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AN EVALUATION OF GEOMETRICAL ROOM ACOUSTICS SIMULATIONS IN OUTDOOR SETTINGS

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ABSTRACT

Several studies have evidenced how a performance-wise selection of architectural features of the urban fabric can mitigate environmental noise in urban areas. For instance, the application of sound absorbing materials and the use of elements such as screens and protrusions over building facades were reported to reduce the sound pressure level over the façade itself, improving acoustic comfort for building users in both indoor and outdoor private spaces, such as balconies and terraces. While several tools able to estimate outdoor sound propagation are available, they are generally not able to estimate the effect of such detailed design variations. In this frame, the use of geometrical room acoustic tools in outdoor settings has emerged. This contribution presents a comparison of the SPL values simulated in an urban courtyard by two geometrical room acoustic tools, i.e., Odeon and Pachyderm, to in situ measured data, increasing the awareness of the potentialities of such tools when employed in outdoor settings.

Keywords: *environmental noise, geometrical acoustics, outdoor, acoustic simulations.*

1. INTRODUCTION

The mitigation of environmental noise pollution in urban areas is essential to protect public health and well-being. Among the noise reduction strategies that can be implemented to reduce environmental noise levels, it is possible to act on architectural design features of the urban fabric [1,2]. Several studies have highlighted that a performance-wise selection of the materials and geometries at the urban microscale can promote outdoor acoustic comfort. More specifically, the application of sound absorbing materials and the introduction of elements such as screens and protrusions on building facades was reported to reduce the noise levels over the façade itself, with consequently improved conditions in indoor spaces and private outdoor ones, such as balconies and terraces [1–3]. Nonetheless, the prediction of the noise levels' variation resulting from architectural design choices is not trivial. Most simulation tools focusing on outdoor noise propagation (e.g., CadnaA, SoundPLAN) cannot handle design features at such a level of detail. Wave-based tools can deal with geometric and material features in detail, but are nonetheless often limited to 2D environments and are computationally expensive, while room acoustic simulation tools, which can account for such design variations with limited computational power, are developed for indoor spaces, and their potential use in outdoor settings needs to be evaluated.
This contribution presents an in situ measurement campaign conducted in a courtyard and compares the measured sound pressure level in outdoor positions with that simulated by two geometrical room acoustic simulation tools, i.e., Odeon and Pachyderm. The goal is to shed light on the extent to which the predictions are close to the measured values, to better understand the potentialities of the use of such tools in outdoor settings.

2. METHOD

2.1 The measurement campaign

A measurement campaign was carried out in May 2021 in a courtyard of Politecnico di Torino (Turin, Italy), used as a

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case-study. In the selected scenario the sound source is seen by the receivers, and therefore wave-based phenomena such as diffraction, that are simplified or neglected by geometrical acoustics, are considered of minor importance. The courtyard is 18.7 m wide and 29.7 m long and is located between 4 educational buildings. A picture of the courtyard is shown in Figure 1. The goal of the measurement campaign was to gather data on the reverberation time and sound pressure level (SPL) at different outdoor positions, located at the courtyard level and at the different floors of one of the buildings at the side of the courtyard. The reverberation time measurements were aimed to gather the data required to calibrate the acoustic models in Odeon and Pachyderm, ensuring that the key acoustic properties of the space were captured by the tools, while the SPL acquisitions were used as reference values to compare the simulated levels by the two tools.

Figure 1. Picture of the case-study courtyard

The measurement equipment consisted of an omnidirectional sound source and two calibrated class 1 sound level meters (model NTI XL2).

The number of measurement positions was defined in light of the relatively simple and symmetric form of the case-study courtyard, and considering the minimum distance from the source positions required by ISO 3382-2:2008 Standard [4] that defines a method for the measurement of reverberation time in ordinary spaces. The source was set at 1.5 m height in a central position in the courtyard (see Figure 3). For the reverberation time (T_{20}), 8 measurement positions at the courtyard level and 3 positions at the different building floors over the façade were considered. The SPL was measured in the 3 façade positions at different floors and in 4 positions at the courtyard level.

A map of the courtyard with the sound source and receiver positions is presented in Figure 2. The receiver positions used for T_{20} measurement are identified with a square and those used for SPL measurement with a circle.

