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COMPARING OPEN-SOURCE ROOM ACOUSTICS SIMULATION TOOLS: PERFORMANCE AND USABILITY INSIGHTS

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ABSTRACT

In previous decades, many studies, including several round robin studies, have been conducted on the validation of room acoustics simulation software for real rooms. However, these earlier studies mainly studied commercial software, did not assess the subjective usability of the software, and the results are less reproducible for several reasons. In recent years, open-source room acoustic simulation tools have increasingly been shared, free to be used and redistributed by anyone subject to the license conditions. These software open the potential to accelerate science and offer opportunities for reproducibility of the results. Open-source tools for room acoustic simulation, however, lack evaluation of their performance and usability. In an effort to promote the usage of open-source acoustic simulation tools, this research presents an approach to compare the performance of open-source simulation software for room acoustics. Furthermore, it intends to be a starting point for a curated performance table of open-source software. Amongst the selected software are wave-based methods, geometrical acoustics methods and machine learning approaches. Simulation results of these software are compared with measurement data from the BRAS database. Furthermore, the usability of these open-source tools have been assessed from an end user standpoint.

Keywords: *room acoustics, simulation, usability*

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1. INTRODUCTION

In previous decades, many studies have been conducted on the development and validation of simulation tools for the prediction of room acoustics using computer simulations. Important papers, in this regard, include the four round robin studies conducted in 1995, 2000, 2005 and 2019 [1–4]. These round robin studies aimed to evaluate different simulation tools for room acoustics by comparing them to each other and to measurements in real rooms. The simulation software included a mix of simulation tools based on the Image-Source Model (ISM) and Ray Tracing (RT) models.

While these publications offer valuable insights into the prediction quality of room acoustics by different software, their practical application is limited. In all studies, the results were anonymized, which significantly reduced the opportunity for reproducibility. Despite the fact that anonymization can be defendable, the value for building engineers and researchers is reduced. As a consequence of the anonymization, they cannot use the results to decide which software fits their use case best.

The quality of room acoustics simulation software not only depends on the suitability of the underlying computational method. The choices on the level of geometrical details, material properties and specific simulation settings as decided by the operator are also very important for a high quality prediction of room acoustics [5]. However, none of the previous round robin studies reported the used simulation settings, which might partly be caused by the fact that the simulations were performed by third parties [1–4]. In particular, the research by Brinkmann et al. (2019) mentions that simplification of the geometrical model was allowed if the simulation algorithm required this [4]. The simplified room geometries however were not provided to the reader. The choice to allow simplification of the geometry and to not report the used simulation settings reduces the reproducibility and certainty of the reported simulation results.

Besides the four performed round robin studies, many other studies have been conducted to compare the performance of room acoustical simulation software with measurement results. Previous publications were found on ScienceDirect, Scopus and Web of Science using the following search terms:

("round robin" OR "validation" OR "comparison" OR "benchmark") AND ("simulation" OR "prediction") AND ("room acoustics" OR "virtual acoustics").

After the search, the found relevant publications were forwards- and backwards traced. Figure 1 shows the previously researched software found in this search process, along with their software license type. It is clear that commercial software has been studied most extensively. A total of 11 publications evaluated the simulation performance of ODEON, which makes it the most extensively evaluated tool. Other commercial tools were found to be evaluated less extensively.

Figure 1 shows that hybrid simulation solvers, utilizing the ISM for the early reflections, and a statistical or RT model for the late reflections, were researched most extensively. Unfortunately, for eight of the cited simulation tools the simulation method was not reported. An additional complication is that these tools do not seem to be available anymore. As shown, simulation software utilizing wave-based or Machine-Learning (ML) methods were not found in the literature.

In their research, Hornikx et al (2024) found 55 unique open-source simulation tools for room acoustics [6]. The results in Figure 1 hint to a lack of understanding the simulation quality of these open-source room acoustics simulation software. In addition, existing literature shows the need for a reproducible method for the comparison of the performance of both open-source and commercial tools. Only three studies reported some simulation settings [7–9].

