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Research Paper

Sensitivity Analysis of Acoustic Parameters in a Theatre Hall: A Case Study of the Maria Zankovetska Theatre in Lviv

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This article explores the potential for modifying acoustic parameters within a theatre hall, using the Maria Zankovetska Theatre in Lviv, as a case study. The study used sensitivity analysis to evaluate how changes in the sound absorption of specific surfaces affect selected acoustic parameters in the horseshoe-shaped theatre hall. A numerical model of the hall is developed and calibrated based on in-situ acoustic measurements to assess the sensitivity of parameters such as reverberation time (T_{20}), early decay time (EDT), clarity (C_{50}), and early sound strength (G_{80}).

The analysis reveals that surfaces such as the stage tower ceiling, stage walls with curtains, audience walls, and seating have the most significant impact on the acoustic parameters. Modifying the sound absorption of these surfaces can affect T_{20}, EDT, C_{50}, and G_{80}. Notably, increasing the absorption of a single surface might not significantly alter C_{50} and G_{80} values, whereas reducing the absorption of surfaces such as seating can lead to noticeable changes in these parameters. These findings provide valuable insights for future renovations and acoustic adjustments, aiming to optimize the theatre's acoustic performance while preserving its historical character.

Keywords: room acoustics; sensitivity analysis; sound absorption coefficient; reverberation time.

1. Introduction

The aim of this article is to investigate the potential for adjusting acoustic parameters in a horseshoe-shaped theatre hall, using the Maria Zankovetska Theatre in Lviv as a case study. The theatre, constructed between 1837 and 1842, stands as a testament to the architectural vision of Ludwig Pichla and Johann Zalcman. Designed with an uncompromising architectural layout, it became one of the largest theatre in Europe, serving as a pivotal hub for artists and cultural institutions. From its inception, the theatre has been the epicentre of cultural life in eastern Galicia, boasting an audience capacity of approximately 1460 seats distributed across the ground floor, side boxes, and four balconies. The theatre has undergone significant changes throughout its history. Between 1941 and 1944, construction damage caused by pile foundation problems required a partial rebuilding of the structure. As a result of this reconstruction, the original balconies and side boxes were replaced with two amphitheatrical balconies, which greatly altered the theatre's interior. In 2017, the theatre underwent a major modernization, which included replacing the flooring in the audience area and installing new seats. The previous seats, heavily upholstered on the bottom and back, had been the primary sound-absorbing elements in the hall since the 1940s rebuild. This resulted in an excessively long reverberation time that was unsuitable for theatrical performances. To address this issue, the decision was made to install new seats of a similar construction to those introduced in the 1940s, aiming to prevent any further increase in reverberation time.

Horseshoe-shaped halls provide good stage visibility and acoustic proximity for the audience, but exhibit acoustic limitations. The construction of multi-tiered boxes, with rich ornamentation and carvings, improves sound dispersion, but at the same time increases acoustic absorption, thereby reducing the reverberation time. The audience is primarily reached via direct sound, while a scarcity of reflections from the side walls reduces the impression of spaciousness. As previous studies have shown, listening conditions are worse in the depths of the boxes due to sound screening by balustrades and attenuation by walls. This problem has been addressed by designing shallow galleries and balconies without dividing the lodges (Barron, 2009) or by using Schroeder diffusers on the rear walls of sub-balcony lodges (Kamisiński, 2012).

Analyzing the acoustic parameters of historic theatres requires both in-situ measurements and numerical model studies (Kamisiński, 2010). In order to develop a numerical model of a theatre hall, it is necessary to determine the surface parameters inside the hall for proper calibration (Pilch, 2020). The basic parameter is the sound absorption coefficient of finishing materials (Prodi, Pompoli, 2016; Rubacha *et al.*, 2019) and auditorium seats (Beranek, Hidaka, 1998; Rubacha *et al.*, 2012). It is also important to consider sound diffusion (Binek *et al.*, 2022; Pilch, 2021; Shtrepi, 2019) as well as sound-reflecting elements (Szeląg *et al.*, 2014; 2020) in the model. Such elements help to control early reflections and eliminate acoustic defects.

