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FROM THEORY TO REALITY: ASSESSING PREDICTIVE MODELS FOR REVERBERATION TIME IN BUILT ENVIRONMENTS

Marco Caniato[1*] **Federica Bettarello**[2]
[1,*] Faculty of Civil Engineering, Building Physics and Business Management, University of Applied Science – 70174, Stuttgart, Germany
[2] Engineering and Architecture Department, University of Trieste, via Valerio 6/a, Trieste, 34127, Italy

ABSTRACT

This research undertakes a rigorous examination of the challenges inherent in predicting reverberation time within enclosed environments. The analysis is grounded in multiple case studies, wherein reverberation time measurements were conducted both prior to and following the installation of sound-absorbing panels. The performance of the panels was evaluated through two distinct laboratory testing methodologies. Virtual models were subsequently developed to replicate the specific characteristics of the analyzed environments, enabling the computation of reverberation time through acoustic simulation software and three theoretical approaches from the literature: Sabine, Eyring and Millington. The findings of this study highlight significant deviations between predicted and measured reverberation times, with theoretical models demonstrating lower accuracy compared to results obtained via acoustic simulations.

Keywords: reverberation time, prediction, 3D simulation, Sabine, Eyring.

1. INTRODUCTION

Reverberation time (RT) is the key parameter in room acoustics as it significantly influences speech intelligibility, comfort and overall acoustic quality in enclosed spaces [1,2]. It is commonly used to assess and design acoustic environments in various settings such as cafeterias, atriums, gymnasiums, multipurpose halls and classrooms [3]. The accurate prediction of reverberation time is crucial for optimizing these environments and ensuring appropriate acoustic conditions for different uses [4].

Conventionally, reverberation time is estimated using empirical and semi-empirical formulas, such as Sabine's formula [5], Eyring's equation [6], Millington's variation [7], Sette proposal [8] and Fitzroy's model [9]. These predictive models are widely employed due to their simplicity and ease of implementation. Sabine's formula, for instance, is based on the assumption of a diffuse sound field and relates reverberation time to the volume of the room and the total absorption provided by its surfaces. Eyring's model introduces a correction for higher absorption levels, while Fitzroy's equation considers non-uniform absorption across different room surfaces. Despite their extensive use, the reliability of these formulas remains questionable [10–13], especially in complex architectural settings where absorption, diffusion, and geometry introduce significant variability.

One of the main challenges in reverberation time prediction is the gap between theoretical estimations and real-world measurements [14]. Scientists, academics and professionals in the field of acoustics often rely on these predictive tools, yet their accuracy is frequently unverified through direct measurements. This discrepancy arises because reverberation time predictions are typically performed during the design phase, before the construction of the actual environment. As a result, the final built space may exhibit acoustic properties that diverge from the initial predictions due to material variations, unforeseen absorptive elements, or unaccounted diffusion effects. Moreover, when designing large and complex spaces such as atriums, gymnasiums or churches, the spatial distribution of acoustic treatment and the presence of furniture, people

*Corresponding author: marco.caniato@hft-stuttgart.de.

and other elements further complicate the accuracy of predictive models [13, 14].

Additionally, the assumptions behind these predictive models are often oversimplified. For example, many of these equations assume that sound energy decays uniformly in all directions, which is rarely the case in real-life environments where reflections and localized absorption play a crucial role. In spaces such as school classrooms and multipurpose halls, variations in ceiling height, partitioning elements and the presence of irregularly shaped surfaces create deviations from idealized conditions, leading to discrepancies between predicted and actual reverberation time values. Furthermore, acoustic treatments such as suspended absorbers, perforated panels or diffusive elements alter the energy distribution in ways that standard models struggle to capture accurately.