Additionally, no previous publications report the usability of the software. For the adoption of room acoustic simulation tools and thereby the enhancement of its value, in particular for open-source software, information on the usability of the software is important.

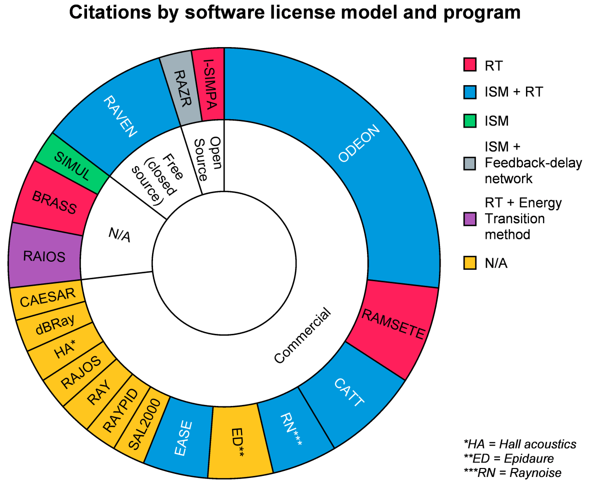

Figure 1. Overview of room acoustics simulation software found in existing literature. Presented are software names, license types, computation methods, and the amount of found publications.

In this research, the simulation performance of four open-source simulation tools for room acoustics will be evaluated. The simulations will be performed by one user, the author, to reduce uncertainty for the user aspect. Of course, many more promising open-source tools are available or could potentially be available in the future. Therefore, this research aims to be a starting point for a curated performance table. The aim of this research is to develop a reproducible method for the validation of simulation tools for room acoustics. This allows new tools to be compared to existing validation data by future researchers.

Furthermore, this research aims to be a starting point for a more extensive investigation into the usability of simulation tools for room acoustics. The potential of such research can lead to an improvement of the usability of existing and new software tools. This can prompt a more rapid adaption of such tools both in academic research and building practice, especially for software utilizing wave-based and ML methods.

2. METHODOLOGY

2.1 Simulation performance

An overview of open-source simulation software for room acoustics is available [6]. All software was analyzed on the following pre-determined selection criteria:

- The software runs on the Windows operating system.
- The software is specifically designed for room acoustics simulation.
- Documentation of the software is available, this includes for example an installation guide and a user manual.
- The software contains a description of the computation method, this could be a scientific publication, for example.
- Detailed 3D geometry input is possible.

The goal was to analyze at least two simulation tools based on Geometrical Acoustics (GA), wave-based and ML methods each. If multiple tools were found which comply with the above criteria, the tools with the most citations were chosen. Thus far, two GA methods, one wave-based and one ML model have been analyzed. Following this analysis, the simulation tools listed in Table 1 are evaluated in this study.

Table 1. Overview of the simulation software to be evaluated in the current research.

Software name	Method	Reference
Pyroomacoustics	GA	[10]
I-Simpa	GA	[11]
dg-acoustics	Wave-based	[12]
Image2Reverb	ML	[13]

The simulation software will be compared to measurement data using common room acoustics parameters from ISO 3382-1 in a real room. This ISO-standard also defines the Just Noticeable Difference (JND) range for these various parameters [14].

In this research, 'Complex room 2' (CR2) from the BRAS database was chosen as the reference room [15]. Many room properties of this room are provided in the database, including the geometry, absorption and scattering data of the materials, and source and receiver positions. Furthermore, the Impulse Responses (IRs) measured in the room are provided as .wav files. This database is open for anyone to use [15].

'Estimated' and 'fitted' random incidence absorption and scattering data of all surfaces in the room are provided in the BRAS database. For the simulations in this research, the 'fitted' absorption coefficients from the database were used. These were computed by solving the Eyring formula for reverberation time based on the measured reverberation time in the room, and correcting the 'estimated' values accordingly [15].