The research conducted encompasses the following key areas. Firstly, the preparation of a numerical model of the theatre and its calibration based on acoustic measurements. This involved creating a digital representation of the theatre's interior that accounted for its architectural features and materials. Calibration was conducted by comparing the model's predictions with measured acoustic parameters collected within the theatre, thereby ensuring accuracy and reliability for further analysis. Secondly, the determination of the values of selected acoustic parameters of the interior under conditions of variable surface absorption using the model. By manipulating the absorption coefficients of various surfaces within the theatre, such as walls, ceilings, and seating, we could observe changes in key acoustic parameters, including reverberation time (T_{20}), clarity (C_{50}), and sound strength (G_{80}). This step was necessary for conducting a sensitivity analysis. The sensitivity analysis was conducted to examine the relationship between the acoustic absorption of selected surfaces and the acoustic parameters, identifying the surfaces that have the greatest impact on shaping these acoustic parameters. This analysis systematically varied the absorption properties of individual surfaces to observe the resulting changes in acoustic parameters. The findings highlighted which surfaces are most critical in influencing the theatre's acoustics, providing valuable insights for future renovations and acoustic improvements.

Through this study, we aim to gain a deeper understanding of the acoustics of horseshoe theatres and analyse the possibility of shaping their acoustic parameters while preserving their historical character.

2. Sensitivity analysis

2.1. Local and global sensitivity analysis

The purpose of sensitivity analysis is to examine the relationship between the input variables x of a model and the output variables y, where $y = g(x)$ and g is the model that maps inputs to outputs (Borgonovo, Plischke, 2016). Two primary techniques for sensitivity analysis are distinguished: local and global. Local sensitivity analysis involves changing the model parameters around specific reference values to determine how small variations in the inputs affect the model's response. According to derivative-based sensitivity analysis (Borgonovo, 2008; Pianosi *et al.*, 2016), the output sensitivity index S_i of the i-th input factor x_i can be calculated using the partial derivative $\frac{\sigma_y}{\sigma_{x_i}}$ evaluated at the nominal value $\overline{x}$ of the input vector $(x_1, x_2, ...)$. The goal of derivative-based sensitivity analysis is to identify which parameters have the most significant impact on the model's outcomes and to understand the nature of that impact.

The advantages of local sensitivity analysis are its ease of use and low computational requirements. For this reason, this approach is widely used in the literature; however, it also has significant limitations (Saltelli, Annoni, 2010). If the model is nonlinear, the results of local sensitivity analysis can be highly biased, as it assumes independence among model's input variables (Tang *et al.*, 2007). If the model inputs are not independent (i.e., when they interact with each other), local sensitivity analysis will underestimate their importance as it does not account for the effects of mutual interaction (Hamm *et al.*, 2006). In such a case, global sensitivity analysis is applicable.

2.2. Regression-based methods

Regression-based sensitivity analysis is a statistical method used to evaluate the impact of changes in the values of independent variables on the outcome of dependent variables in a regression model (Iooss, Lemaître, 2015; Manache, Melching, 2008; Saltelli *et al.*, 2004). This method is particularly useful for identifying the factors that have the greatest influence on the model and for supporting informed decision-making.

The primary step in regression-based sensitivity analysis is the computation of the sensitivity coefficient for each independent variable. This coefficient measures how much a change in a given variable affects the model's outcome. Thereby, the value of this coefficient indicates whether that variable has a strong or weak impact on the model.

One of the main sensitivity indicators in this category is the standardized regression coefficient (SRC). To calculate the SRC, a regression model between the input vector x_i and the output variable y is fitted using the least squares method:

$$y = b_0 + \sum_{i=1}^{N} b_i x_i, \tag{1}$$

where b_0 and b_i are the regression coefficients corresponding to the i-th input variable of the model. Equation (2) can be used to calculate the SRCs for different input values:

$$S_i = b_i \frac{\sigma_{x_i}}{\sigma_y}, \tag{2}$$

where σ_{x_i} is the standard deviation of the i-th model input and σ_y is the standard deviation of the model output.

Regression-based sensitivity analysis methods are global in nature and can examine the entire input space for variations. However, their actual level of comprehensiveness depends on the experimental design and the number of simulations providing data to establish the regression relationships. Although these methods are generally computationally efficient, they do not provide significant information on parametric interactions.

In the present study, sensitivity analysis methods based on regression were applied. The aim was to assess the impact of changes in the acoustic parameters of the Maria Zankovetska Theatre hall in Lviv on the changes in the sound-absorbing properties of individual surfaces within the hall. Based on the model results, inferences were drawn, and the surfaces and groups of surfaces exhibiting the greatest impact on the interior acoustics were identified.

