DOI: 10.61782/fa.2025.0012

FORUM ACUSTICUM EURONOISE 2025

A HISTORICAL OVERVIEW OF HIGINI ARAU'S PROPOSAL FOR CALCULATING REVERBERATION TIME (1988)

Julián Álvarez[1*] **Ramon Graus**[2] **Helena Martín-Nieva**[3]

[1] Department of Physics, Universitat Politècnica de Catalunya, Spain
[2] Department of Theory and History of Architecture, Universitat Politècnica de Catalunya, Spain
[3] Department of Human Sciences, Universidad de La Rioja, Spain

ABSTRACT

In 1988, Barcelona physicist Higini Arau-Puchades published in international journal *Acustica* an alternative to Sabine's classical formula for reverberation time (T). Arau's formula resulted from a process of reflection that began in 1985, when Arau came into contact with Lothar Cremer during the acoustic renovation of the Palau de la Música Catalana in Barcelona, which architect Oscar Tusquets was restoring. Arau proposed a formula that considered the non-uniform distribution of absorbing material in a concert hall. Consequently, the decay rate of sound was quantified in the three directions X, Y and Z. Of course, Arau went on to use his formula in the auditorium designs that he undertook in the 1990s. He developed it in a second paper published in 1998, while his first paper cut a path in the scientific field. During the 2000s, several articles comparing Arau's work with other known formulae led to his formula being incorporated in the statistical calculation section of some of the most highly regarded computer programs on international acoustic design. We aim to analyse the impact of Arau's proposal in international academic publications to date.

Keywords: *architectural acoustics, reverberation time, non-diffuse field, Higini Arau-Puchades, Lothar Cremer.*

[*]***Corresponding author***: *julian.alvarez@upc.edu.*

1. REVERBERATION TIME IN ROOMS WITH UNIFORM DISTRIBUTION OF ABSORPTION

1.1 Sabine (1900)

US physicist Wallace C. Sabine (1868-1919) published his studies on reverberation time in seven issues of the periodical *The American Architect and Building News*, between April and June 1900 [1-7]. He had started to research this area in 1895, when Harvard University asked him for advice on how to correct severe acoustic problems in the lecture room of Fogg Art Museum [1, p. 3], which architect Richard Morris Hunt had designed in a semi-circular shape, like old Greek theatres.

In these first articles, which combined experimental measurement of the phenomenon with its physical and mathematical analysis, Sabine formulated a hyperbolic law where the reverberation time in a space would be inversely proportional to its average absorption coefficient [2].

In turn, we owe to US physicist William S. Franklin (1863-1930) the mathematical workings that demonstrated the definitive form of Sabine's equation (1) for calculating reverberation time in 1903 [8]:

$$T = \frac{0.161V}{\sum_i S_i \alpha_i + 4mV} \tag{1}$$

In the framework of statistical theory, the equation (1) provided a global value for the behaviour of sound over time in a particular space that would enable comparisons with other rooms that are known for their acoustics.

1.2 Eyring (1930)

When Sabine had passed away, the publication of his *Collected Papers*, in 1922, spread his legacy worldwide [9]. However, it was soon shown that his equation (1) was suitable for "live" rooms, but not as appropriate for rooms that had a high level of absorption surfaces, such as those of radio stations. US physicist Carl F. Eyring (1889-1951), who worked for Bell Telephone Laboratories, drew up a general theory [10] that could be applied to all types of rooms and was formulated as follows:

$$T = \frac{0.161V}{-S\ln\left(1-\bar{\alpha}\right)+4mV} \tag{2}$$

2. REVERBERATION TIME IN ROOMS WITH NON-UNIFORM DISTRIBUTION OF ABSORPTION: TAKING X, Y, Z INTO ACCOUNT

2.1 Bagenal (1942)

Hope Bagenal (1888-1979), a British architect specialised in acoustics, had grasped back in 1942 the difficulties of assessing reverberation time in rooms when the distribution of absorbent material was not uniform. Without a clear theory, he merely pointed out that: "Another factor also enters into reverberation design. It applies in practice specially to studios and small halls. Reverberation in rectangular rooms really consists of three sets of inter-reflections set up between the three pairs of parallel opposite surfaces. It is important that these three reverberation times should be roughly of equal length and blend into one smooth tone." [11, pp. 113–115].

