DOI: 10.61782/fa.2023.1164

ACOUSTIC OPTIMIZATION OF CONCERT HALLS USING THE RAY TRACING METHOD

Mariana Domnica Stanciu[1,*] **Gheorghe Dron**[1,2] **Ioan Calin Rosca**[1] **Voichita Bucur**[3]
[1] Department of Mechanical Engineering, Transilvania University of Brasov, B-dul Eroilor 29, 500036 Romania
[2]Siemens Industry Software Romania, Brasov, Nine, Bulevardul Gării 13A, Brașov 500227, Romania
[3] RMIT University, School of Science, Melbourne, GPO Box 2476, VIC 300, Australia

ABSTRACT

In contemporary concert hall designs, engineers must precisely integrate acoustic quality requirements with complex geometric form. The need for modern tools that combine the two aspects, which are often at odds with each other, is therefore obvious. Integrating acoustics into CAD and CAE tools can be done in different ways. Complexity can range from the simple Sabine equation scenario to much more sophisticated real-time finite difference time domain (FDTD) analyses. The purpose of the article was to analyze an innovative method of geometric optimization of a concert hall based on a set of acoustic parameters, using two software: Simcenter 3D and HEEDS (Hierarchical Evolutionary Engineering Design System) MDO. The optimization was done iteratively, based on algorithm known as multiple objective tradeoff study (MOSHERPA). The advantage of this approach is that the MOSHERPA algorithm finds optimal solutions along a Pareto front, the optimal being represented by a number of points in the Pareto front. In the first stage, starting from the results obtained in the DOE (Design of Experiments) analysis for the 4 kHz frequency band, the correlations between the geometric variables and the acoustic parameters were determined. From the results obtained in the first stage, a very good correlation was observed between the geometric ratio L/W (length by width) and IACC (Interaural Cross Correlation).

*Corresponding author: mariana.stanciu@unitbv.ro

Keywords: *acoustic, optimization, concert hall, multiple objective tradeoff study (MOSHERPA), ray tracing method.*

1. INTRODUCTION

In the design of contemporary concert halls, engineers must integrate the acoustic quality requirements, which are often contradictory, with complex geometric shapes [1]. The need for modern tools that combine the two aspects, which are often in contradiction with each other, is therefore obvious, for which many simulation and optimization methods have been developed [1]. The main measures defined by standards ISO 3382-1:2009 to characterize an acoustic quality of a concert hall, are reverberation time (RT), sound strength (G), early decay time (EDT), balance between early and late arriving energy (C80 and others), early lateral energy measures (LF and LFC) [2].
According to ISO 3382-2, the estimation of the reverberation time is done starting from the determination of the alteration time over a limited range of 30 dB, starting from a value 5 dB below the stationary level. According to studies carried out by [3], for 100 performance concert halls around the world, Table 1 shows the ranges of values of acoustic parameters for classical music concert halls, considered for the middle frequency bands (500, 1000 and 2000 Hz) [3]. Baron [4] considered that the acoustic parameters in the standard should be measured taking into account the objective measurement conditions, such as: occupancy of the concert hall with an audience; taking the stage; source location; directivity of the source, position of the receivers. The reference [4] recommends that measurements be taken in the six octave bands from 125–4,000 Hz. Integrating acoustics into CAD and CAE tools can be done in different ways. The complexity can vary

from the simple Sabine equation scenario to the much more sophisticated real-time finite difference time domain (FDTD) analyzes [5–7]. Based on the state of the arts studies, different specific design and acoustic analysis tools are highlighted, with the aim of finding a "solution space" for any new problem using different architectural languages. Whether a numerical simulation method or a hybrid one is applied, they are all based on a set of acoustic variables that are normalized, the results having to fall within certain value ranges [8–12].

Table 1. Value range of acoustic parameters for classical music concert halls [3].