In the studied model, the input parameters were the sound absorption coefficients of individual surfaces and groups of surfaces. The surfaces were grouped based on the type of material used for finishing and the location of the surfaces within the hall. Overall, the surfaces were divided into 14 groups, distinguishing between their location on the stage and in the audience area.

3. Analysis of acoustic parameters in the theatre hall

3.1. Description of the theatre hall

The Maria Zankovetska Theatre accommodates a total of 799 seats, with 531 seats located on the ground floor and an additional 268 seats distributed across two balconies. The main hall, encompassing approximately 5400 m^3, is connected to an 8000 m^3 scenic box, providing ample space for stage setups and scenery changes. For detailed parameters of the theatre hall, see Figs. 1 and 2, and Table 1.

Table 1. Parameters of the Maria Zankovetska Theatre in Lviv.

No.	Parameter	Value
1	Total volume V [m^3]	13 400
2	Audience hall volume V_w [m^3]	5400
3	Stage volume V_{sc} [m^3]	8000
4	Orchestra pit volume V_{or} [m^3]	80
5	Stage surface area S_{sc} [m^2]	410
6	Orchestra pit surface area S_{or} [m^2]	40
7	Total number of seats N	799
8	Number of seats on the ground floor N_p	531
9	Number of seats in balconies N_l	268
10	Audience volume per person [m^3/person]	5.63

3.2. Measurements of acoustic parameters in the theatre hall

The theatre's acoustic parameters were selected for analysis according to general literature recommendations (Barron, 2009) and International Standard ISO 3382-1 (International Organization for Standardization, 2009). The evaluation focused on early decay time (EDT), reverberation time (T_{20}), clarity (C_{50}), and early sound strength (G_{80}), with the curtain open and the stage empty. Impulse response measurements in the audience area were conducted according to the standard, using software for simultaneous recording from two microphones. All measurements were taken at a height of 1.2 m above the floor surface, while omnidirectional sound sources were positioned at three locations on the stage at a height of 1.5 m. The location of the sound source was chosen to cover all characteristic points on the stage: proscenium near the axis, deep side stage, and deep stage near the axis of the hall (Fig. 1).

The analysis of impulse responses was performed using software to determine all necessary acoustic pa-

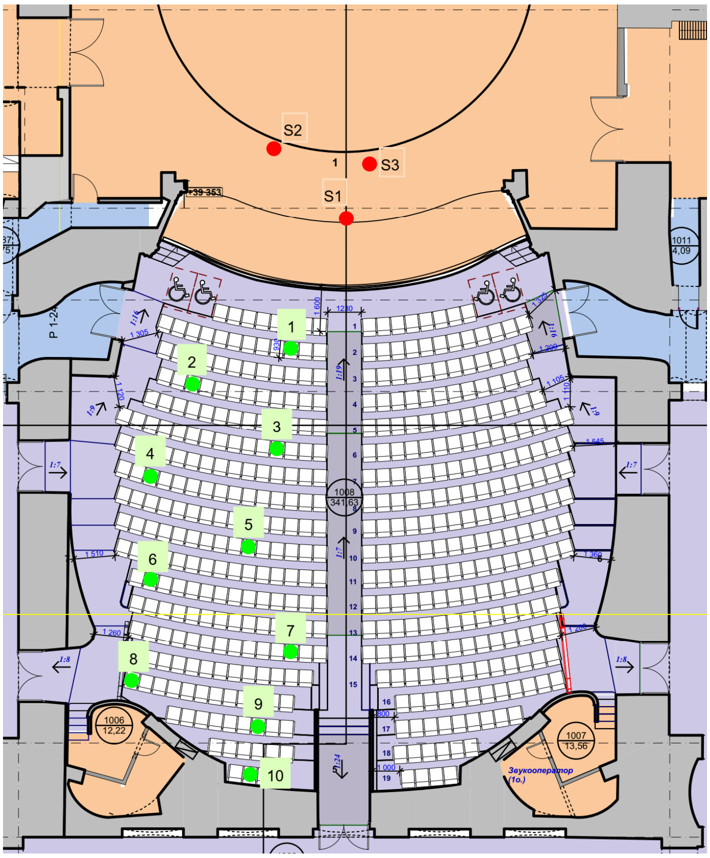

Fig. 1. Positions of the sound sources and microphones in the theatre's hall.