2.2 Fitzroy (1959)

Shortly afterwards, US acoustic engineer Dariel Fitzroy (1898-1977) noted deviations from the formulae of Sabine (1) and Eyring (2) when they were applied in rooms where the absorption is nonuniformly distributed. Supported by a large number of measurements in rooms of these characteristics, and without seeming to be aware of Bagenal's opinion, he stated that "…the sound field may tend to settle into a pattern of simultaneous oscillation along a rectangular room's three major axes—the vertical, the transverse, and the longitudinal. […] In its simplest case, a rectangular room, we are presented with three sets of parallel boundaries. If the energy oscillates simultaneously between each pair of boundaries—the author is aware that this is highly speculative—the average absorption in each pair would control the sound wave excursions between that specific pair during the 60-db decay period." [12, p. 893].
From his measurements, he inferred an equation (3), without mathematical proof, that brought the estimated reverberation time closer to the measured values in rooms of these characteristics:

$$T = \left(\frac{S_x}{S}\right)\left(\frac{0.161V}{-S\ln\left(1-\bar{\alpha}_x\right)+4mV}\right)+\left(\frac{S_y}{S}\right)\left(\frac{0.161V}{-S\ln\left(1-\bar{\alpha}_y\right)+4mV}\right)$$
$$+\left(\frac{S_z}{S}\right)\left(\frac{0.161V}{-S\ln\left(1-\bar{\alpha}_z\right)+4mV}\right) \tag{3}$$

2.3 Cremer (1978)

German acoustic consultant Lothar Cremer (1905-1990), in his book *Die wissenschaftlichen Grundlagen der Raumakustik* (1978) with Helmut A. Müller (1930-2015), translated into English as *Principles and applications of room acoustics* (1982), dedicated the chapter "Refinements of the reverberation formulae based on geometric considerations" to reflections on how to assess the impact on reverberation time of a non-uniform distribution of the absorbent material in a room. He recommended dividing "…the total surface area first into several large 'principal surfaces', which can be regarded as encountered by the sound rays one after the other ('in series'); and to subdivide these large surfaces into smaller areas with different absorption, which can be regarded as encountered side by side ('in parallel'). The smaller subdivisions are first averaged arithmetically, to determine the mean absorption coefficients for each of the principal surfaces. Those values are then transformed to the corresponding absorption exponents, and are averaged arithmetically…" [13, p. 235].

2.4 Arau-Puchades (1988)

Thirty years after Fitzroy, Higini Arau-Puchades (b.1946), a Spanish physicist specialised in acoustics, was also concerned about cases of non-diffuse fields. Between 1982 and 1989, when he was director of the Laboratori General d'Assaigs i Investigacions [General Laboratory for Testing and Research], he advised on acoustic improvements for the Palau de la Música Catalana, the most important concert hall in Barcelona, designed by architect Lluís Domènech i Montaner in 1905 [14]. The refurbishment was led by architects Oscar Tusquets and Lluís Clotet. There, Arau-Puchades worked with Lothar Cremer who, from 1973, had collaborated on the design of many concert halls in Spain [15].

Figure 1. From right to left, Higini Arau-Puchades, Lothar Cremer and Oscar Tusquets at the Palau de la Música Catalana of Barcelona. Photo: Pau Barceló (1985), Centre de Documentació de l'Orfeó Català.

The Palau de la Música Catalana was a masterpiece of *Catalan Modernisme* (Art Nouveau). Its ceiling was covered in ceramic tiles, the side walls were formed of a type of glass curtain wall and work could only be done on the absorption of the stalls area. This was a prototypical example of sound propagation in a non-diffuse field, which could not be modified as it was a listed building.

