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RESEARCH ARTICLE

Algorithmic Variations of Acoustic Materials and Shapes Implementation in the Interior Space for Room Acoustics Optimization

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ABSTRACT

This study aims to fill the gap between the endless possibilities of the parametric design process and the detailed acoustic analyses. The developed methodology consists of a custom parametric algorithm that explores the variations of possible interior implementations based on material properties, geometrical formations, and positions in the room to optimize the acoustic response of the space. The proposed methodology assists the design process in the very early phase and explores diverse options. In the first stage, all variations are evaluated in Pachyderm for rapid feedback and to reduce the possibilities for further analysis. The second stage was a detailed evaluation of the first design selection in Odeon and the selection of the best design proposal from the generated. The implemented parametric approach is described, and the final approved design evaluations are presented.

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1. Introduction

Designing a new concept for architects to start by separating spaces by areas needed for their specific functions is common. The later stages of the design include further analysis of the height of these spaces. When the final volume of the venue is designed, it must incorporate all necessary installations and interior elements that form the final shape. However, most architects neglect the importance of acoustics and the connection between the volume and acoustic properties of the materials implemented in their designs. As mentioned in Peters (2011), drawing is rarely used as a mechanism for predicting sonic performance. Often, architects emphasize the importance of visual perception and utility–colors, textures, styles of materials, or easy maintenance–regardless of acoustics. The excessive use of reflective materials such as marble or ceramics, exposed concrete, self-levering floors, and glass partitions can lead to prolonged reverberation times, poor speech intelligibility, echo effects, and other unwanted acoustic phenomena. With the development of this algorithm, we intend to create a simple way of illustrating how integrating different acoustic materials can benefit the overall acoustic qualities of a room in the early design phase. Similar studies have been conducted, mostly focusing on a specific area of a room as an acoustic optimization: ceiling design (Rumpf *et al*., 2017; Rumpf *et al*., 2018; Peters, 2009), canopy, or back wall design. Our intent is to alter the surfaces that are usually included in acoustic treatments. Another goal was to compare the data collected from Pachyderm and Odeon and evaluate the benefits and drawbacks of using both programs.

With the development of building information modelling (BIM) software such as Revit and ArchiCAD, which are commonly used among architects, the volumes of spaces are easily predefined and can be acoustically examined at early stages, along with the materials intended for implementation. However, if multiple volume shapes and size variations are to be examined for specific acoustic properties, a parametric design software is preferable. According to recent studies (Peters *et al*., 2021; Sorano *et al*., 2019; Mirra *et al*., 2023; Gardner *et al*., 2021; Van der Harten, 2014), Grasshopper and Pachyderm are seldom used for running acoustic simulations within the parametric design environment, leading to rapid results and feedback on the generated design. Peters, et.al. defined the "parametric acoustics" and the "parametric acoustics workflow" where modelling and simulation are performed in the same environment. Nine design techniques for the parametric workflow were defined in their results. Four of them were used in this study: reflection mapping, geometry exchange, material and geometry mapping, and exploration of the design space.

The aim of this experimental study is to define a "parametric script" that first generates simple "shoebox" type spaces defined by their dimensions of length, width, and height, with multipurpose use but primary function of speech/lecture. Second, different amounts of acoustic materials are generated on the walls and ceiling in order to optimize the acoustical performance of the space by predefined conditions, and finally to evaluate the results of the generated design.

2. Methodology

When acoustic comfort is discussed, several parameters must be considered, and detailed acoustic analysis usually requires specialized software. However, the initial evaluation of the acoustic quality of multiple rooms can easily be performed by determining the Reverberation Time (RT) in Grasshopper or Pachyderm. Subsequently, the analysis can proceed in Odeon to verify the initial RT results and examine other acoustic parameters, such as EDT, STI, C50, and C80.