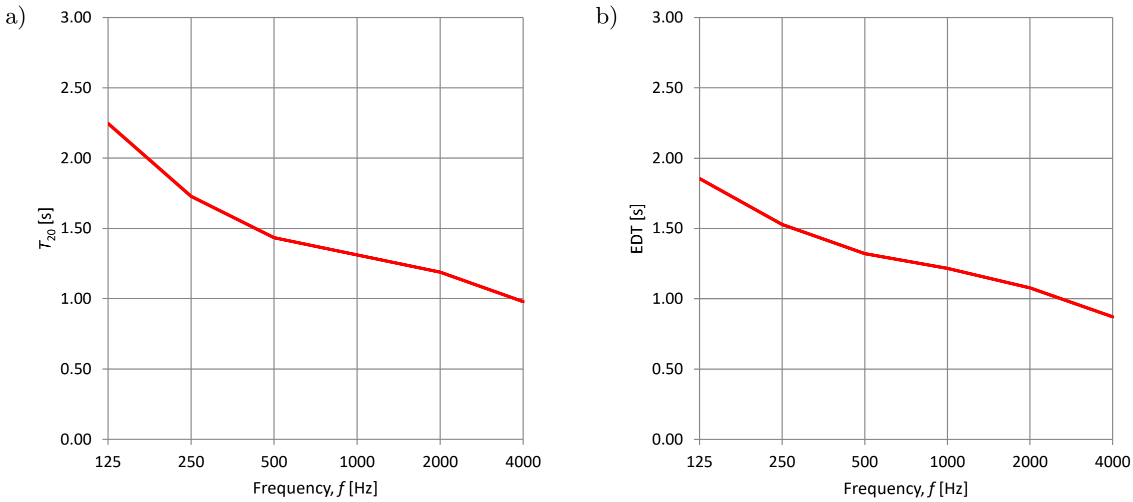

Fig. 2. Measured values of: a) T_{20} and b) EDT.

rameters. The determined values of T_{20} and EDT are shown in Fig. 2.

The reverberation time characteristics, specifically T_{20} and EDT, are affected by the finishing materials used in the hall. The primary sound-absorbing element is the audience seating. An overhanging auditorium layout has been designed for the hall, featuring auditorium seats with medium-thickness upholstery mounted on stepped platforms. This arrangement allows for high sound absorption coefficients in the mid- and high-frequency ranges. However, the absorption coefficient values at low frequencies are lower.

Another significant sound-absorbing element is the stage decorations suspended in the stage box, which also provide high sound absorption in the mid and high-frequency ranges but low absorption at low frequencies. The walls, ceiling, and balcony balustrades are made of concrete, resulting in very low absorption coefficients across the entire frequency spectrum. Consequently, the hall lacks low-frequency sound-absorbing elements, leading to significantly higher reverberation times at 125 Hz and 250 Hz.

A more detailed analysis of the hall's reverberation was conducted based on the average EDT values measured at each point (see Table 2).

Table 2. Mean values of the EDT for the frequency ranges 500 Hz–1000 Hz.

EDT_m [s]			
Point no.	Source position S1	Source position S2	Source position S3
1	1.80	1.86	1.67
2	1.45	1.90	1.64
3	1.38	1.66	1.56
4	1.15	1.63	1.46
5	1.16	1.32	1.16
6	1.19	1.24	1.19
7	1.17	1.34	1.21
8	1.01	1.09	1.12
9	1.01	0.98	1.04
10	0.97	1.12	1.22
Mean	1.23	1.41	1.33
RMSD	0.24	0.31	0.22

Analysis of the mean EDT values revealed that the highest values were recorded in areas closest to the stage, while the lowest values were found at the rear of the auditorium, particularly in the space beneath the balcony. This suggests that the stage area exhibits greater reverberation compared to the auditorium, primarily because it has a volume that is 50 % larger than that of the auditorium. Significant changes in EDT were also observed depending on the depth of the sound source on stage. For the sound source positions S2 and S3, located deep on the stage behind the proscenium, the EDT values were significantly higher compared to source position S1, located at the proscenium. This indicates that the acoustic parameters of the stage and hall differ and that the position of the sound source is considerably affected by the stage decorations.

