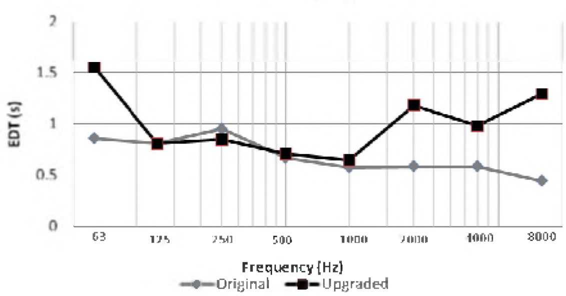

Figure 10: Early Decay Time vs. Frequency for Simplified Model

5.3 Clarity (C80)

It is generally accepted that clarity values above one are acceptable [11]. The results for clarity for each of the modeled cases are given in Figures 11 and 12. All four room scenarios performed well above the standard. The original room material cases performed noticeably better, particularly in the 1000 to 4000 Hz range. The detailed rooms had higher clarity values than the simple rooms. Given that clarity is a comparison of constructive to destructive sound waves, it is suggested that the sound trapping effects of the detailed room and original materials may have led to higher clarities because destructive interference was not as prevalent.

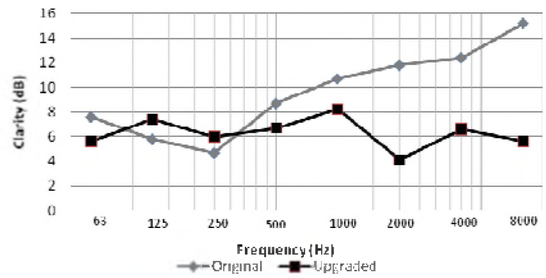

Figure 11: Clarity vs. Frequency for Detailed Model

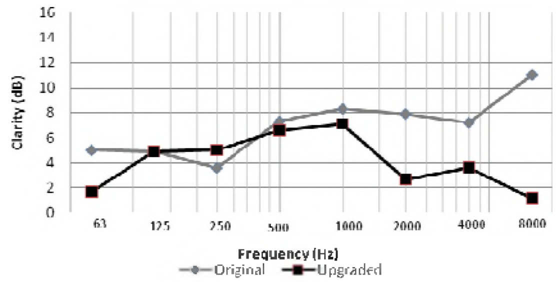

Figure 12: Clarity vs. Frequency for Simplified Model

5.4 Speech Transmission Index (STI)

It should be noted that the details of the HVAC system was not incorporated in any of the models. The effects of the presence of the HVAC system can be a major influence to the STI value. The proposed space in this building is intended to have an innovative type of HVAC system which would be difficult to simulate.

However, the authors have been informed by the architects that this new HVAC system design is expected to be very quiet and should not drastically alter the results. The STI results are illustrated in Figures 13 and 14. The generally accepted ideal range for STI with the given purpose of this space is 0.5 to 0.75 [9]. The results for this parameter were similar to those for clarity except that they differed from each other by only approximately 10%. The room modeled

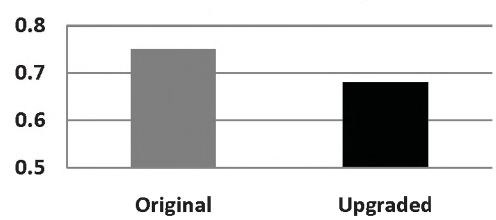

Figure 13: STI Results for Detailed Model

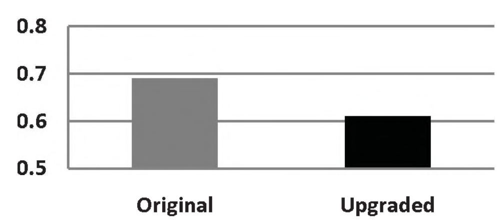

Figure 14: STI Results for Simplified Model

with the original materials performed better with the detailed room model having the best results. All four room designs performed within the range of acceptable values.

While the modeled results for the lecture hall were reasonable, the decay times were lower than expected and the clarity and STI values were above average. It was found that the upgraded materials resulted in an increase in the predicted decay times as anticipated. However, the upgraded surface materials also resulted in lower clarity and STI results.

Given the large margin of variability in most of the results, questions toward the validity of the software are raised. On average, the parameters varied by approximatly36%. However, in consideration of the different modeled input designs, some variation is to be expected.

6. DISCUSSION OF ERRORS

The decay time results presented in the previous section were considerably lower than ideal and also differed depending on the materials used and level of model detail. These can be attributed to a number of sources of error associated with the model input and computation.

As stated in an earlier section, the choice of material property input is important as an inappropriate choice of absorption or scattering coefficient can greatly affect the accuracy of the modeled results. This was regarded as the largest source of error due to the newer style of surface materials used for this building which was not included in ODEON's material data bank. It is assumed that some of the assumed values used for these materials may have influenced the accuracy of the results.

It was also found that some of the calculation approximations used by the ODEON led to truncation errors. Although these errors were small, they may have carried an additive effect throughout the series of calculations. This can be especially so for a complicated space as large as the lecture hall in this study. Other assumptions regarding the modeling of the rooms complicated geometry is another possible source for error. As the amount of approximations increased, so did the chance for error. Finally, the assumption associated with neglecting the impact of the HVAC on the STI prediction may have also resulted in error in this metric's results.

7. DESIGN RECOMMENDATIONS

The secondary objective of this project was to suggest design improvements for the grand lecture hall. It was found that the upgraded materials used did provide greater reverberation and early decay times [7]. However, these upgrades also decreased the clarity and speech transmission indexes. The changes in the clarity and STI were not significant enough though to greatly impact the room, the increase in reverberation time and EDT would improve the sound quality of this space. The early decay time values for the frequency range of 1000Hz to 4000Hz, where speech naturally occurs, was a key parameter to consider.

A live room concept, which can monitor the room acoustics and display the results, is also recommended, especially considering that the room is an engineering teaching hall. This way, the room could be used for demonstration tutorials to assist students in the understanding of room acoustics and architectural material properties. By this, the instructor would be able to demonstrate acoustic experiments for the students.

8. CONCLUSIONS

The primary focus of this research was to evaluate a lecture hall in a preconstruction condition. The secondary goal was to determine how to acoustically optimize the lecture hall's design. This was accomplished through implementation of the ODEON software to predict several different acoustical parameters. Several combinations of materials, wall construction and ceiling designs were modeled to provide evidence of which combinations offered the best acoustical results.

The reverberation time of the detailed grand lecture hall was relatively low for a room of its size. This was due to the pyramid ceilings and absorptive surfaces. This may cause problems for lecturers without the aid of speaker amplification. It is a common trend in room design to design the space to be absorptive and lessen sound propagation, however, this can cause both speaker and listener fatigue.

If anything, this study showed the importance of designing and optimizing the acoustics of a room intended for a learning environment. The merit of using design software like ODEON was also demonstrated.

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