To calculate the demand for the optimal reverberation time of the rooms in question, the target reverberation time for mid-frequencies between 500 Hz and 1000 Hz, T_{Soll}, was computed in accordance with the DIN 18041:2016-03 standard (DIN 18041, 2016) as a matter of room volume. After the identification of an optimized acoustic material layout, a subsequent RT calculation was performed using Wallace Sabine's formula based on the volume, surface areas, and absorption coefficients of the materials applied.

The research strategy employed in this study consists of three stages for analyzing the reverberation time using empirical and simulation methods. We first calculated Rt using Wallace Sabine's equation, which extrapolates the role of reverberation time as a function of the volume and material absorption characteristics. We then applied these equations to Grasshopper, where they are computationally linked with parametric room geometries developed within the same platform. This approach enables the use of an iterative and flexible process to examine RT in a variety of spatial configurations and material allocations.

To enhance the analytical process further, we constructed an algorithm that produces differentiated room structures, including wall and ceiling arrangements, with variations in features. The configuration, position, and material type are determined in relation to the room size and proportion so that the resulting geometries follow acoustic optimization rules. This algorithm also varies the spatial parameters with respect to changing room dimensions and material attributes for a broader analysis. A precise explanation of the rules integrated into the model is provided below.

Upon theoretical estimation, we performed a physical simulation using the Pachyderm plug-in in the Grasshopper. Pachyderm utilizes a ray-tracing algorithm to simulate the propagation of rays through the provided geometries, considering absorption, diffusion, and reflection as material properties. For usage with the designed acoustic treatment in Pachyderm, we specified three categories of materials: absorber, reflector, and diffuser, and their corresponding average absorption and scattering coefficients. When generating the materials, the front wall and floor were not treated, and common materials were assigned: ordinary plaster for the wall and a hardwood floor finish. The algorithm was instructed to create material variations for the side walls, back wall, and ceiling to provide controlled and systematic material optimization.

To simplify the process of transitioning from modelling to simulation, we designed a custom algorithm within Grasshopper to automatically export all geometries and their respective material properties. The algorithm we developed using the Pancake library for Grasshopper helps smoothly transfer data from Rhino and Grasshopper to third-party simulation environments. By automating it, we eliminated the possibility of human error, ensured consistency, and allowed us to iterate quickly between different room configurations and material scenarios.

Finally, we verified and compared the results with the Odeon software, which employs another acoustic simulation technique based on hybrid ray tracing and image-source models. The same geometries, material properties, and source and receiver points for the selected volumes are transferred into Odeon to compute the reverberation time under controlled conditions. The comparative analysis of the theoretical (Wallace Sabine), Pachyderm, and Odeon results illuminates the accuracy and limitations of each method, exposing inconsistencies due to geometric complexity and scattering effects, which are not well represented by empirical equations.

This three-step procedure allows for multilayered acoustic assessment, combining theoretical calculations, physical simulations, and validation using specialized software, guaranteeing a comprehensive understanding of reverberation time behavior in various room geometries.

2.1. Volume Variations

To conduct the experiment, 41 rooms were generated, with basic "shoebox" shapes and volumes varying between 500 m^3 and 7000 m^3. The "shoebox" design was selected for its common use as easily implemented in architectural idea layout and lower construction values of the shape. For each of the generated rooms, the initial materials were the same: wooden floors, plaster walls, and plaster ceilings. The absorption coefficients of these materials were applied to the first RT calculation based on Wallace Sabine's formula. The definition of the spaces by their dimensions of length(y), width(x), and height(z) was made by combinations according to Table I. Of all 50 possible combinations, nine were excluded based on z>x or z>y, as those proportions are more unlikely to be used. In Fig. 1, All generated volumes are presented.

2.2. Material Implementation

When defining the positioning of the generated materials on the surfaces, the "front wall" and "floor" were excluded as possible areas, and they were assigned with common materials – basic plaster for the wall and hardwood floor finish. The algorithm was set to generate variations in the sidewalls, backwall, and ceiling.