Analysis of the C_{50}, parameter responsible for assessing music clarity was also carried out. The measured values of this acoustic parameter are presented for three sound source positions in Table 3.

The average value of the clarity index C_{50} is in the range of 1.3 dB–1.9 dB. A high root mean square deviation (RMSD) indicates significant variation in this parameter across different audience locations. Analysis of the measurements reveals that the lowest values occur at the centre of the hall, while higher values are found near the stage and at the rear wall. Overall, the measured values at the specific points are generally favourable for speech intelligibility.

Table 3. Mean values of the clarity index C_{50} for the frequency range 500 Hz–2000 Hz.

C_{50m} [dB]			
Point no.	Source position S1	Source position S2	Source position S3
1	5.2	3.0	1.7
2	1.9	4.0	0.8
3	1.2	1.3	0.9
4	1.9	2.5	–0.5
5	0.1	–0.7	0.0
6	–0.5	0.7	0.3
7	1.0	1.6	1.8
8	0.0	0.4	2.0
9	3.4	2.2	3.6
10	3.2	3.8	2.2
Mean	1.7	1.9	1.3
RMSD	1.7	1.4	1.2

An analysis of the early G_{80} sound strength distribution is shown in Table 4.

Table 4. Mean values of the sound early strength G_{80} for the frequency range 500 Hz–1000 Hz.

G_{80m} [dB]			
Point no.	Source position S1	Source position S2	Source position S3
1	6.8	1.8	2.0
2	4.1	2.9	0.4
3	5.6	0.8	0.6
4	4.4	–0.9	–1.5
5	4.7	0.6	2.7
6	1.5	–0.6	–0.4
7	3.8	1.2	2.2
8	2.3	0.1	1.1
9	2.9	1.4	1.9
10	2.1	0.4	–0.9
Mean	3.8	0.8	0.8
RMSD	1.6	1.1	1.3

The results indicate that the early G_{80} sound strength is highest near the sound source and decreases with distance. The location of the sound source significantly affects the G_{80} sound strength. When the sound source is positioned deep within the stage behind the proscenium, there is a notable reduction in sound strength of up to 5 dB at points closest to the stage. This reduction occurs partly because the sound source is farther from the audience, leading to lower energy in the direct sound, but it is primarily due to the absence of early sound reflections. The depth of the stage lacks surfaces that could support and transmit these early reflections to the audience, so listeners primarily receive direct sound. The analysis of acoustic parameters shows that the sound source's position on stage greatly impacts the acoustic parameters. The G_{80} analysis reveals that the stage layout in the analysed configuration (without scenery) offers no support for early reflections.

These results indicate that EDT, C_{50}, and G_{80} values significantly depend on the location of the measurement point in the auditorium as well as on the position of the sound source on the stage. For further research, average values of the acoustic parameters calculated from all observation points in the auditorium will be used to provide a comprehensive assessment of the hall's acoustic properties. Additionally, to eliminate the influence of the sound source position on stage, future studies will focus only on measurements from the proscenium location.

3.3. Numerical model of the theatre hall

To estimate the acoustic parameters of the theatre with a full audience, we developed a numerical model using ISIMPA software (Fig. 3). This application employs an advanced geometrical model based on ray tracing and the image sources method to simulate sound propagation within the theatre space. The model was constructed using geometric data obtained through photogrammetric methods and incorporates the specific sound absorption and scattering coefficients of the interior surfaces.

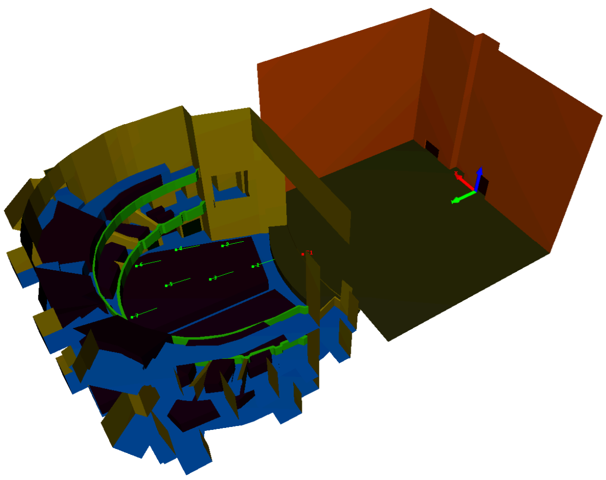

Fig. 3. View of the interior of the Maria Zankovetska Theatre showing the acoustic model in its actual state.