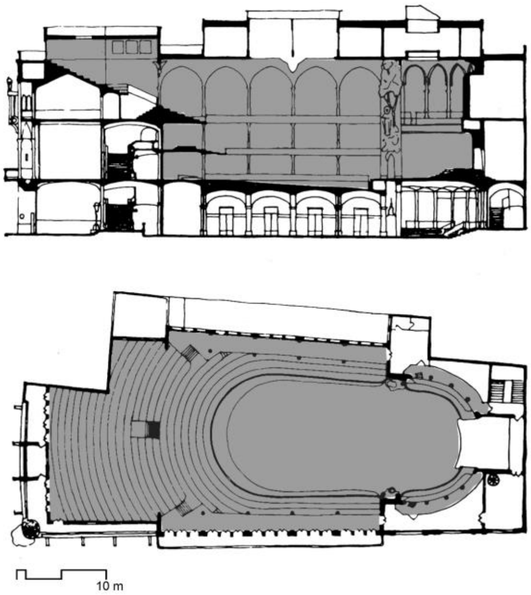

Figure 2. First floor plan and cross-section of the Palau de la Música Catalana (1905-1908).

From conversations between Arau-Puchades and Cremer, Arau-Puchades's dissatisfaction with classic formulae for determining reverberation time in a non-diffuse field began to emerge. As Higini Arau-Puchades explained to a journalist, first he tried an approach to the problem that he showed to Cremer, who "responded to the theory, saying that his calculations were focused on a linear reverberation curve from top to bottom and that in no case did this linearity occur. Stimulated by the problem, Arau averaged the absorption coefficients so that 'now I can calculate all the decays of the reverberation curve'." [16].

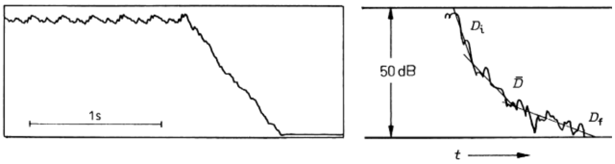

Figure 3. Left, sound decay in a diffuse field, right, sound decay in a non-diffuse field [17, p. 54].

In May 1986, Higini Arau-Puchades presented his theory to the specialised journal *Acustica*. The article was published in the March issue of 1988 under the title "An improved reverberation formula" [18].
Returning to Fitzroy's approach (3), Arau-Puchades proposed that the varying degree of reflectivity of the pairs of walls that make up a room could be broken down using the following convention:

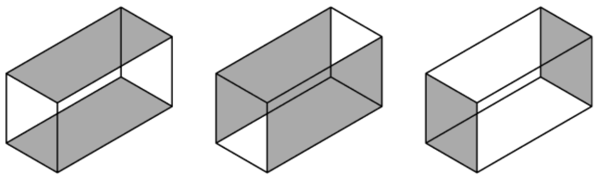

Figure 4. Pairs of parallel surfaces according to Arau-Puchades [18].

Arau-Puchades considered that the reverberation time of a room with non-uniform absorption would be equal to the area-weighted geometrical mean of the reverberation periods in each one of the directions considered [18, p. 166]. Therefore, in his theory, Arau-Puchades proposed the coexistence of simultaneity (three parallel walls at the same time) and sequentiality (reflections occur on each wall, one after the other).

$$T = \left(\frac{0.161V}{-S\ln(1-\bar{\alpha}_x) + 4mV} \right)^{x/S} \left(\frac{0.161V}{-S\ln(1-\bar{\alpha}_y) + 4mV} \right)^{y/S} \cdot \left(\frac{0.161V}{-S\ln(1-\bar{\alpha}_z) + 4mV} \right)^{z/S} \quad (4)$$

In addition, we know that Lothar Cremer stressed in conversations with Higini Arau-Puchades “that all theories that try to demonstrate the non-diffuse case should be able to calculate the reverberation time T and EDT, the Early Decay Time” [19, p. 4]. In fact, Arau-Puchades’s mathematical approach allows this aspect to be obtained using a log-normal distribution [18, pp. 166–170].

In the same article, Arau-Puchades described the application of his formula to various rooms and compared the results with the predictions of Sabine (1) and Eyring (2) and with some real measurements. This was a generalisable theory that was close to the results of Sabine and Eyring in rooms with a uniform distribution of absorption. In addition, to demonstrate its suitability, Arau-Puchades used the experimental data of Koesten [20] and Mehta & Mulholland [21] to support his proposal.

If we go back to the example of the Palau de la Música Catalana, the pairs of walls were broken down according to Figure 5. Table 1 shows the calculation of the absorption coefficient values and Table 2 compares the estimated and measured results.

