DOI: 10.61782/fa.2025.0479

FORUM ACUSTICUM
EURONOISE 2025

Input Data for Room Acoustic Simulations: Ray-Based vs Hybrid Models Of a Rectangular Room

Giulia Fratoni[1*] **Dario D'Orazio**[1]
[1] Department of Industrial Engineering, University of Bologna, Italy

ABSTRACT

Ordinary rooms typically feature rectangular shapes and absorbing ceilings, contributing to non-uniform sound absorption distributions. Consequently, non-diffuse sound fields require accurate predictions of room acoustic criteria since the early stages of acoustic design. The test environment for this study is a rectangular room with air-backed sound-absorbing materials at the ceiling and low-scattering surfaces. In this context, room criteria predictions were made using analytical formulas, energy-based geometrical acoustic simulations, and a hybrid room acoustic simulator combining wave-based and ray-based engines. Then, the consistency between the three prediction approaches and measurements - the experimental reference throughout this study - is evaluated. The work focuses on the input data employed in the analytical model and the boundary conditions assigned for the two numerical approaches. Focusing on the sound-absorbing tiles of the suspended ceiling, the results identify substantial discrepancies among the methods' input data. These gaps, which are more evident within the low-mid frequency range, are provided and discussed.

Keywords: *wave-based simulations, boundary conditions, non-uniform absorption distribution, absorption coefficients.*

1. INTRODUCTION

Numerical models are essential tools for predicting the sound field in challenging real-world scenarios, such as environments with a non-uniform distribution of sound-absorbing surfaces [1]. The accuracy of acoustic simulations strongly depends on the reliability of the boundary conditions used as input data, which typically involve energy-based sound absorbing coefficients obtained through ISO 354 measurements [2]. While energy-based datasets are widely available in the literature [3, 4], accessible lists of frequency-dependent pressure-based boundary conditions for wave-based simulation techniques remain limited. As a result, sound absorption coefficients – typically provided by materials' technical datasheets - are often converted into complex surface impedances through non-unique processes [5]. This work investigates the differences in input data between a hybrid wave/ray-based engine and two standard prediction tools: the Sabine formula and a geometrical acoustics model.

2. METHOD

2.1 The rectangular environment

The present work examines a secondary school classroom (25 students) with a rectangular shape, a volume of 159 m³, and an acoustically treated air-backed ceiling with two different materials [6, 7]:

- **Material 1: perforated gypsum board**
  Perforation percentage: 18%
  Thickness: 8 mm
  Placement: at the ceiling's center (~ 45%)
- **Material 2: high-density rock wool**
  Density: 70 kg/m^3
  Thickness: 22 mm
  Placement: at the ceiling's perimeter (~ 55%)

The acoustic absorption properties of the ceiling tiles were measured in the reverberation chamber at the University of Bologna following the procedures outlined in ISO 354. Moreover, in-field acoustic measurements were conducted

[*] ***Corresponding author***: *giulia.fratoni2@unibo.it*

in the rectangular room in furnished and unoccupied conditions, in compliance with ISO 3382-2. The collected room acoustic criteria are experimental reference throughout the study.

2.2 Prediction models

2.2.1 Analytical formula

The reverberation time, T, has been calculated with Sabine's formula:

$$T = \frac{55.3}{c_0}\frac{V}{A} \quad \text{(s)}, \tag{1}$$

where c_0 is the speed of sound (m/s), V is the volume of the room (m^3), and A is the total equivalent absorption area (m^2), which is expressed as:

$$A = \sum_{i=1}^{n} \alpha_i S_i + \sum_{i=j}^{o} A_{obj,j} \quad (\text{m}^2), \tag{2}$$

where n is the number of the i-th surface, α_i is its absorption coefficient, S_i is the area of the i-th surface (m^2), o is the number of the j-th object, and $A_{obj,j}$ is its equivalent absorption area (m^2). Table 1 provides α and A_{obj} for the case under study.

Table 1. Sound absorption coefficients, α, and equivalent absorption areas, A_{obj}, to predict the reverberation time with Eqs. 1, 2. Data are provided by literature and standards [3, 4, 7].

	S (m^2)	α					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Floor	53	0.01	0.01	0.02	0.02	0.02	0.02
Walls	60	0.10	0.04	0.04	0.04	0.04	0.04
Windows	11	0.08	0.04	0.03	0.03	0.03	0.03
Closet	9	0.02	0.02	0.02	0.04	0.04	0.05
Material 1	20[1]	0.31	0.72	0.85	0.72	0.59	0.54
Material 2	25[1]	0.37	0.82	0.84	0.82	0.79	0.71
	n.	A_{obj}					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Chairs	25	0.02	0.02	0.02	0.04	0.04	0.05
Students	20[2]	0.10	0.15	0.35	0.50	0.50	0.55

[1]Considering 85% of the available ceiling surface.
[2]Considering 80% of the maximum occupancy for the active conditions.