The absorption coefficients for the floors and walls were adapted from values measured in the laboratories of the Department of Mechanics and Vibroacoustics at AGH University of Krakow, Poland for similar venues, such as the Lviv Opera (Kamisiński *et al.*, 2009). Additionally, absorption coefficients for the stage were determined through direct in-situ measurements taken within the theatre.

To ensure the accuracy of our predictions, the numerical model underwent calibration to match the measured reverberation times obtained within the theatre. This calibration process ensures that the simulated acoustic environment closely reflects real-world conditions, providing a reliable basis for analysing and optimizing the theatre's acoustic performance.

The calibration of the model involved a two-stage process to ensure that the results obtained from the developed acoustic model were consistent with the results of measurements of acoustic parameters in the hall of the Maria Zankovetska Theatre in Lviv. The first stage involved a preliminary selection of sound absorption coefficients for the individual surfaces in the analysed hall. This process was based on a detailed visual inspection of the space, identification of the finishing materials used, laboratory testing of selected material samples, and analysis of available and relevant literature data. The collected data provided the basis for the initial setting of model parameters.

The second stage of validation involved iterative tuning of the model. Each step of the iteration involved fine-tuning of the sound absorption coefficients and then verifying that the calculation results obtained from the model are consistent with the results of measurements taken in the theatre hall. Corrections to the absorption coefficients were carried out until the compatibility criterion was met, that is, when the difference between the average T_{20} reverberation times calculated from the model and measured in the hall did not exceed 5 %. The criterion adopted corresponds to the just-noticeable difference (JND) for reverberation time. It was assumed that this approach would ensure that the model is consistent with the actual acoustic conditions in the theatre hall. The validated model then served as the starting point for further analysis, which is the focus of this article.

The values of sound absorption and scattering coefficients of each surface group after model calibration are shown in Table 5.

Figure 4 illustrates the percentage of sound absorption contributed by each surface group within the total sound absorption within the theatre. The values presented are averages for the 500 Hz and 1000 Hz frequency bands. Upholstered seats and the stage ceiling, which features textile stage decorations, demonstrate the highest levels of sound absorption. These two surface groups possess both high sound absorption coefficients and cover extensive surface areas, collectively accounting for over 50 % of the overall sound absorption within the hall. In contrast, the auditorium and stage walls have relatively low sound absorption coefficients; however, their large surface areas significantly contribute to sound absorption, approximately 20 % (see Fig. 4).

3.4. Sensitivity analysis

3.4.1. Input parameters to sensitivity analysis

Sensitivity analysis of changes in the acoustic parameters of the theatre hall in response to variations

Table 5. Sound absorption and scattering coefficients of surfaces and surface groups used in the theatre hall model: a refers to auditorium, while s indicates stage materials.

No.	Surface group	S [m^2]	a [–] s [–]	f [Hz] 125	250	500	1000	2000	4000
1	A:balcony ceiling	341.8	a	0.13	0.16	0.16	0.18	0.19	0.19
			s	0.10	0.12	0.15	0.20	0.25	0.30
2	A:ceiling	338.2	a	0.13	0.16	0.16	0.18	0.19	0.19
			s	0.10	0.12	0.15	0.20	0.25	0.30
3	S:ceiling	371.8	a	0.24	0.48	0.99	0.99	0.99	0.99
			s	0.10	0.12	0.15	0.20	0.25	0.30
4	A:walls	939.8	a	0.13	0.16	0.16	0.18	0.19	0.19
			s	0.10	0.12	0.15	0.20	0.25	0.30
5	S:walls	750.0	a	0.13	0.16	0.16	0.18	0.19	0.19
			s	0.10	0.12	0.15	0.20	0.25	0.30
6	A:front box barriers	111.1	a	0.13	0.16	0.16	0.18	0.19	0.19
			s	0.10	0.12	0.15	0.20	0.25	0.30
7	A:floor	358.2	a	0.13	0.16	0.16	0.18	0.19	0.19
			s	0.10	0.12	0.15	0.20	0.25	0.30
8	S:floor	422.4	a	0.21	0.19	0.11	0.12	0.13	0.15
			s	0.10	0.12	0.15	0.20	0.25	0.30
9	Portal	84.9	a	0.13	0.16	0.16	0.18	0.19	0.19
			s	0.10	0.12	0.15	0.20	0.25	0.30
10	A:windows	22.0	a	0.25	0.16	0.16	0.18	0.19	0.20
			s	0.10	0.12	0.15	0.20	0.25	0.30
11	S:back curtain	327.5	a	0.13	0.16	0.16	0.18	0.19	0.19
			s	0.10	0.12	0.15	0.20	0.25	0.30
12	A:seats	567.8	a	0.70	0.78	0.81	0.85	0.84	0.81
			s	0.30	0.40	0.50	0.60	0.70	0.70
13	A:doors	31.0	a	0.20	0.10	0.10	0.10	0.10	0.10
			s	0.10	0.12	0.15	0.20	0.25	0.30
14	A:barriers	124.8	a	0.13	0.16	0.16	0.18	0.19	0.19
			s	0.10	0.12	0.15	0.20	0.25	0.30