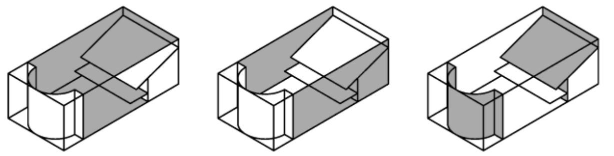

Figure 5. Allocation of surfaces in the study on the Palau de la Música Catalana, Barcelona [18].

Table 1. Dimensional ratios and absorption coefficients of the Palau de la Música Catalana, Barcelona [18, p. 171].

Dimensions	Percentage area	Absorption coefficients		
		$\bar{\alpha}_i$ (energy)	$\bar{\alpha}_i$ (decay)	$\bar{\alpha}_{av}$ (whole energy average)
Ratio: Non rectangular form	$\frac{x}{S} = 0.407$	$\bar{\alpha}_x = 0.250$	$\bar{\alpha}_x = 0.287$	$\bar{\alpha}_{av} = 0.385$
V = 10,352	$\frac{y}{S} = 0.296$	$\bar{\alpha}_y = 0.543$	$\bar{\alpha}_y = 0.784$	
S = 2,438	$\frac{z}{S} = 0.297$	$\bar{\alpha}_z = 0.413$	$\bar{\alpha}_z = 0.532$	

Table 2. Comparison of estimations of reverberation time according to various formulae and the experimental measurements of the Palau de la Música Catalana, Barcelona [18, p. 173].

Eyring (2)	Fitzroy (3)	Arau-Puchades (4)	Experimental
1.37 s	1.57 s	1.44 s	1.47 s

Ten years later, in 1998, Arau-Puchades revisited his article of 1988 with the aim of expanding his results to a general theory of acoustic values of rooms [22]. Its development was based on ideas proposed by Mike Barron, characterised for the case of non-uniform distribution of absorption [23].

3. INTERNATIONAL IMPACT OF ARAU-PUCHADES’S FORMULA

3.1 Use in Arau Acústica for the design of concert halls

The following are notable among the early collaborations of Higini Arau-Puchades, now with his office Arau Acústica and with architects designing concert halls using his method: the Auditori Enric Granados in Lleida (1983-1995) and the Teatre-Auditori de Sant Cugat (1989-1994), both by the firm Artigues & Sanabria; L’Auditori of Barcelona (1987-1999) and Kursaal in San Sebastián (1990-1999), both by architect Rafael Moneo; and the reconstruction of the Gran Teatre del Liceu of Barcelona (1994-1999), with architects Ignasi de Solà-Morales, Lluís Dilmé and Xavier Fabré. These early works catapulted him to consultancy on over 200 auditoriums in Spain and over twenty in other countries, including the refurbishment of the Teatro alla Scala of Milan (2002-2004) and the Tonhalle of St. Gallen, with Bosshard Vaquer Architekten (2009-2010), or the new Filharmonia im. Mieczysława Karłowicza in Szczecin (2007-2014), with Barozzi Veiga [14].

Considering the great demand for collaboration, Higini Arau-Puchades and Lluís Jutglar, a professor at the Universitat de Barcelona, developed their own software for acoustic verification of rooms, which formed part of the firm’s unpublished know-how [14].

In addition, Arau-Puchades widely disseminated his equation (4) through his handbook, the *ABC de la acústica arquitectónica* (1999). This is one of the most widespread handbooks on acoustics in Spanish. Beyond the didactic needs of the book, he dedicated 17 pages to showing chronologically the scientific contributions of Sabine’s formula to his proposal. He included critical commentaries on the formulae of Sabine, Eyring, Norris, Millington, Sette, Fitzroy, Gomperts, Kosten, Pujolle, Kuttruff and

Wernly, and on computer approaches with ray tracing [24, pp. 227–242].

3.2 Implementation of Arau-Puchades's equation in international professional software

In fact, the publication of Arau-Puchades's equation (4) coincided with the development of the first computer programs that aimed to simulate the behaviour of sound in its three dimensions. Furthermore, Arau-Puchades's formula began to be compared favourably with other statistical methods and the results achieved with these computer simulations. An article published in 2000 by Brazilian engineer Sylvio R. Bistafa and Canadian researcher John S. Bradley [25] was fundamental for the successful dissemination of Arau-Puchades's proposal. Table 3 shows the results of this study, in which seven equations that assessed absorption in a different way were compared with real laboratory measurements. Arau-Puchades's formula had the lowest errors at all frequencies.