This study aims to critically evaluate the reliability of commonly used reverberation time prediction methods in different indoor environments. By comparing theoretical estimations with in-situ measurements, we seek to identify the limitations of current models and propose possible improvements to enhance their predictive accuracy. The findings will contribute to a better understanding of how reverberation time should be estimated in practical applications, bridging the gap between theoretical calculations and real-world acoustic performance. Ultimately, improving reverberation time prediction methods will help engineers and designers create more effective and comfortable acoustic environments, particularly in spaces where intelligibility and sound clarity are essential.

Therefore, a crucial question in room acoustics is whether reverberation time can be accurately predicted before a space is built. Analytical models provide quick estimations, but often rely on simplified assumptions about sound propagation, absorption, and diffusion. On the other hand, 3D simulations attempt to provide a more detailed analysis but require extensive input data, including precise absorption coefficients, geometric properties and material characteristics. The main issue is that both analytical and simulation-based predictions often fail to match measurements, raising concerns about their accuracy and applicability in practical acoustic design.

Understanding the limitations of these methods is essential for improving acoustic predictions. Several factors contribute to the discrepancies, including variations in material absorption coefficients, the impact of diffusive elements and inaccuracies in defining boundary conditions in simulations. These challenges necessitate a critical assessment of current methodologies and the exploration of potential refinements in reverberation time prediction.

2. MATERIALS AND METHODS

The study follows a three-step methodology:

- *Measurements*: reverberation time is measured in different acoustic environments under two conditions: before acoustic treatment (highly reverberant) and after treatment (less reverberant). Measurements include impulse response analysis, macro-geometric data collection and photographic documentation for spatial reconstruction. Different measurement techniques, such as sine sweep and impulse response methods, were used. In order to reduce the number of parameters, always the same sound absorption material were used. This choice allows us to exclude the influence of the acoustic treatment on the final results of the prediction of both analytical models and 3D simulations. In order to insert a constant variable, the sound absorbing materials were always used in form of suspended panels.

  The acoustic properties of the material (polyester fibers, 5 cm thickness) were measured in the laboratory and the re-measured in another laboratory in two different reverberant rooms to confirm the results previously obtained and reduce the error [17,18].
- *Prediction*: reverberation time is estimated using both analytical formulas (Sabine, Eyring and Milling and Sette) and 3D simulation tools. Key challenges in this phase include:
  - Determining accurate sound absorption coefficients from laboratory tests.
  - Precisely computing the surface areas of objects.
  - Assessing the reliability of absorption data applied to real environments.
  - Evaluating whether predictive models perform consistently in environments with varying reverberation levels and volumes.
  - Understanding the role of different sound-absorbing materials in RT predictions.
  - Assessing the influence of room geometry and spatial distribution of absorbing surfaces on reverberation time outcomes.
- *Comparison*: the predicted reverberation time values are compared with in-situ measurements, highlighting discrepancies and assessing the accuracy of different prediction methods. Particular attention is given to the impact of complex geometries and mixed absorption conditions, which may introduce deviations

between theoretical and measured reverberation time values.

3. RESULTS AND DISCUSSION

Here, for the sake of brevity, only 2 different environments are presented. The overall study involved more than 20 different volumes.
Figures 1 and 2 refer to a canteen and report the results of the comparison between measured and predicted values, using the formula of Sabine, Eyring and Millington and Sette are reported for the scenario Ante Operam (before acoustic treatment) and Post Operam (after acoustic treatment).

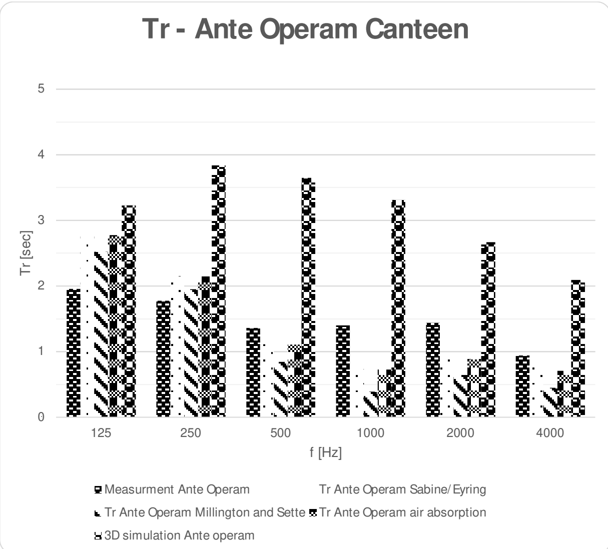

Figure 1. Comparison between measured and predicted values using analytical models and 3D simulation of a Canteen. Ante Operam.