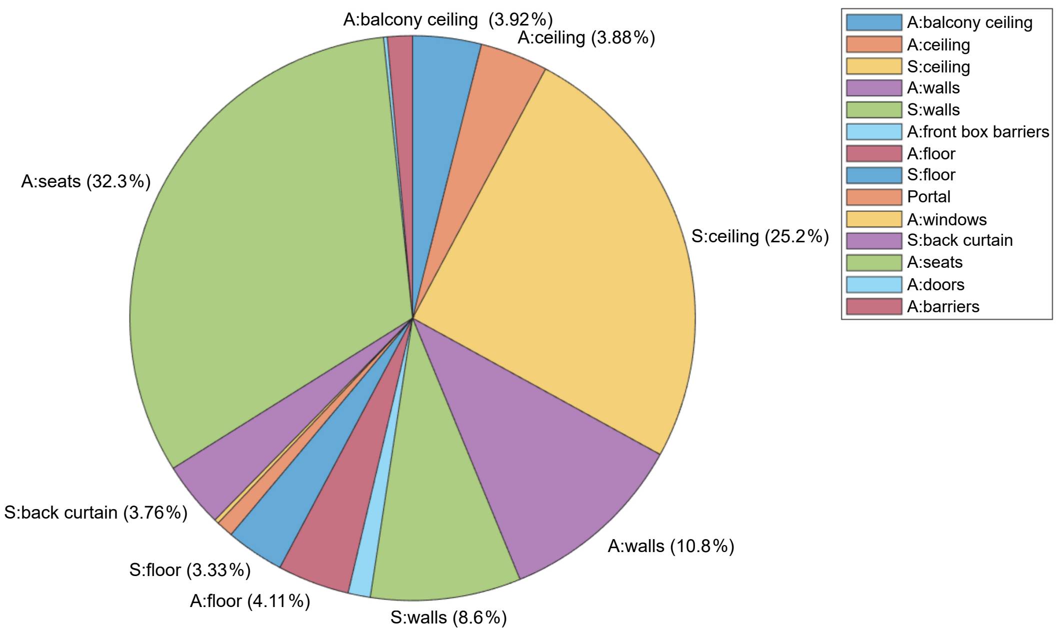

Fig. 4. Sound absorption (average values for 500 Hz and 1000 Hz) of each group of surfaces in the total sound absorption.

in the acoustic absorption of individual surfaces was conducted based on the results of numerical calculations performed using the calibrated model of the theatre hall. During the calculations, the input parameters were modified, assuming a variable value of the sound absorption coefficient. The impact of these changes in sound absorption was assessed based on the average values of the acoustic parameters for the entire hall. The effect of the sound scattering coefficient on the acoustic parameters of the hall was neglected in this study. Previous studies on the sensitivity of concert hall parameters to global changes in the sound scattering coefficient have shown that this influence is small and can be neglected (Pilch, 2024). On the other hand, local analyses of the changes in acoustic parameters after the installation of sound diffusers on the rear wall of the sub-balcony niche showed that the addition of sound diffusion causes locally significant changes in acoustic parameters (Kamisiński, 2012).