Wave-based solvers require surface impedance data for their calculations. The surface impedance of the boundary materials are not provided in the database. Mondet et al. (2020) describe a method to approximate the surface impedance of a material based on different material types and the random incidence absorption coefficient [16]. Their proposed method was applied to approximate the surface impedance of the materials.

The export of the simulated IRs as .wav files for further post-processing was preferred. For post-processing of IRs, the ITA-Toolbox was used [17]. For software that does not allow exporting the simulated IRs, the objective room acoustic parameters computed by the software were used. This will be clearly denoted where applicable in the results section.

All calculations were performed using the same settings, geometry, and source-receiver positions in accordance with the original measurements. The provided geometry from the database was simplified to fit the purpose of room acoustic simulations and to reduce computation times.

For simulation software based on GA and wave-based methods, the simulation settings provided in respectively Tables 2 and 3 were used. The environmental settings are in accordance with the environment in the room during the measurement [15].

Pyroomacoustics required the development of a custom script for the simulation of detailed 3D rooms with varying frequency-dependent material properties. This functionality can be coded by combining various examples and issues from the Github repository.

The ML software uses photographs of the room to generate the IRs. The photographs from the BRAS database were used for the computations [15].

Wave-based solvers are known to require high computational power. Their usefulness lies especially in the lower frequencies, below the Schroeder frequency, where wave interference plays a large role in the resulting acoustic field. This phenomenon is often called the 'large room assumption', which is assumed to be valid above the Schroeder frequency in the current room (219 Hz) [18]. The simulation using the wave-based solver ran until 355 Hz, which is the upper band limit of the 250 Hz 1/1-octave

Table 2. Simulation settings to be used for simulation software based on GA in room BRAS CR2.

GA — Simulation settings BRAS CR2	
Relative humidity [%]	41.7
Room temperature [°C]	19.5
Atmospheric pressure at 20°C[Pa]	101325
Source directivity [-]	Omni
Source noise type [-]	Pink
Receiver directivity [-]	Omni
Number of sound rays N [-]	5000
Receiver detection sphere radius r_d [m]	0.1
Calculation method [-]	Energetic
Image-source order [-]	3
Maximum sound pressure decay [dB / Pa]	-35 / 3.55e-7
Impulse response length [ms]	3140
Air absorption [-]	False
Time granularity of the histogram [ms]	5
Frequency range 1/3-octave [Hz]	50 - 10000
Frequency range 1/1-octave [Hz]	63 - 8000

band and 315 Hz 1/3-octave band.

For reproducibility and further research purposes, supplementary materials are provided [1]. The supplementary materials include the used 3D room geometry, absorption and scattering coefficients of the materials in the room, source and receiver positions, and all simulation results. Furthermore, the approximated frequency-dependent surface impedance is provided for all materials. The developed Pyroomacoustics script is provided and can also be found in Github issue #392 [2]. For dg-acoustics, the generated mesh and simulation script is provided. Finally, for Image2Reverb, the used photographs are provided.

[1] https://github.com/Building-acoustics-TU-Eindhoven/OSS_RoomAcoustics

[2] https://github.com/LCAV/Pyroomacoustics/issues/392

Table 3. Simulation settings to be used for simulation software based on wave-based methods in room BRAS CR2.

Wave-based — Simulation settings BRAS CR2	
Air density at 20°C[kg/m^3]	1.204
Atmospheric pressure at 20°C[Pa]	101325
Source directivity [-]	Omni
Impulse response length [ms]	3140
Air absorption [-]	False
Characteristic length of the mesh L_c [m]	0.45
Maximum f for simulation [Hz]	355

2.2 Software usability

Software usability, or usability in general, is not an absolute metric. Rather, it is dependent on different personal factors, including, but not limited to, the task the user aims to achieve and the previous experience of the user [19]. In ISO 9241-11:2018, usability is defined as the *"extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use"* [20]. According to Brooke (1995), questionnaires and attitude scales are often used when the usability of a system is to be researched [19]. General attitude scales are available, however these are long questionnaires and require a sufficiently large group of typical users [21].