Acoustic parameter	The range of values
Reverberation time, RT30 (s)	1.8 – 2.2
Early Decay Time, EDT (S)	1.25 – 1.7
Clarity, C80 (dB)	+1.6
Definition, D50 (%)	+43
Interaural Cross Correlation, IACC (-)	0.34 – 0.4

Subjective studies of room acoustics have shown that acoustic parameters obtained from impulse response can be correlated with specific aspects of the room. The term just noticeable difference JND (just noticeable difference) represents the minimal change in acoustic parameters, perceptible by listeners [13 – 16].
Starting from the theoretical considerations, in the present work a method of determining the shape of a concert hall was studied by using ideal acoustic parameters calculated with the Ray Tracing method [17 – 21]. There are several methods that are used to model sound propagation, namely ray based methods; wave based methods and statistical methods. The Ray Acoustics solution uses the assumption of a stationary front where there is a source that vibrates at a constant and continuous frequency. In the case of the acoustic model in this study, the source has a constant magnitude as a function of frequency. It propagates in the considered domain, from the source to the receiver, and the interferences between the rays are taken into account [21].
Ray Acoustics calculates the wave propagation in two stages [5, 18, 19]: the first time, the geometric calculation basically consists of identifying all the propagation paths between a source and a microphone ("ray path"), using the method of Ray Tracing; then the physical calculation: using the results from the geometric calculation, for each source-microphone pair and for each "ray path", the wave propagation is calculated, in the frequency domain. At the end, the results are summed up in the complex to have a complete picture of the frequency response corresponding to each microphone.
Because "Ray tracing" methods are not adapted to sound wave diffusion phenomena, the Ray Acoustics solver also uses a time simulation method called "Particle tracing" [14, 20–22].
This method is based on the generation (at each source) and propagation of a very large number of particles carrying acoustic energy. At each contact with a surface, a particle loses energy due to absorption and is either reflected or scattered (Lambert's law of diffusion). A sphere is used as a particle collector at the receiver position. The arrival time and residual energy from each collected particle are used to construct the echogram (impulse response) corresponding to each microphone. It should be noted that this process is carried out for each frequency band separately. Finally, the solver offers users a hybrid method that manages to combine the advantages of the two methods, Beam Tracing and Particle Tracing. The results of this hybrid simulation are presented in the form of a response to an impulse, hybrid this time, therefore different from the response to an impulse obtained from the Ray Tracing method.
The study addresses both how to develop the acoustic model by introducing it into the Ray Acoustics solution from Simcenter 3D and HEEDS MDO, as well as the compatibility issue between the programs and the solutions identified based on the statistical analysis.

2. DEVELOPMENT OF THE ACOUSTIC MODEL

To study the variation of acoustic parameters depending on the layout of the room, an acoustic model was created using the Simcenter 3D program. The study started from the following design requirements: the parallelepiped shape of the concert hall (shoebox), with a number of 2000 seats and the total area of the hall: 1000 m^2; the predefined material configuration for the occupied room; feasibility limits in terms of dimensional ratios: $0.5 \leq$Height/Width≤ 2; $0.8 \leq$Length/Width ≤ 2.5, where height is denoted H, width is denoted W and length (L).
The purpose of the hall - concert hall for classical music, with the dimensions of the stage: height: 1.2 m; length: 10 m; width: variable depending on the width of the room. In the next step the output files that make up the acoustic model were imported into the HEEDS MDO program. The acoustic parameters calculated with the Ray Acoustics solution, as well as the geometric parameters describing the shape of the hall, were labeled so that HEEDS MDO received input and output variables corresponding to the parameters from Simcenter 3D.

The connection of the two programs represents a closed loop that generates at each iteration a different shape and, implicitly, different acoustic parameters as can be seen in Figure 1.

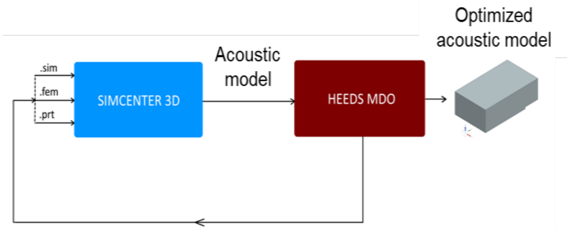


Figure 1. Schematic representation of the connection loop between Simcenter 3D and HEEDS MDO.