The defined materials are commonly used in acoustic applications. The absorber was based on a pyramid-shaped polyurethane foam panel with an average absorption coefficient of 0.9. For the reflector, we used a standard wooden panel with an average of 0.03, 12 mm plywood over a 50 mm airgap. Finally, for the definition of the diffuser, we used the properties of an average = 0.05, for a solid wood diffuser.

After choosing the materials, we had to define rules for positioning them on the selected surfaces. Depending on the type of surface and proportion of the room, different positions and quantities can be suitable for these three materials. We wanted to have the option of having all materials on any treated surface, but in different amounts. The first rule defines the position of the materials according to the surface on which they are implemented and the proportions of the room. The second rule defines the area occupied by the materials, depending on the volume of the room. Both the rules are presented in Tables II and III.

2.3. Customized Algorithm

Three different methods for calculating the reverberation time were used in the Grasshopper algorithm (Fig. 2). T_{Soll}, used for the target value from the DIN 18041:2016-03 standard, was calculated using the following formulas:

For "music" V < 1000 m^3 = $TSoll, A1 = (0,45\, lgV/m3 + 0,07)\, s$

For "speech" 1000 m^3< V < 5000 m^3 = $TSoll, A2 = (0,37\, lgV/m3 - 0,14)\, s$

For "sport" 5000 m^3 < V < 10000 m^3 = $TSoll, A5 = (0,75\, lgV/m3 - 1,00)\, s$

TABLE I: VOLUME GENERATION

	/meters/				
$X_{/width/}$	8	12	16	20	24
$Y_{/length/}$	8	12	16	20	24
$Z_{/height/}$	8	12			

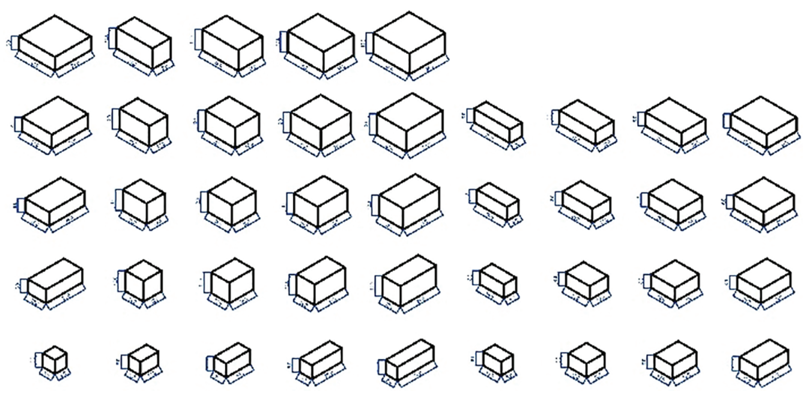

Fig. 1. Generated volumes.

TABLE II: Conditioning of Material Positions by Room Proportions

Conditions	Absorption	Diffusion	Reflection
I-st y>1,5x		*Back wall*	
	Center	Random	Periphery
		Side walls	
	At end	Random	At beginning
		Ceiling	
	At end	Random	At beginning
II-nd 1,5x>y>x y<x<1,5y		*Back wall*	
	Center	Random	Periphery
		Side walls	
	Random	Random	Center
		Ceiling	
	Periphery	Random	Center
III-rd x>1,5y		*Back wall*	
	Middle	Random	Ends
		Side walls	
	Random	Random	Center
		Ceiling	
	Ends	Random	Middle

TABLE III: Conditioning of Material Area as % of Surface by Room Volume

Conditions	Absorption	Diffusion	Reflection
V<1000 m^3		*Back wall*	
	100%	0	0
		Side walls	
	0	66%	33%
		Ceiling	
	33%	33%	33%
1000 m^3< V<5000 m^3		*Back wall*	
	66%	0	33%
		Side walls	
	33%	33%	33%
		Ceiling	
	33%	33%	33%
V>5000 m^3		*Back wall*	
	100%	0	0
		Side walls	
	66%	33%	0
		Ceiling	
	66%	33%	0