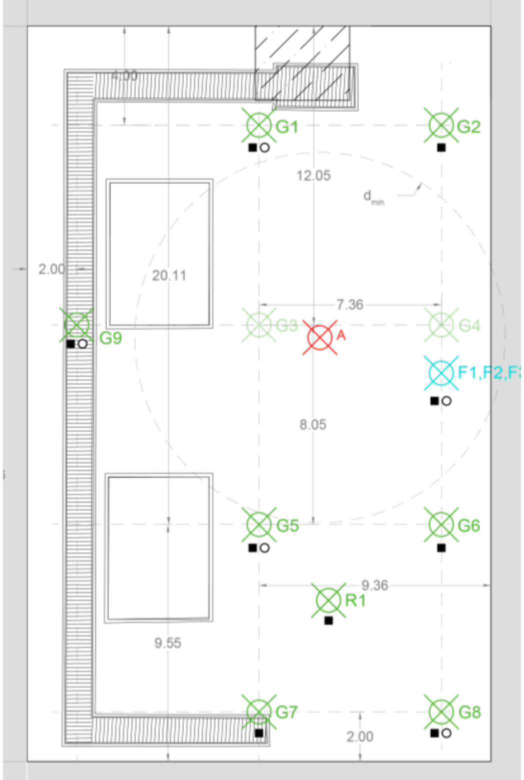

Figure 2. Map of the courtyard with the positions of the sound source and receivers.

The signal used for the SPL measurement was white noise and that used for the reverberation time was an exponential sine sweep [5].

The receivers at the courtyard level were at 1.5 m height while those over the façade were at ~1 m height with respect to the corresponding floor. The acquisitions were performed from 125 to 4000 Hz. The data processing to determine the reverberation time was performed on the impulse response signals using Audacity in combination with Aurora plug-in [6].

During the measurement campaign, the equivalent SPL of background noise was 55 dB in the noisiest position (in position G8 in Figure 2., which is close to the university hallway). The equivalent SPL at 1 m distance from the source was in the range between 87 dB and 88 dB.

Figure 3. Picture of the source and receivers in the courtyard (right) and façade receivers positions (left)

2.2 Virtual model and acoustic simulations

Odeon v 16 and Pachyderm v 2.0.0.2 were used to run the simulations. Odeon is a widely used commercial tool and has been validated in various studies [7–13], while Pachyderm is a free tool integrated in Grasshopper/ Rhinoceros, that was validated in [14,15] and whose results were compared to Odeon ones in [3]. Both tools are based on geometrical room acoustic principles and combine image-source method (for early reflections) and ray tracing one (for late reflections). The simulation settings defined for both tools are a transition order (i.e., reflection order after which the simulation switches from image-source method to raytracing) of 2, cut-off time of 5000 ms. The number of rays in Odeon is set at 300000 while in Pachyderm it is automatically defined using the “minimum convergence” option of the ray-tracing component in Grasshopper. Sensibility tests were preliminary performed on both tools by varying the simulation settings (cut off time up to 8000 ms, transition order up to 3, ray number up to 500000) to evaluate the stability of the simulated acoustic parameters as a function of these settings, evidencing negligible variations with respect to those obtained with the above-mentioned settings. Since among the considered tools only Odeon supports edge diffraction calculation, it was disabled for intercomparison purposes with Pachyderm.

An acoustic model was set to reproduce the measurement conditions (microphone and source positions) and the acoustic properties of the materials applied to the surfaces of the courtyard. The virtual model of the courtyard is shown in Figure 4. In Odeon, the virtual model was enclosed within a perfectly sound absorbing box to simulate an outdoor setting.

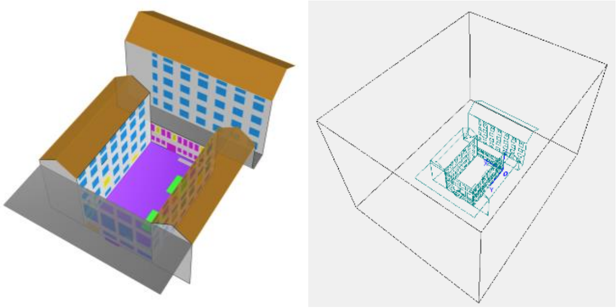

Figure 4. The virtual model of the courtyard in Rhinoceros (left) and Odeon (right).