At each iteration, HEEDS MDO (*Hierarchical Evolutionary Engineering Design System)* varies the parameters related to the layout of the hall and then uses the solver in Simcenter 3D (Icare) to calculate the acoustic parameters corresponding to the layout. HEEDS MDO modifies a copy of the input files generated in Simcenter 3D (.prt, .fem, .sim) and generates new output files for each iteration.
They can be saved for all iterations (meaning they can be opened, viewed and post-processed in Simcenter 3D) or just the result values can be kept in HEEDS MDO. 15 concert halls studied [3] in Concert halls and opera houses: music, acoustics, and architecture [3] were taken as reference for which the relevant data for the following studies were extracted. The variation range of the H/W and L/W ratios were taken as a reference to choose the initial layout of the hall (Fig. 2).

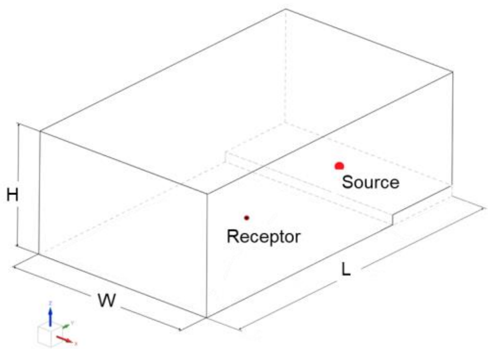


Figure 2. The geometric and acoustic model of the hall.

3. RESULTS AND DISCUSSION

3.1 Dimensional ratio variation (length, width, height)

Starting from the results obtained in the DOE (*Design of Experiments*) analysis (*Screening/Response Surface*) for the 4 kHz frequency band, the correlations between the geometric variables and the acoustic parameters were determined (Fig. 3). From the obtained results, a very good correlation can be observed between the geometric ratio L/W (length by width) and IACC (Fig. 4.). Knowing that the IACC must be between 0.34 and 0.4 and the ratio between length and width L/W varies between 1.5 and 1.8 as in the analysis for the 15 concert halls, it turns out that the points that satisfy the two conditions are in the gray area highlighted in Figure 4. Taking into account that there is a good correlation between EDT and RT30, and they change according to the same geometric ratio H/W, the two parameters vary as in Fig. 5. The highlighted points are the design variables chosen based on the parameters from the previous steps: IACC, EDT and the L/W and H/W geometric ratios.

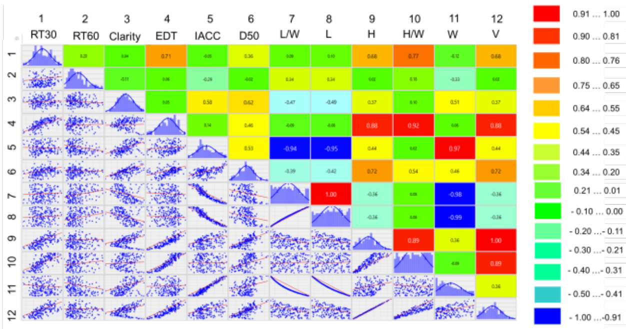


Figure 3. Schematization of the results obtained from the DOE analysis.

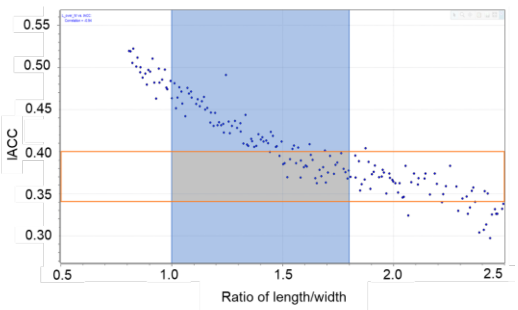


Figure 4. Variation of the IACC parameter as a function of the L/W ratio.