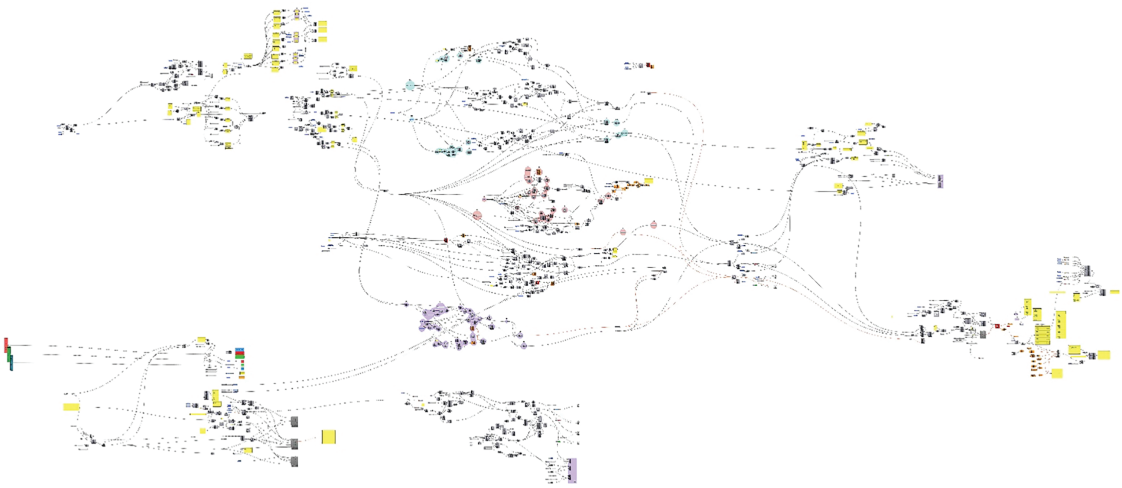

Fig. 2. Customized algorithm in Grasshopper.

The reverberation time for the volumes before and after the generated treatment was calculated using Wallace Sabine formula:

$$RT6o = 0.161\,V/S\alpha$$

where *RT60* is the time in seconds required for a sound to decay 60 dB, V is the volume of the room, S is the boundary surface area and α is the average absorption coefficient.

For comparison with the previously mentioned formulas, we additionally calculated the reverberation time using the integrated ray-tracing simulation in Pachyderm for one source and receiver. Furthermore, we examined some of the acoustically treated volumes generated in Odeon to verify the results.

2.4. Generated Acoustic Material Implementation

Following the rules described in Tables II and III, Grasshopper modelled all the materials as preconditioned. All generated acoustic treatments are presented in Fig. 3. Some of the results are shown in Figs. 4–6, where blue is absorption, green is reflection, and red is diffusion.

3. Results

Although these results are based on average coefficients and do not specify RT for different octave bands, the collected data are essential for initial concept build-up and can be extremely useful for architects and architectural students when analyzing spaces, their acoustic functions, and the need for