The acoustic calibration of the model was performed independently for the two tools, by comparing the mean of the measured at the courtyard level and in the outdoor positions over the façade with the corresponding average values obtained through simulation.

The acoustic properties of the materials were initially set according to literature data [16–18] and, as concerns scattering properties, based on the surface irregularities. Based on the differences between the simulated and measured $T_{20,}$ the octave bend absorption and scattering coefficient were varied to minimize the T_{20} deviations, following two independent processes for the two tools considered.

At the end of the process, the values simulated by Pachyderm exhibit a deviation of less than 5%, i.e., the Just Noticeable Difference for reverberation time (JND_{RT}) defined by ISO 3382-1:2009 Standard [4] in the range 125 to 500 Hz, and inferior to 10% for the remaining values, that is considered indicative of a minimum practically important difference [19,20]. The T_{20} simulated by Odeon for both courtyard and façade receivers is below or close to the JND_{RT} (±5% threshold) in the range between 250 and 4000 Hz. Despite the calibration process of the acoustic coefficients (up to 20% variation), the deviation between simulated and measured T_{20} at 125 Hz could not be reduced within the 10% threshold, resulting in a difference between 18-19% at the end of the model calibration. The agreement between the measured and simulated T_{20} for the two tools is shown in .

Table 1. Evaluation of the overall SPL difference found between measurement and simulations

	SPL difference [dB]							MAE façade [dB]	MAE courtyard [dB]
	F1	F2	F3	G1	G5	G8	G9		
Pachyderm	0.1	0.3	0.5	1.6	1.5	1.9	1.8	0.3	1.7
Odeon	0.4	0.6	0.1	1.4	1.3	1.5	1.6	0.4	1.5

Overall, these results are considered acceptable and consequently, the acoustic model is calibrated for the engineering scope of the study.

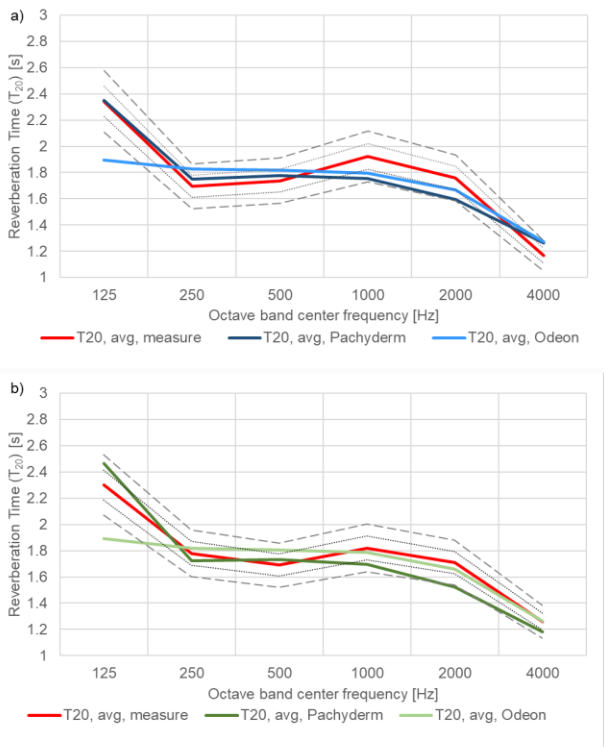

Figure 5. Measured octave band T_{20} at the courtyard level (a) and over the façade (b) compared to the ones simulated by Odeon and Pachyderm.

2.3 The evaluation of the simulation outcome

The comparison of the simulated and measured sound levels was performed considering the overall SPL values and, for a more detailed investigation, considering the octave-band SPL values. Both the overall and the frequency-dependent SPLs are referred to the range from 125 to 4000 Hz, coherently with the calibration process. The agreement between the overall SPL values was assessed by calculating the absolute difference between them in each position and as an average value for the courtyard/façade positions (this latter value corresponds to the Mean Absolute Error, MAE). The error found for the frequency-depended investigation was calculated based on the difference between the measured and simulated SPL based on [21], identified in the following as JND Error [-]. The JND Error was calculated according to Equation 1.

$$JND\ Error = \frac{\sum_{n=1}^{N_{Freq}} \sum_{i=1}^{N_{Pos}} \frac{\left|SPL_{measured,n,i} - SPL_{simulated,n,i}\right|}{JND_{SPL}}}{N_{Freq} \cdot N_{Pos}} \tag{1}$$

where N_{Freq} is the number of frequency-dependent values considered (in this case the SPL values in the different octave bands), N_{Pos} is the number of measurement positions.