In this research, the usability of the simulation tools will be assessed by the first author from the viewpoint of a user of simulation software for room acoustics. The user has three years of experience with simulation software for room acoustics and performing room acoustic measurements. However, the user has limited experience in coding and bugfixing of software tools.

The task is to perform room acoustic simulations and extract the results in order to compare them to known measurement data. Steps to achieve this process are:

1. Getting familiar with the tool and the steps required to achieve the desired results.
2. Importing a 3D-geometry file for the simulation.
3. Assigning boundary conditions for the simulation.

4. Assigning source and receiver locations for the simulation.
5. Assigning the correct settings, as presented in Tables 2 and 3.
6. Running the simulation.
7. Extracting the simulation results.

Based on this task, experienced usability problems will be discussed. An extensive research into the usability of the software with an adequately large user group is outside the scope of this research due to time constraints. However, an idea of the overall user-friendliness of the simulation software is available for potential future users.

3. RESULTS

3.1 Simulation results

Mean reverberation times (T20), early decay times (EDT) and speech definition (D50) in 1/1-octave bands from 63 to 8000 Hz for each source-receiver combination are presented. [3] All unprocessed results, IRs and raw data are available in the supplementary material. Furthermore, the script used for post-processing of the IRs and raw data from I-Simpa is provided.

In Figure 2, the mean spectral reverberation time (T20) in the room is presented. The data shows that from the simulated results, none of the utilized tools predict the reverberation time consistently within the JND range. I-Simpa predicts the reverberation times closest to the measured data in all 1/1-octave bands. Pyroomacoustics shows a larger deviation from the measured data. Furthermore, dg-acoustics tends to overestimate the reverberation time in the room in the 1/1-octave bands below the Schroeder frequency. Lastly, Image2Reverb overestimates the reverberation times below the Schroeder frequency, but estimates closer to the measured T20 above.

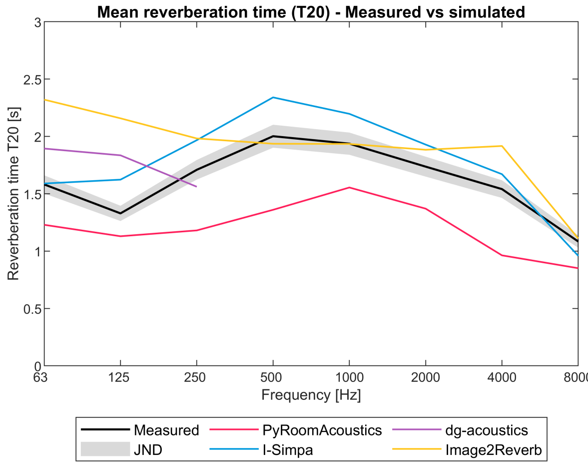

Figure 2. Mean measured and simulated results of the reverberation time (T20) in the reference room.

Figure 3 presents the computed results for the early decay time (EDT) in the room. Again, the results computed by I-Simpa show the closest agreement with the measured data. The results computed by Image2Reverb show a better agreement with the measurement data above the Shroeder frequency in the room (219 Hz) than below. dg-acoustics again tends to overestimate the EDT in the lower frequencies, but approached the JND range in the 250 Hz 1/1-octave band. Finally, Pyroomacoustics shows a large deviation from the measured data with the exception of the 63 Hz 1/1-octave band.