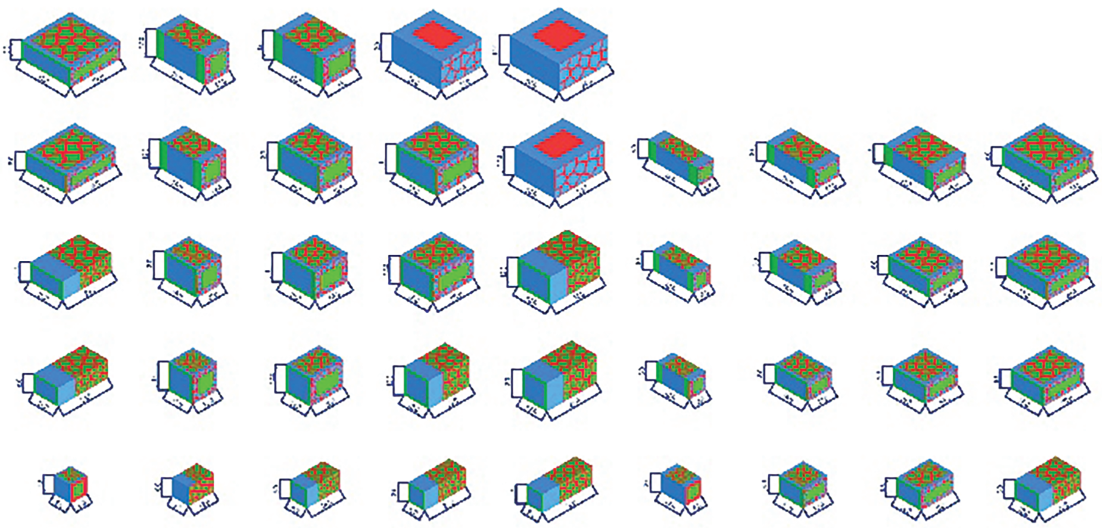

Fig. 3. Generated acoustic treatment.

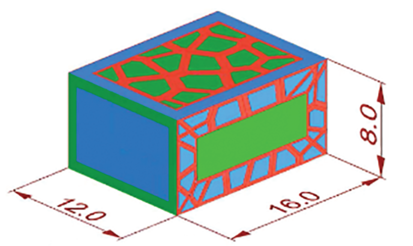

Fig. 4. First rule by proportion; 1000 m^3 < V < 5000 m^3.

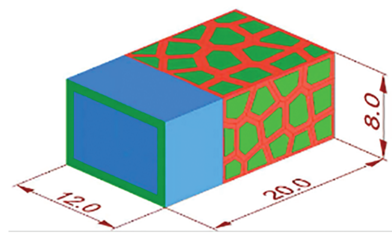

Fig. 5. Second rule of proportion; 1000 m^3 < V < 5000 m^3.

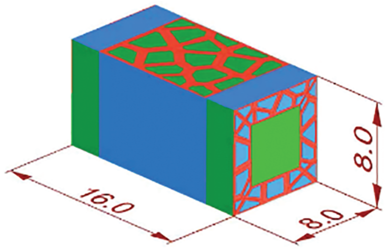

Fig. 6. Third rule by proportion; 1000 m^3 < V < 5000 m^3.

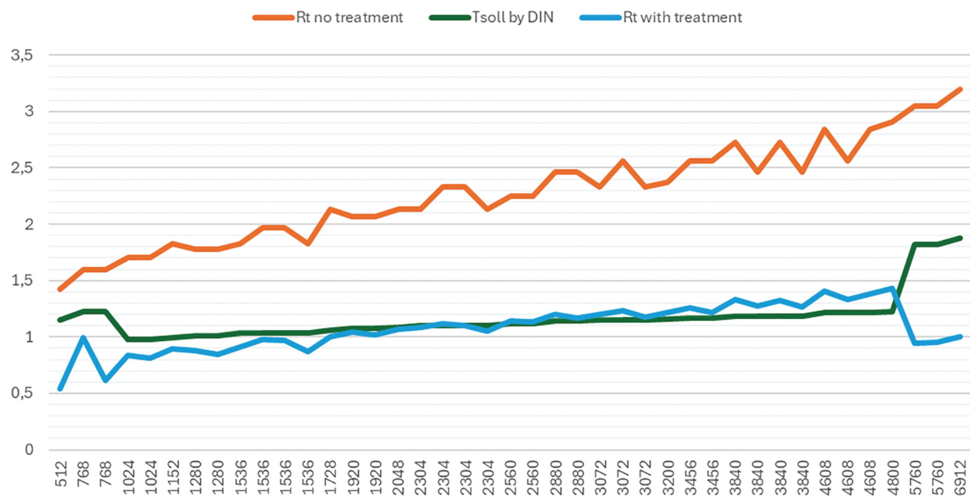

Fig. 7. Calculated data from Grasshopper algorithm.