Table 3. Overall average relative errors of the analytical predictions of reverberation time for ten sound-absorbing configurations in the simulated classroom, according to Bistafa and Bradley [25, p. 1727].

	Overall average relative error (%)		
	Frequency bands included in the averages		
	1 kHz	500 Hz–2 kHz	125 Hz–4 kHz
Sabine (1)	38.8	31.6	21.5
Eyring (2)	42.6	35.7	24.7
Millington	36.1	30.4	21.1
Cremer	26.7	23.9	17.4
Kuttruff	68.0	63.5	49.3
Fitzroy (3)	92.0	95.8	65.7
Arau-Puchades (4)	22.9	22.7	16.7

The same article compared these statistical results with those obtained from two computer programs, RAYNOISE 3.0 of LMS Numerical Technologies NV (Leuven, Belgium) and ODEON 2.6 of the Department of Acoustic Technology at the Danmarks Tekniske Universitet (Lyngby, Denmark). Reading the article prompted the developers of ODEON software to incorporate Arau-Puchades's formula in their program, probably already in version 5.0 of 2001[1]. Of course, over time, the ray-tracing and wave-based algorithms have improved considerably, but at that time the formula played a notable role in the adjustment of this parameter.

Other researchers have incorporated Arau-Puchades's formula in more specific software such as WINRT60 1.0. This is a program for calculating reverberation time designed by Tor Erik Vigran, professor of the Norges teknisk-naturvitenskapelige universitet (NTNU), in 2006. Using this program, it was possible to calculate the reverberation time of a room using formulae by Sabine (1), Eyring (2) and Arau-Puchades (4) [26]. Likewise, in 2015, STRUTT by Arup incorporated the Arau-Puchades equation in its v5.15.12 [27]. This is a plug-in for MICROSOFT EXCEL that includes a large number of functions for acoustic calculations.

3.3 A proposal with a long history

A simple bibliometric approach shows that the article "An improved reverberation formula" [18] has been cited 40 times in articles indexed in the Web of Science, 64 times in Scopus and 138 times in Google Scholar[2]. The Figure 6 indicates that interest in the model proposed by Arau-Puchades increased notably from the year 2000.

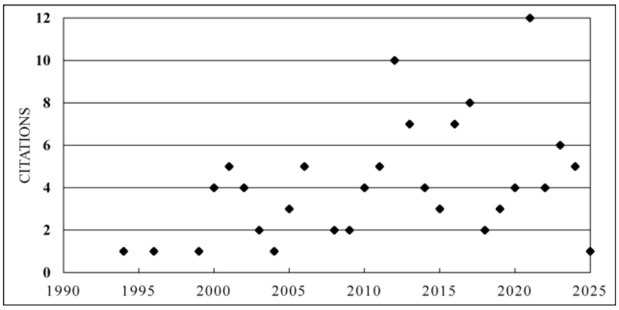

Figure 6. Number of citations per year of "An improved reverberation formula" [18], as recorded in Google Scholar on 23 March 2025.

As noted above, the study by Bistafa and Bradley of 2000 [25] showed that Arau-Puchades's model (4) obtained the lowest relative errors compared to the reverberation time measured in the laboratory. A similar result was obtained by French researchers Joël Ducourneau and Vincent Planeau in 2003. They concluded that, among all the models studied, which included Sabine (1), Eyring (2), Millington, Pujolle, Arau-Puchades (4) and Fitzroy (3), "The Arau-Puchades's model, which is adapted to non-

[1] Claus Lynge Christensen, personal communication (e-mail), December 27, 2024.

[2] Consulted: March 23, 2025.

uniformly distributed absorption, is the closest to the experimental results (maximal relative error <20%)" [28, p. 853].

After these two articles, numerous researchers have shown interest in Arau-Puchades's model, which has been incorporated in some handbooks such as *Sound insulation* by Carl Hopkins (2007) [29, p. 42], *Building acoustics* by Erik Tor Vigran (2008) [30, p. 122], and *Acústica de salas: projeto e modelagem* by Eric Brandão (2018) [31, p. 461].