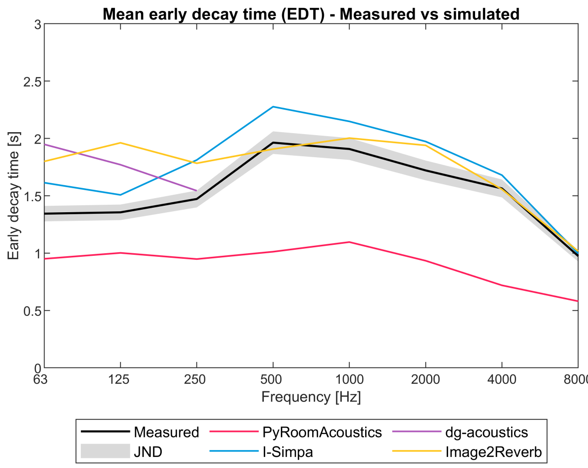

Figure 3. Mean measured and simulated results of the early decay time (EDT) in the reference room.

Considering the speech definition (D50), presented in Figure 4, I-Simpa shows simulated results close to the measured speech definition and mostly within the JND range. Above the Schroeder frequency (219 Hz), Image2Reverb starts to show good agreement with the measured results. The estimations by dg-acoustics are slightly outside the JND range. Pyroomacoustics seems to overestimate the speech definition in the room most when

[3] The results from I-Simpa were computed by the software instead of by post-processing of the IRs.

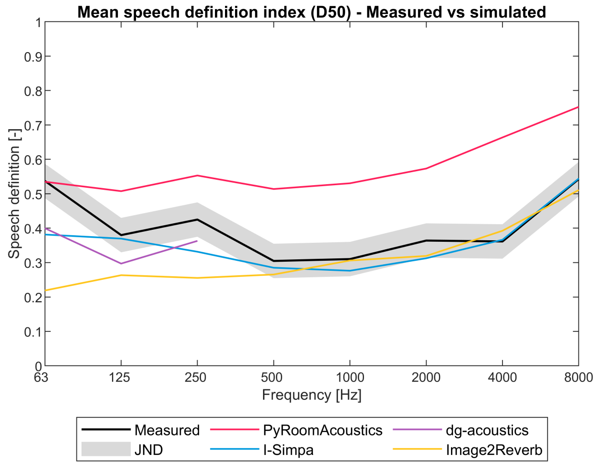

Figure 4. Mean measured and simulated results of the speech definition (D50) in the reference room.

compared to the measured results.

3.2 Software usability

In general, most simulation tools were code-based, which requires the user to be familiar with, for example, code language and command line interfaces. For the imagined user of the tools, this reduced the usability of such tools. In this section, specific usability problems will be described for each simulation tool.

3.2.1 Pyroomacoustics

Some usability problems were encountered while using Pyroomacoustics. To start, the functionality required for this research required the development of a script combining various examples and issues from the GitHub repository. The developer expressed interest in uploading the developed script from this research as an example, possibly resulting in an improved usability for future users.

There are multiple methods to simulate a room and each provided example on the GitHub repository uses a different method. This can result in confusion for selecting the best method and for the available simulation settings.

During simulation, Pyroomacoustics does not return any feedback to the user. The user does not know what the software is currently working on. To improve usability, the implementation of feedback for the user and, for example, a timer to show the expected simulation time left can be very useful.

3.2.2 I-Simpa

One of the usability problems encountered with I-Simpa was an inconsistent import of the 3D-file. It is not very clear whether the user has to choose meters or millimeters when importing the model. This can only be seen after importing the model. A function that can detect very large or very small room volumes to warn the user about possible errors might be useful to reduce these errors.

Adding custom materials to the simulation was not very intuitive. Custom boundary conditions can be defined in *Project/Project database/Materials/User*. Since custom boundary conditions are such an important setting for most simulations, a better workflow for this setting can improve the usability of the software.

3.2.3 dg-acoustics

For the dg-acoustics simulation tool, many particular settings had to be learned before a simulation could be started. No guidelines for system settings are provided in the documentation, such as the required length of the mesh and the according CFL-number. This resulted in a lot of communication with one of the developers before a simulation successfully ran.