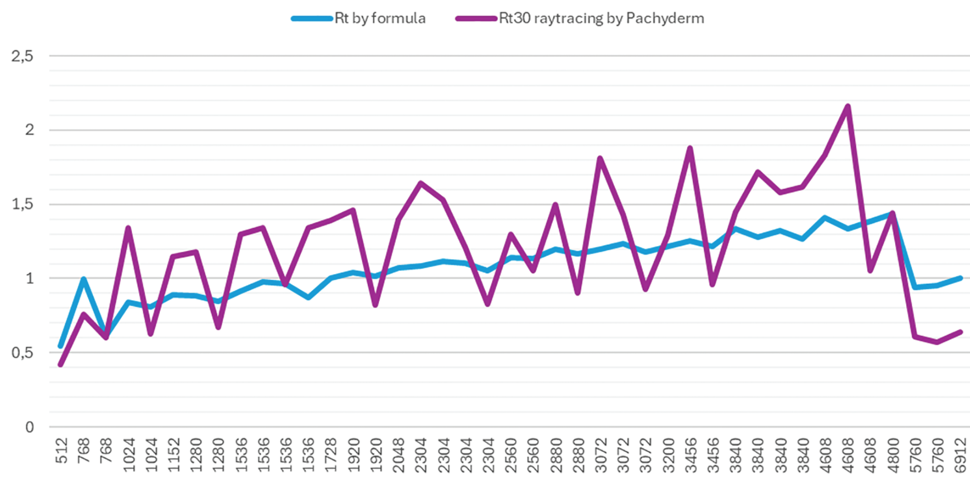

Fig. 8. Reverberation time in Pachyderm by raytracing versus Grasshopper algorithm.

acoustic treatment. Fig. 7 summarizes the results of the reverberation times for each volume collected from Grasshopper. Some conclusions can be drawn from it: first, there is a significant margin between the targeted RT for the volumes, defined by the standard and the RT of the untreated volumes with basic materials; second, the generated acoustic implementation for the volumes between 1000 m^3 < V < 5000 m^3 /lecture/ has close values of RT to the targeted; third, it is visible how multiple spaces with the same volume have different generated treatments because of the conditioning of the proportions; fourth, the conditioning of the volumes V < 1000 m^3 /music/ and V > 5000 m^3 /sports/ leads to significantly lower RT values than expected.

The previously mentioned results were derived from calculations of reverberation time using the Grasshopper formula. For comparison we calculated RT for all volumes by ray tracing in the Pachyderm. The results are shown in Fig. 8. There is a significant difference between these calculations, and even between equal volumes. For further analysis, we selected six rooms, two from each rule by proportion, that had RT values close to the targeted T_{Soll}. All six rooms were imported into Odeon with the same material properties and source and receiver points.