4. CONCLUSIONS

Finally, we might wonder about the opportunity at the end of the 1980s [32, pp. 390–391] to propose a new model for calculating reverberation time at a time in which new room acoustic parameters were being developed, such as *Deutlichkeit* [D50, definition] (1953), Early Decay Time [EDT] (1970), Clarity [C80] (1974) and G-Strength (1976) [33-35]. However, considering that many of these parameters continue to be governed by reverberation time [36], it makes sense to have as accurate statistical models as possible.

In fact, the model proposed by Higini Arau-Puchades aimed to respond to the need to improve the prediction of reverberation time in a non-diffuse field and took these new parameters into account. The same model enabled determination of the Early Decay Time, as had been suggested by Lothar Cremer.

Nevertheless, it was not an easy model to apply. As we have seen in the case of the Palau de la Música Catalana, the acoustic consultant had to select with criteria the pairs of surfaces that would be assigned to the directions X, Y and Z. For this reason, whoever applies the model must know how the equation works to be able to understand the results that are obtained.

5. ACKNOWLEDGMENTS

This paper is part of the R&D grant PID2022-138760NB-C21, funded by MICIU/AEI/10.13039/501100011033/ and ERDF/EU.

Lucille Banham with her usual care and rigour has translated the original text from Spanish to English.

6. REFERENCES

[1] W. C. Sabine, "Architectural acoustics, I: Introduction," *The American Architect and Building News*, vol. LXVIII, no. 1267, pp. 3–5, Apr. 1900.

[2] W. C. Sabine, "Architectural acoustics, II: Reverberation: Absorbing power of wall-surfaces," *The American Architect and Building News*, vol. LXVIII, no. 1269, pp. 19–22, Apr. 1900.

[3] W. C. Sabine, "Architectural acoustics, III: Reverberation: Approximate solution," *The American Architect and Building News*, vol. LXVIII, no. 1271, pp. 35–37, May 1900.

[4] W. C. Sabine, "Architectural acoustics, IV: Reverberation: Rate of decay of residual sound," *The American Architect and Building News*, vol. LXVIII, no. 1272, pp. 43–45, May 1900.

[5] W. C. Sabine, "Architectural acoustics, V: Reverberation: Exact solution," *The American Architect and Building News*, vol. LXVIII, no. 1274, pp. 59–61, May 1900.

[6] W. C. Sabine, "Architectural acoustics, VI: Reverberation: The absorbing power of an audience, and other data," *The American Architect and Building News*, vol. LXVIII, no. 1276, pp. 75–76, Jun. 1900.

[7] W. C. Sabine, "Architectural acoustics, VII: Reverberation: Calculation in advance of construction," *The American Architect and Building News*, vol. LXVIII, no. 1277, pp. 83–84, Jun. 1900.

[8] W. S. Franklin, "Derivation of equation of decaying sound in a room and definition of open window equivalent of absorbing power," *Physical Review (Series I)*, vol. 16, no. 6, pp. 372–374, Jun. 1903, doi: 10.1103/PhysRevSeriesI.16.372.

[9] W. C. Sabine, *Collected papers on acoustics*. Cambridge, MA, London: Harvard University Press, 1922.

[10] C. F. Eyring, "Reverberation time in 'dead' rooms," *J Acoust Soc Am*, vol. 1, no. 2A, pp. 217–241, Jan. 1930, doi: 10.1121/1.1915175.

[11] H. Bagenal, *Practical acoustics and planning against noise*. London: Methuen & Co.Ltd., 1942.

[12] D. Fitzroy, "Reverberation formula which seems to be more accurate with nonuniform distribution of absorption," *J Acoust Soc Am*, vol. 31, no. 7, pp. 893–897, Jul. 1959, doi: 10.1121/1.1907814.

[13] L. Cremer and H. A. Müller, *Principles and applications of room acoustics: vol. 1*. London: Applied Science, 1982.

[14] J. Álvarez, R. Graus, and H. Martín-Nieva, "Higini Arau y la acústica de salas: el camino hacia su reconocimiento internacional," in *Redes Transnacionales de la Arquitectura Española (1976-2006): 1.er seminario RETRANSLATES*, Barcelona: Iniciativa Digital Politècnica, 2025, pp. 20–21. doi: 10.5821/ebook-9791387613174.