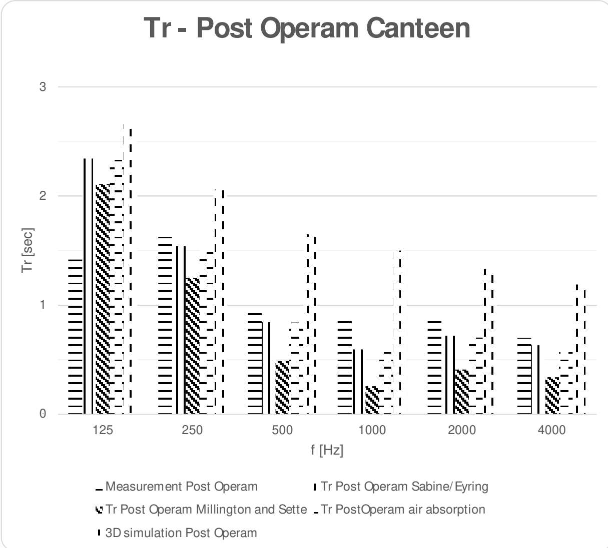

Figure 2. Comparison between measured and predicted values using analytical models and 3D simulation of a Canteen. Post Operam.

The analysis clearly demonstrates that analytical models fail to accurately predict reverberation time in both scenarios. While 3D simulations exhibit greater precision, they still lack full reliability, consistently underestimating post-treatment conditions and showing mixed accuracy in the pre-treatment scenario.
Figures 3 and 4 illustrate the results for an atrium, comparing measured and predicted values using the Sabine, Eyring, Millington, and Sette formulas for both the Ante Operam (before acoustic treatment) and Post Operam (after acoustic treatment) conditions.

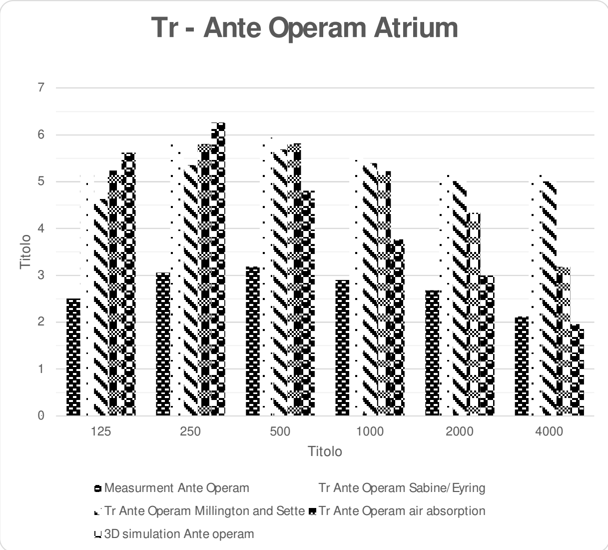

Figure 3. Comparison between measured and predicted values using analytical models and 3D simulation of an atrium. Ante Operam.