2.2.2 GA and hybrid DGFEM/GA simulations

Two 3D models of the classroom were created using SketchUp: one for geometrical acoustics (GA) simulations with Odeon [8] and the other for hybrid wave/ray-based simulations (DGFEM/GA) with Treble [9]. The subdivision of layers includes the floor, walls, windows, chairs, closets, and acoustic treatments on the ceiling (Material 1 and Material 2). The primary distinction between the models lies in the 3D modeling of each desk-chair pair:

- for GA simulations, each pair was modeled as a single box (0.4 m x 0.4 m x 0.8 m);
- for hybrid wave/ray-based simulations, each furnishing piece was represented by a double 2D face.

Windows, and doors were modeled as indentations within surfaces in the second model (see Fig. 1), as suggested by the documentation of the hybrid room acoustic simulator.

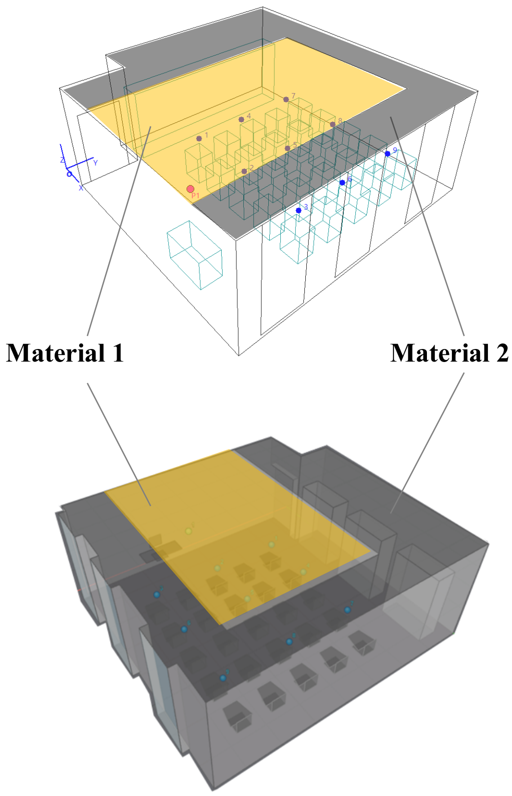

Figure 1. View of the 3D models used for GA simulations (top) and hybrid DGFEM/GA simulations (bottom).

A parallel calibration process of the 3D models was conducted, modifying the ceiling material properties while keeping the same input data for other surfaces. The calibration criterion was to maintain discrepancies between measured and simulated reverberation time (T_{20}) values within 10% of the measured values in each octave band [10].

3. RESULTS AND DISCUSSIONS

The calibration was performed using the average $T_{20,occ}$ measured across nine receivers evenly distributed throughout the seating area (see Fig. 1). The occupied state defined the acoustic conditions in real-use scenarios [7]. Fig. 2 provides the average reverberation time $T_{20,occ}$, derived from measurements, analytical formula (see Eqs. 1 and 2), and both numerical models (initial and final values).

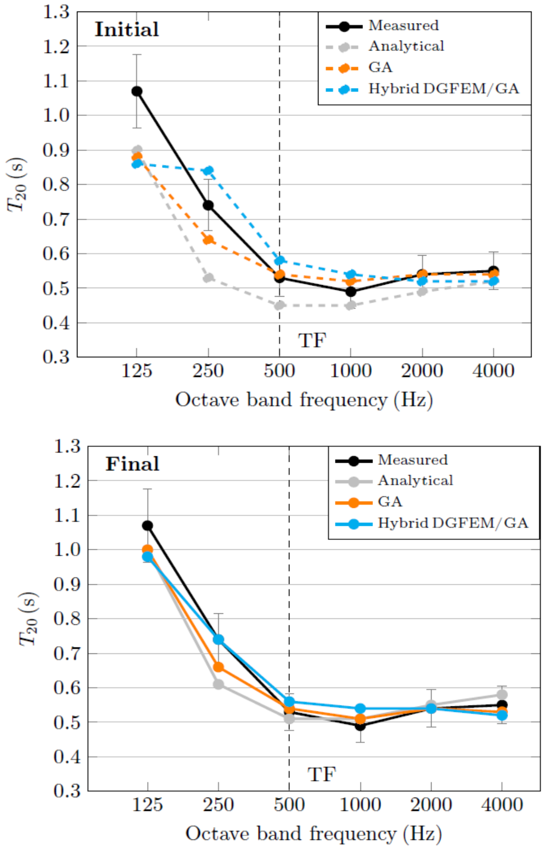

Figure 2. Measured, analytical, GA results, and hybrid DGFEM/GA results before and after the calibrations. Reverberation time in occupied conditions $T_{20;occ}$ against the frequency in octave bands. TF is the transition frequency of the hybrid model (500 Hz).

The absorption coefficients (α) of the final configuration (models' calibration) show some discrepancies from those measured in the reverberation chamber (ISO 354) and those used in Sabine's analytical formula (see Table 2). The results indicate a potential discrepancy of up to 25% in input data at mid-low frequencies (125 Hz - 500 Hz) between numerical and analytical models, with lower discrepancies below 15% at mid-high frequencies (1000 Hz - 4000 Hz).

Table 2. Measured α (ISO 354), corrected values for analytical formulas (EN 12354-6), GA input data (Odeon), and hybrid DGFEM/GA input data (Treble). In the latter case, the wave-based portion of the engine employs the estimated materials' frequency-dependent complex surface impedance.