Constructive variants were extracted from the DOE study that meet all the conditions both in terms of shape and acoustic parameters. In total, 7 constructive variants were extracted from a total of 600 (200 for each frequency band). Averaging the hall's aspect ratios resulted in ratios of 0.62 for H/W and 1.71 for L/W, values very close to those of the halls considered to be the best in the world.

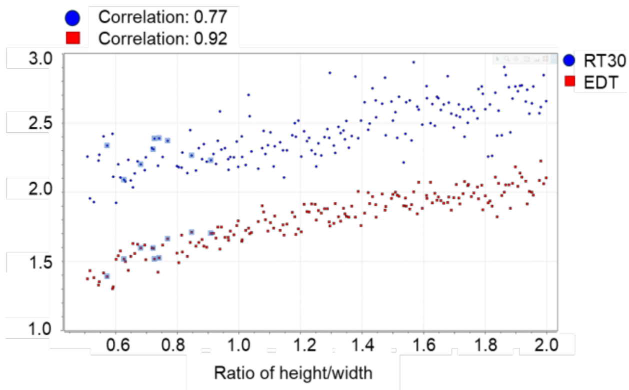


Figure 5. Variation of EDT and RT30 depending on the ratio between height and width H/W.

3.2 The study of variation of opening angle α

Another aspect that was considered for the shape of the hall is the opening angle, denoted α. The dimensional ratios were considered constant and the angle α is variable between 0° and 20° with a step of 0.1° for 200 iterations in total. This is how it went from the rectangular model shape to the trapezoidal shape (Fig. 6).

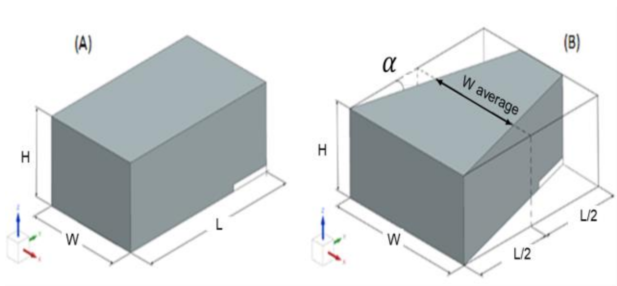


Figure 6. Variation of opening angle α: a) rectangular model; b) trapezoidal shape.

The obtained results show that there is a correlation between the variation of the angle α and the acoustic parameters IACC, D50 and C80 (Fig. 7). As the angle α increases, the value of the IACC parameter decreases. This is explained because the IACC parameter is mainly influenced by sidewall reflections. However, considering the small variation range of this acoustic parameter, the angle α does not have a relevant influence. Even if the angle α is changed, most of the points determined by DOE are still in the optimal range of 0.34 and 0.4.

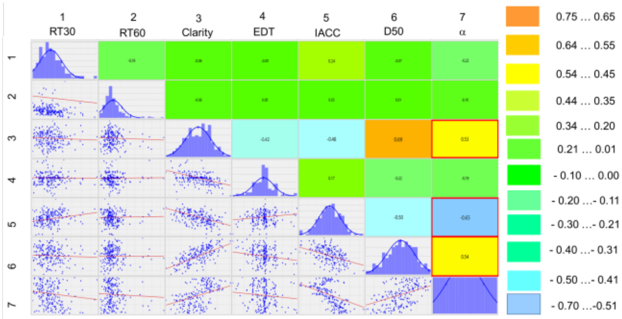


Figure 7. Correlations between angle α and acoustic parameters IACC, D50 and C80.

3.3 The variation of the acoustic parameters according to the position of the receiver in the hall

All the results presented previously considered the receiver in the same position, denoted by coordinates (0,0) in Fig. 8. However, it was noticed that depending on the receiver location inside the hall, there is a degradation or an improvement of some acoustic parameters. As the audience seats are spaced from the stage, sidewalls and back wall, the receiver variance has been reduced by 10% to account for this. Also, a symmetry plan (YZ) across the hall width has been considered for the variance field of the receiver. This approach allowed to reduce the number of iterations needed to cover the entire audience area simulated by the receiver.