Furthermore, there is no clear way to convert known absorption data to impedance data included with the software. The usability will improve when guidelines or a method is provided for this functionality.

Finally, the computational demand of the software is very large, requiring the use of high performance computers for the simulation of any room other than some very small rooms with a very coarse mesh.

3.2.4 Image2Reverb

Regarding Image2Reverb, while the software usability for running a simulation was relatively good, the steps required for the software to work can be a bit cumbersome. For example, it is required to resize the photographs to a very small size to be used by the software [13]. Furthermore, the required code to run the particular software instance was uploaded in a GitHub comment in issue #32, but was not found in the original repository.

The Windows operating system is supported by the software, however required changing a few settings in the configuration file. For this step, help from the developer was required and can be read in Github issue #35.

4. DISCUSSION

In this research, one room was chosen as the validation case. The room has a relatively small size with acoustically hard boundary conditions, which introduces interference in the sound field in the lower frequencies. Because of this challenging environment, this room offers a valuable first insight into the performance of the software tools. For further evaluation, other rooms should be introduced as test subjects. The software settings and environment conditions of these rooms should be reported similarly to this publication. The BRAS database offers two more real rooms, a chamber music hall and a large auditorium, which could be good validation cases [15].

In this research, only the objective quality of the simulations was evaluated using room acoustical parameters reverberation time (T20), early decay time (EDT) and speech definition (D50). However, a large part of a simulation is also the subjective quality of the simulation, which can be assessed through an auralization study. These studies require a sufficiently large group of test subjects, and is out of the scope of this research.

The presented usability of the software does not accurately represent the actual usability of the software. Rather, it represents the experience of a single user with the software, which is by far not representative of the general usability of the software. Quantifying the usability of the presented software requires an extensive research with a sufficiently large group of users using the System Usability Scale (SUS) or other usability questionnaires [19]. Additionally, more practical insights into the usability of the presented software could, for example, be gained by employing Nielsen's '10 Usability Heuristics for User Interface Design' [22]. However, the goal of this research is to encourage more research into the topic of software usability for room acoustics simulation software. As previously mentioned, no research into the topic of software usability in this context has been performed yet. Therefore, while not fully representative, the current work offers a first insight into the possibilities and encourages future work on this topic.

5. CONCLUSION AND FUTURE WORK

Four open-source simulation tools for room acoustics were evaluated in a real room situation. The simulation tools included methods based on Geometrical Acoustics (GA), wave-based methods and Machine-Learning (ML) methods. The simulation results are compared using objective room acoustical parameters to measured data. In addition, first insights into the usability of the software are provided.

The results show varying agreement with the measurement data. In general, I-Simpa, based on GA, shows very good simulation results when compared to the measured data. The other software based on GA, Pyroomacoustics, shows larger deviations from the measurement results. The wave-based software dg-acoustics shows an overestimation in the lower octave bands. Due to long computation times, this software was only used for simulations up to the Schroeder frequency in the room. Finally, Image2Reverb, a ML method shows large deviations in the octave bands below the Schroeder frequency, however agrees better with the measured data in the higher octave bands.

Some insights on the usability are provided by describing a few usability challenges for each tool. Most tools are without a Graphical User Interface (GUI), which require experience in working with, for example, code language and virtual environments. More specific usability problems are described for each simulation tool.

Future research could focus on expanding the results from this research with more simulation tools, both open-source and commercial, and by simulating other real rooms following the same methodology. The goal of this work is to initiate the development of a curated performance table to allow users to make informed decisions for their simulation tool of choice. In addition, software usability could be expanded upon by a more comprehensive study using usability scales with a sufficiently large user group and by applying Nielsen's '10 Usability Heuristics for User Interface Design' [19] [22]. Finally, subjective simulation quality of these simulation software for room acoustics may be researched in more detail in an auralization study.

6. ACKNOWLEDGMENTS

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