		α					
		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Material 1	Measured	0.36	0.85	1.00	0.85	0.69	0.63
	Analytical formula	0.31	0.72	0.85	0.72	0.59	0.54
	GA (final)	0.20	0.55	0.72	0.61	0.50	0.46
	Hybrid (final)	0.16	0.65	0.74	0.69	0.59	0.46
Material 2	Measured	0.44	0.97	0.99	0.97	0.93	0.83
	Analytical formula	0.37	0.82	0.84	0.82	0.79	0.71
	GA (final)	0.24	0.63	0.72	0.70	0.67	0.60
	Hybrid (final)	0.36	0.68	0.72	0.71	0.69	0.61

These discrepancies can be attributed to various factors:

- The inevitable differences in the 3D modeling choices according to the relative guidelines for each numerical approach (see Fig. 1).
- The effective surface area considered in different approaches: while the analytical formula accounts for the reduction of ceiling surface due to ventilation and lighting installations (around 15% of the total available area), simplified 3D models do not include such details.
- The combination of sound-absorbing properties with further information in numerical models, i.e., scattering coefficients *s*, while the analytical formula's assumption considers a diffuse sound field.
- The way the scattering coefficient is handled in different GA approaches, influencing the calculation of room criteria.

- The intrinsic uncertainty in comparing α values directly assigned to surfaces in GA simulations with α values used to derive complex acoustic impedances in wave-based simulations. In the case under study, the DGFEM simulator estimates a reflection coefficient vector that best represents the input absorption coefficients, minimizing the following function.

$$\chi = |\hat{\alpha} - \alpha_{input}|^2 \qquad (3)$$

Function to be minimized

Computed from the surface impedance model

Given by users

4. CONCLUSIONS

This work assesses the different input data required for two acoustic simulation approaches - a ray-based and a hybrid wave/ray-based engine - to predict the reverberation time across the frequency in the case of a rectangular room with non-uniform sound absorption distribution. By focusing on sound-absorbing air-backed ceiling tiles, the preliminary results reveal gaps up to 25% between the input data of analytical and numerical models in the mid-low frequency range (125 Hz - 250 Hz - 500 Hz) and up to 15% in the mid-high frequency range (1000 Hz – 2000 Hz – 4000 Hz). The outcomes suggest the need to consider a significant dispersion range for α values when comparing input data used directly in GA simulations with the α values corresponding to complex acoustic impedances employed in the DGFEM part of hybrid simulations. Further research in different test environments is needed to expand the findings and provide more accurate recommendations for managing boundary conditions in hybrid wave/ray-based simulations.

5. ACKNOWLEDGMENTS

The authors would like to thank Professor Luca Barbaresi and Dr. Domenico De Salvio for their kind support during the acoustic measurements.

6. REFERENCES

[1] G. Marbjerg, J. Brunskog, C. H. Jeong (2018). The difficulties of simulating the acoustics of an empty rectangular room with an absorbing ceiling. *Applied Acoustics*, *141*, 35-45.

[2] ISO 354:2003 Acoustics - Measurement of sound absorption in a reverberation room.

[3] T. Cox, P. D' Antonio, Acoustic absorbers and diffusers: theory, design and application, CRC Press, 2016.

[4] M. Vorländer, Auralization: Fundamentals of Acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality, Springer, 2020.

[5] B. Mondet, J. Brunskog, C.-H. Jeong, J. H. Rindel, From absorption to impedance: Enhancing boundary conditions in room acoustic simulations, *Applied Acoustics* 157 (2020) 106884.

[6] G. Fratoni, D. D'Orazio, L. Barbaresi, M. Garai, L. Cappellini (2023, February). Mixing materials in false ceilings to increase sound diffusion in education spaces. In *INTER-NOISE and NOISE-CON congress and conference proceedings*, 265(2), 5002-5006, Institute of Noise Control Engineering.

[7] D. D'Orazio, G. Fratoni, V. Tardini (2025). The Italian standard on classroom acoustics UNI 11532-2: 2020 explained through case studies. *Applied Acoustics*, *231*, 110498.

[8] G. M. Naylor, Odeon—another hybrid room acoustical model, *Applied Acoustics* 38 (2-4) (1993) 131–143.

[9] F. Pind, C.-H. Jeong, A. P. Engsig-Karup, J. S. Hesthaven,J. Strømann-Andersen (2020). Time-domain room acoustic simulations with extended-reacting porous absorbers using the discontinuous Galerkin method, *The Journal of the Acoustical Society of America,* 148 (5), 2851–2863.

[10] M. Vorländer (2013). Computer simulations in room acoustics: Concepts and uncertainties. *The Journal of the Acoustical Society of America*, *133*(3), 1203-1213.

[11] G. Fratoni, D. D'Orazio, M. Garai (2023, September). Uncertainty of input data for wave-based room acoustic simulations in large non-trivial environments, *Proceedings of Forum Acusticum 2023*, 123-130, European Acoustics Association (EAA). DOI: 10.61782/fa.2023.1114.