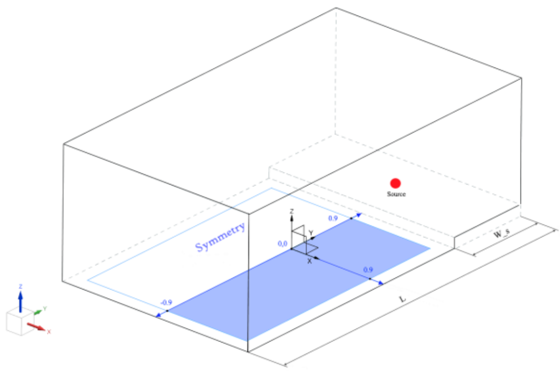
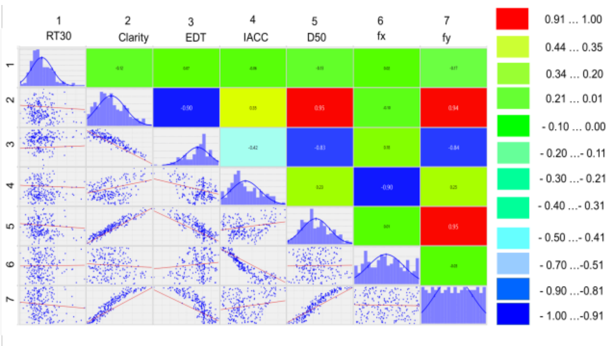


Figure 8. Variation of the receiver inside the concert hall.

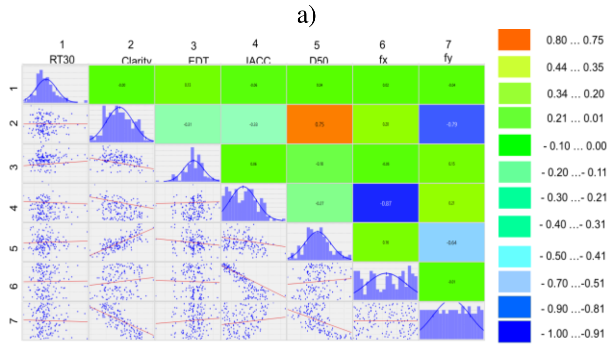
It is important to note that the variation of C80, D50 and EDT parameters is significant along its longitudinal direction. The functions have a minimum (in the case of the D50 and C80) and a maximum (in the case of the EDT) near the center of the hall except for the stage area. The variation of the receiver in the transverse direction has a relevant impact only for the IACC parameter which decays approximately linearly near the sidewalls.

Also, an important observation is that the acoustic parameters have a different behavior in the front part of the hall compared to the back part.

To better understand the correlations between the position of the receiver and the acoustic parameters, the hall was divided into two: up to the minimum point of the function and after the minimum point. Thus, two distinct areas were highlighted: the front part of the hall (Fig. 9a) and the back part (Fig. 9b).



a)



b)

Figure 9. Results of the receiver position variation study: a) Results obtained by the DOE study for the front of the hall; b) Results from the DOE study for the back of the room.

4. CONCLUSIONS

In the study of the variation of the acoustic parameters based on the model with a single receiver, the following conclusions can be highlighted:

- The single-receiver acoustic model is useful to establish a starting point for the optimization;
- In order to more accurately establish the acoustic quality, it is necessary to determine the acoustic parameters in different positions on the audience area inside the hall. For this reason, several receivers were added to the acoustic model, which led to a greater complexity of the co-simulation, but allowed a global view of the acoustic parameters variation.

The advantages of this approach are:

- Calculation of the average values for the acoustic parameters so that they can be compared with the experimental determinations in the already existing concert halls;
- Global vision of the hall's acoustics;
- Calculation of standard deviations from the average values of the acoustic parameters to study the uniformity of the acoustic quality.

5. ACKNOWLEDGMENTS

This research was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS/CCCDI – UEFISCDI, project number 61PCE/2022, PN-III-P4-PCE2021-0885, ACADIA – Qualitative, dynamic and acoustic analysis of anisotropic systems with modified interfaces.

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