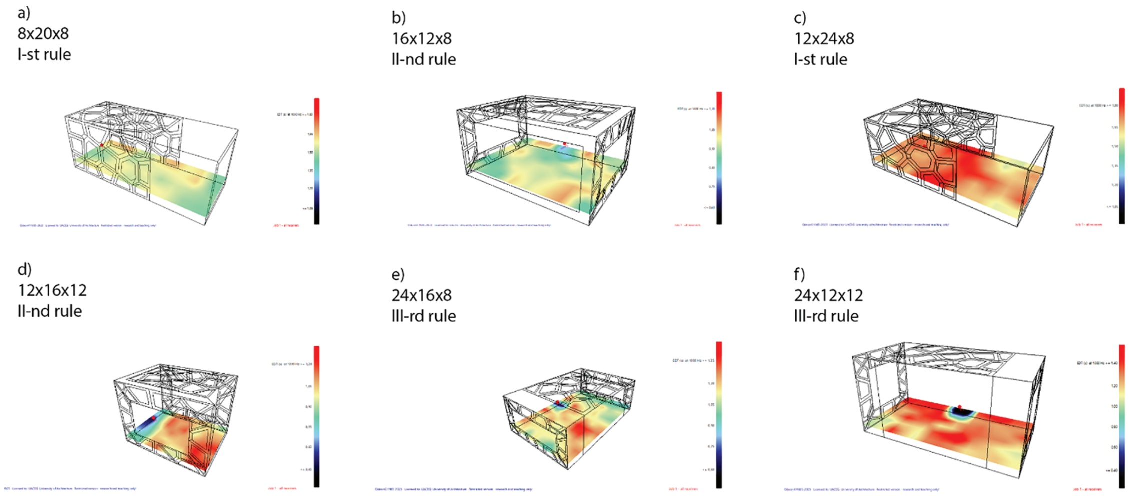

Fig. 9. Color grid maps of EDT from Odeon for the selected rooms.

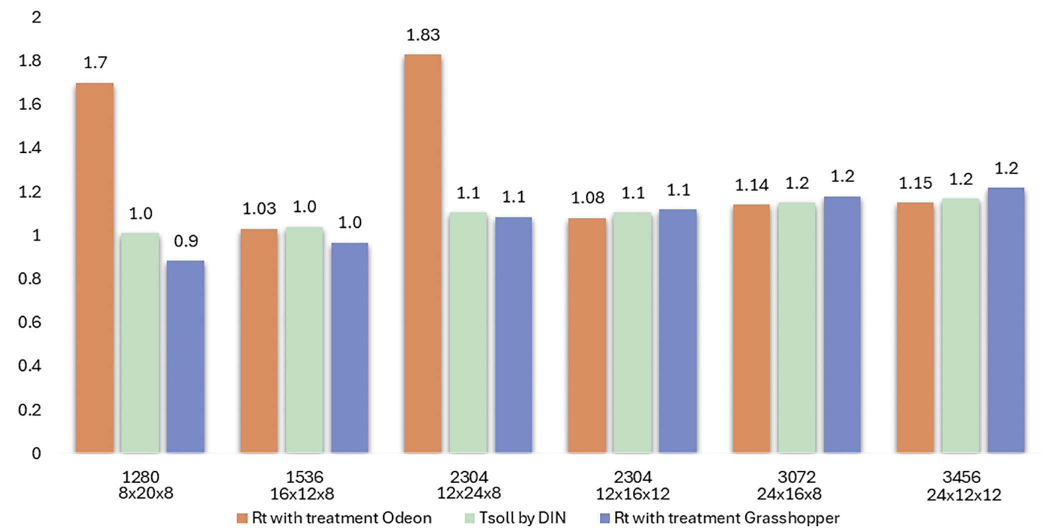

Fig. 10. Grasshopper and Odeon results for RT.

In Fig. 9, the selected rooms are displayed with a color grid analysis of the EDT from Odeon. Volumes c) and a) resemble the I-st rule of proportion, where the materials are not evenly distributed on the surfaces and absorption is mainly focused on the back of the room. This results in a louder front and quiet back, with no reflections that contribute to the main sound. The second rule, volumes b) and d), has a more even distribution of materials and more reflections from the lateral walls, leading to even sound distribution in the rooms. The third rule, volumes e) and f), has a somewhat similar distribution except for the two ends of the back wall and ceiling towards the side walls. Here, we can see a decline in the EDT, mostly in the corners of the rooms, but otherwise a homogeneous soundscape.

Finally, we compared the results for RT with treatments from Grasshopper, RT from Pachyderm, T_{Soll} and RT from Oden to validate the results. In Fig. 10, we can see that the calculated RT from Grasshopper is almost identical to that of the target, where one is based on the volume of the room and the other on the volume and total area of absorption. For the Odeon calculations, the position of the generated materials, as well as the scattering coefficient of the diffusers in the case of the first rule of proportion, affect the results, whereas in the second and third scenarios, the Odeon results do not differ from those calculated by Grasshopper. This could mean that the more homogeneous the treatment of the surfaces, the more accurate the results we will be able to receive from Grasshopper using the RT formula. Fig. 11 shows the comparison results from Pachyderm and Odeon, where we can see that RT from Pachyderm does not correspond completely with Odeon, although both programs used ray tracing. Significant differences are observed in two volumes with the I-st and II-nd rule of proportion, while the other four volumes have closer results.