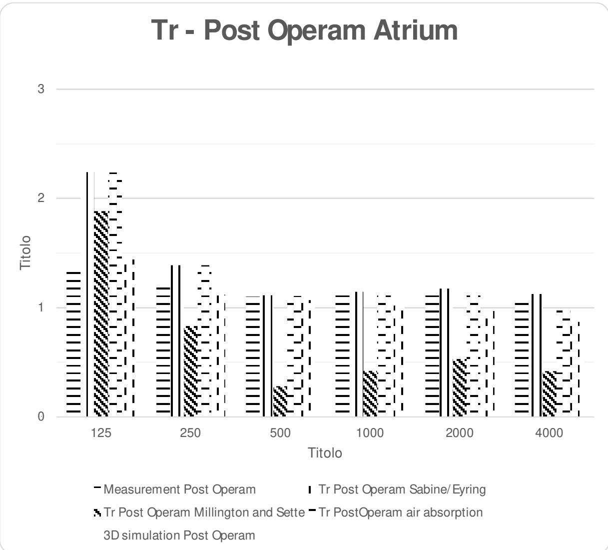

Figure 4. Comparison between measured and predicted values using analytical models and 3D simulation of an atrium. Post Operam.

It is evident that analytical models struggle to predict both scenarios, particularly at lower frequencies, which present greater challenges. Although 3D simulations demonstrate improved reliability, they still fail to accurately estimate low-frequency reverberation times.

The study reveals that neither analytical formulas nor 3D simulations provide consistently reliable RT predictions, aligning partially with previous research findings [19]. Standard predictive models do not perform equally well in highly reverberant and minimally reverberant environments. Furthermore, differences in room volume do not significantly affect prediction accuracy; however, variations in room usage (e.g., gymnasiums versus conference halls) introduce additional uncertainties.

The accuracy of absorption coefficients obtained from laboratory tests is questionable when applied to real spaces, as material properties may change during installation. The geometry of a given environment and the specific materials used significantly influence deviations between predicted and measured reverberation time values. Computational models require careful calibration, as discrepancies in input parameters -such as surface absorption coefficients and reflection properties - can lead to significant errors in reverberation time predictions.

Additionally, geometric complexities, the presence of furniture, variations in temperature and humidity [20] and other environmental factors further complicate reverberation time predictions, leading to discrepancies between theoretical estimates and empirical measurements [21-23]. The study also underscores the limitations of available absorption coefficient databases and the challenges in accurately defining geometric parameters in computational models.

The findings indicate that while analytical and computational approaches provide valuable insights, they must be applied with caution, considering the inherent assumptions and limitations of each method. A hybrid modeling approach that integrates empirical measurements with computational simulations may offer a more robust framework for reverberation time prediction.

4. CONCLUSIONS

This study highlights the limitations of current reverberation time prediction methodologies, emphasizing the need for improved models that better account for real-world variability. While analytical and simulation-based approaches remain fundamental tools in acoustic design, their limitations must be acknowledged, and validation through in-situ measurements should be prioritized. Future research should focus on refining predictive models and incorporating more accurate data on material absorption and spatial configurations.

Furthermore, improving predictive models necessitates:
• The development of hybrid approaches combining analytical and computational methods.
• More extensive measurement campaigns to refine absorption coefficient databases.
• Better integration of environmental factors, such as furniture and human occupancy, in RT estimations.
• Advanced modeling techniques incorporating probabilistic approaches to address material and geometric uncertainties.
• Validation studies systematically comparing different predictive models with measured data.

The results suggest that a more holistic approach to RT prediction is required, balancing theoretical models with empirical data to bridge the gap between predictive tools and real-world acoustic performance. This research contributes to the ongoing effort to refine acoustic design methodologies, ultimately leading to more accurate and reliable RT predictions across diverse environments. Enhancing RT prediction models will enable architectural acoustics to better support the design of functional and acoustically optimized spaces.
To address these challenges, a Round Robin Test on reverberation time prediction is being organized, inviting researchers and practitioners to participate in a comprehensive study comparing analytical models and 3D simulations. This initiative aims to enhance understanding of the reliability of existing methods and to propose advancements in reverberation time prediction techniques. Those interested in participating are encouraged to contact marco.caniato@hft-stuttgart.de by December 2025.

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