[15] G. Vallejo Ortega and J. I. Sánchez Rivera, "Lothar Cremer in Spain: his influence on the architect García de Paredes," in *INTER-NOISE 2012, New York, August 19-22*, New York: Institute of Noise Control Engineering, 2012.

[16] J. Guerrero Martín, S. Fondevila, L. Bonet Mojica, and A. Mallofré, "El físico Arau y su teoría de la reverberación," *La Vanguardia*, Barcelona, p. 26, Jan. 21, 1989.

[17] H. Arau-Puchades, "Aproximació científica a un problema formal: contribució acústica al disseny arquitectònic: En record al prof. Eng. Lothar Cremer," *Revista de Física*, no. 7, pp. 50–57, 1994.

[18] H. Arau-Puchades, "An improved reverberation formula," *Acustica*, vol. 65, no. 4, pp. 163–180, Mar. 1988.

[19] H. Arau-Puchades, "Revisión del tiempo de reverberación: El método de cálculo, la precisión predictiva y la Ley," in *TecniAcustica'10: León, octubre 2010*, León: Sociedad Española de Acústica, 2010, pp. 1–16.

[20] C. W. Kosten, "International comparison measurements in the reverberation room," *Acustica*, vol. 10, no. 5/6, pp. 400–411, 1960.

[21] M. L. Mehta and K. A. Mulholland, "Effect of non-uniform distribution of absorption on reverberation time," *J Sound Vib*, vol. 46, no. 2, pp. 209–224, May 1976, doi: 10.1016/0022-460X(76)90438-7.

[22] H. Arau-Puchades, "General theory of the energy relations in halls with asymmetrical absorption," *Building Acoustics*, vol. 5, no. 3, pp. 163–183, Sep. 1998, doi: 10.1177/1351010X9800500302.

[23] M. Barron and L.-J. Lee, "Energy relations in concert auditoriums, I," *J Acoust Soc Am*, vol. 84, no. 2, pp. 618–628, Aug. 1988, doi: 10.1121/1.396840.

[24] H. Arau-Puchades, *ABC de la acústica arquitectónica*. Barcelona: Ceac, 1999.

[25] S. R. Bistafa and J. S. Bradley, "Predicting reverberation times in a simulated classroom," *J Acoust Soc Am*, vol. 108, no. 4, pp. 1721–1731, Oct. 2000, doi: 10.1121/1.1310191.

[26] T. E. Vigran, *Manual for WinRT60, version 1.0*. Trondheim: Gray literature, 2006.

[27] "Strutt Revision History," Strutt Acoustics. Accessed: Mar. 27, 2025. [Online]. Available: https://strutt.arup.com/help/

[28] J. Ducourneau and V. Planeau, "The average absorption coefficient for enclosed spaces with non uniformly distributed absorption," *Applied Acoustics*, vol. 64, no. 9, pp. 845–862, Sep. 2003, doi: 10.1016/S0003-682X(03)00047-1.

[29] C. Hopkins, *Sound insulation*. Oxford: Butterworth-Heinemann, 2007.

[30] T. E. Vigran, *Building acoustics*. London, New York: Taylor & Francis, 2008.

[31] E. Brandão, *Acústica de salas: Projeto e modelagem*. São Paulo: Blucher, 2016.

[32] R. T. Beyer, *Sounds of our times: Two hundred years of acoustics*. New York: Springer, 1999.

[33] J. S. Bradley, "The evolution of newer auditorium acoustics measures," *Canadian Acoustics*, vol. 18, no. 4, pp. 13–23, Oct. 1990.

[34] M. Barron, "The development of concert hall design–A 111 year experience," *Proc. of the Institute of Acoustics*, vol. 28, no. 1, p. [1-14], 2006.

[35] R. Lacatis, A. Giménez, A. Barba Sevillano, S. Cerdá, J. Romero, and R. Cibrián, "Historical and chronological evolution of the concert hall acoustics parameters," in *Proc. of Acoustics'08: Paris, June 29-July 4, 2008*, Paris: SFA, 2008, pp. 4377–4382.

[36] M. Skålevik, "Reverberation time–The mother of all room acoustic parameters," in *Proc. of 20th International Congress on Acoustics, ICA 2010: 23-27 August 2010, Sydney*, Sydney: International Commission for Acoustics, 2010, pp. 1–5.