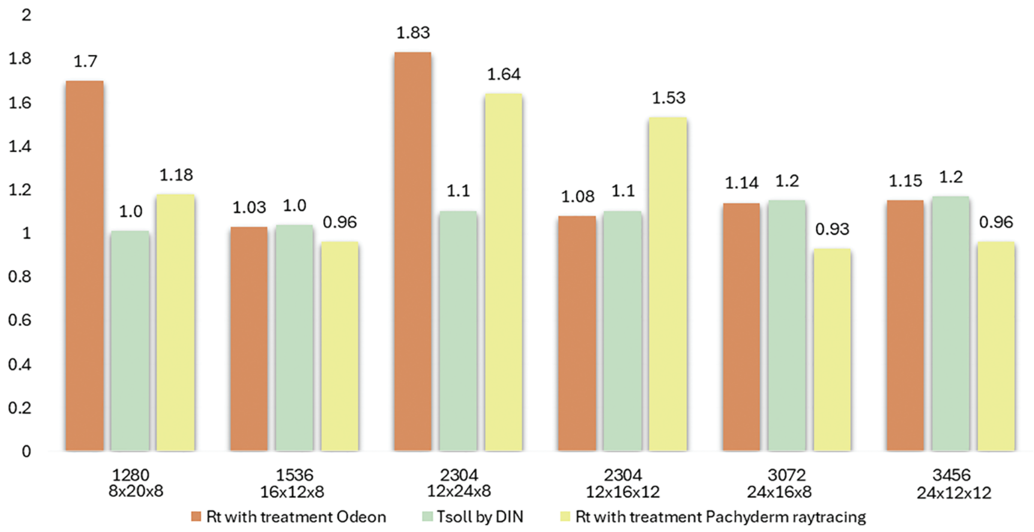

Fig. 11. Pachyderm and Odeon results for RT.

4. Discussion

The proposed algorithm has the potential to aid architectural education and practice by optimizing the simulation of multiple acoustic designs for various spaces, easily and rapidly visualizing the results. Although we used specific conditioning, other rules of position and new materials can be incorporated in future experiments. We cannot omit the limitations of this study based on the use of average absorption coefficients instead of analyzing the whole octave band spectrum. For future analysis we can also include other acoustic parameters such as EDT and clarity for comparison. Additionally, more complex room volumes can be included in the generative process – vineyard shaped, elliptical, asymmetrical volumes etc. As a living being, this algorithm can expand and evolve in complexity, as can the generated designs. Further development can include form generation by patterns and a more even distribution of materials according to interior design concepts and acoustic applications. We hope that this study will encourage more professionals to explore the potential of "parametric acoustics" as a simulation within the digital architectural environment.

5. Conclusion

Developing such an algorithm, which allows architects and interior designers to build an idea of the space of a hall, the materials they have used and how they affect the acoustic environment, is something that can make a bridge between architecture and acoustics in the early design stage. Grasshopper and BIM modeling programs are inevitable in today's architectural practice and even though the acoustic results from the algorithm are based on empirical calculations and average coefficients, they are sufficient for implication when even material distribution is chosen for the volumes. Nevertheless, when the examined variations of materials and volumes become more complex, the use of professional software with simulation methods and acoustic engineers is mandatory for detailed results. We hope to continue developing this algorithm and have the opportunity to implement it in a real project on-site for a future case study.

This research was presented at the DAS/DAGA Conference in Copenhagen 2025 (Madzharova & Shishkov, 2025).

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Data Availability Statement

This research data associated with this article is available on request from the authors.

Conflict of Interest

The authors declare that they do not have any conflict of interest.

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