The difference found between the simulated and measured SPLs are discussed on the basis of the JND_{SPL} and on the 3 dB threshold reported in [22,23] that is associated to a “just perceptible” change in apparent loudness.

3. RESULTS AND DISCUSSION

The results of the evaluations with respect to the overall SPLs simulated in the different positions are reported for Pachyderm and Odeon in Table 1. The absolute differences in SPL are detailed for each of the considered façade and courtyard positions and as average values of the differences (MAE) for both positions.

The results highlight that the predicted SPLs by Odeon and Pachyderm are close to the measurement, meaning that the tools were able to model the sound energy at the different locations with reasonable accuracy. When considering the absolute differences in overall SPL found at the specific locations, values inferior to the JND_{SPL} were found for both Odeon and Pachyderm estimations at the façade positions (F1, F2 and F3), while larger differences were found in the courtyard, with values larger than the JND_{SPL}, although in all cases below the 3 dB threshold.

This trend can be caused to the presence of elements in the courtyard (e.g., a stack of sand, a water tank and inhomogeneities in the cobblestone paving) that were not included in the simulations and that may have affected the measured SPLs in those positions. The MAE found for the façade positions are 0.3 dB and 0.4 dB for Pachyderm and Odeon, respectively, while those for the courtyard positions are 1.7 and 1.5 dB.

The results of the frequency-dependent evaluation of the simulated SPL, i.e., the calculated JND Errors, are reported in Table 2.

Table 2. Evaluation of the frequency-dependent *SPL* different found between measurement and simulations.

	JND Error for façade positions [-]	JND Error for courtyard positions [-]
Pachyderm	1.6	1.6
Odeon	1.4	1.5

The JND Errors highlight more marked SPL differences when considering the octave band values, which were not evidenced by the comparison of the overall SPL values. The JND Errors reported for both simulation tools at the courtyard and façade positions are ~1.5. These results evidence that the mean difference found is on average 1.5 times the $\mathrm{JND_{SPL}}$ (i.e., ~1.5 dB), which is considered reasonably acceptable considering the 3 dB threshold.

4. CONCLUSIONS

This study investigates the reliability of the use of room acoustic simulation tools to predict outdoor SPLs, considering two simulation programs based on geometrical acoustic principles, i.e., Odeon and Pachyderm. A measurement campaign in a courtyard has been carried out to obtain the T_{20} and the SPL in outdoor positions at the courtyard level and over the façade of one of the side buildings, at the different floors. The virtual models of the courtyard are calibrated based on the measured T_{20}, by adjusting the acoustic properties of the materials in order to minimize the differences between the measured and simulation T_{20} values. The ability to predict SPL values in different positions is then assessed on the calibrated acoustic models, on the basis of the agreement between the overall SPLs and the octave-band center frequency SPLs. In summary, a good agreement is found between measured and simulated SPLs, with all differences inferior to the 3 dB threshold that marks a just perceptible change in apparent loudness. For façade positions, the difference in the overall SPL falls below the $\mathrm{JND_{SPL}}$. These results suggest that Odeon and Pachyderm were able to capture the key acoustic properties of the courtyard and that a good agreement was found between the measured and predicted SPLs values in acoustically calibrated model. This outcome suggests that room acoustic tools can be used to reliably estimate SPLs values in outdoor scenarios similar to the one of this study. It must be however marked that typically geometrical room acoustic models neglect or simplify wave-based phenomena such as diffraction effect, which may have a marked effect in urban settings. Nonetheless, in outdoor scenarios such as the one here considered, i.e., simple geometries with an unobstructed path between source and receivers, the use of this type of tools was proved reliable for sound level estimations.

Further development of this work may include the analysis of different urban scenarios, the presence of multiple sound sources or linear sound sources, the consideration of a wider set of acoustic parameters and simulation tools, also including the currently emerging wave-based ones, and perceptual-based evaluations. Moreover, the comparison of the measured and simulated impulse responses is endorsed for a more detailed analysis.

5. ACKNOWLEDGMENTS

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