The adopted testing method involved altering the sound absorption coefficient of one surface or group of surfaces at a time. These values were modified within a range of ±50 % of their base values from the calibrated model, in increments of 10 %. For materials with high sound absorption coefficients, it was not possible to reduce their value by 50 %, so their absorption coefficient was increased to a maximum of 1.00 only. To present the results in a comparative format, we converted the change in the sound absorption coefficient into a change in acoustic absorption. Thus, the sensitivity of the hall's acoustic parameters was evaluated based on the change in absorption of each specific surface or surface group.

3.4.2. Analysed output parameters

The sensitivity analysis conducted focused on selected interior acoustic parameters. The EDT and reverberation time T_{20} were chosen to evaluate reverberation. Reverberation time is an indicator for evaluating the acoustics of an interior in the context of its intended function. EDT was included because it is sensitive to changes in the levels of early sound reflections in the room. Additionally, the analysis examined the sensitivity of changes in the clarity index C_{50}. The C_{50} index allows for evaluation of how the early reflection energy contributes to the total energy reaching the audience. Thus, it is important to analyse the impact of the placement of materials with different sound-absorbing properties in the theatre hall. Furthermore, the analysis also included the early sound strength G_{80}, which is essential for assessing the level of early sound reflections in a space and influences the perception of proximity to the sound source.

The choice of these parameters enabled a full and comprehensive analysis of the hall's acoustic characteristics. The analysis was carried out using the average values of the parameters for the 500 Hz and 1000 Hz octave bands, or in the case of the C_{50m} index – the average values across the 500 Hz–2000 Hz frequency range.

4. Analysis of results

4.1. Regression analysis and sensitivity indexes

Sensitivity analysis was conducted using linear regression analysis. This method allows for a quantitative evaluation of how changes in the sound absorption of individual surfaces affect the acoustic parameters. In this analysis, the values of the theatre's acoustic parameters were related to the JND. This approach enables the standardisation of the effects of changes in sound absorption, allowing for direct comparison of their impact on the hall's acoustic parameters. The JND values for the parameters analysed are shown in Table 6.

Table 6. JND for the analysed acoustic parameters.

No.	Parameter	JND
1	T_{20}	5 % of T_{20}
2	EDT	5 % of EDT
3	C_{50}	1 dB
4	G_{80}	1 dB

In order to analyse sensitivity, SRC was utilized. The sensitivity index, denoted by $S_{\text{param},i}$, was determined for the parameters T_{20m}, EDT_m, C_{50m}, and G_{80m} related to the JND for each i-th surface (see Table 5). Standardisation ensures that the value of the sensitivity index $S_{\text{param},i}$ reflects both changes in sound absorption and the area of particular groups of surfaces. The index was calculated in accordance with the following equation:

$$S_{\text{param},i} = b_{1,i} \frac{\sigma_{\Delta Ai}}{\sigma_{\Delta \text{JNDparam},i}} \tag{3}$$

where the standard deviation of the change in sound absorption, denoted here by $\sigma_{\Delta Ai}$ is calculated for each i-th group of surfaces. The change in the sound absorption $DA_i = A_{i,k} - A_{i,0}$ is defined as the difference between the sound absorption for the k-th value $A_{i,k}$ and the initial value $A_{i,0}$. The index k refers to the change in sound absorption The standard deviation of the change in acoustic parameter values related to JND ($D\text{JND}_{\text{param},i}$) is denoted by $\sigma_{D\text{JNDparam},i}$. The change in the acoustic parameters related to JND: $D\text{JND}_{\text{param},i} = \text{JND}_{\text{param},i,k}(A_{i,k}) - \text{JND}_{\text{param},i,0}(A_{i,0})$ is defined as the difference between the parameter values determined for the k-th value of sound absorption and those determined for the initial value of $A_{i,0}$.

The regression coefficients $b_{0,i}$, $b_{1,i}$ were determined from the regression model $D\text{JND}_{\text{param},i} = f(DA_i)$ for each i-th group of surfaces as follows:

$$\Delta\text{JND}_{\text{param},i} = b_{0,i} + b_{1,i}\Delta A_i. \tag{4}$$

4.2. Quantitative analysis

An analysis was performed to evaluate the sensitivity indexes ($S_{\text{param},i}$) of the various acoustic parameters related to the JND. Based on the $S_{\text{param},i}$ values, the surfaces with the most significant impact on each parameter were identified. A standard significance level of 0.05 was employed. A linear relationship between the change in JND ($D\text{JND}_{\text{param},i}$) and the change in sound absorption (DA_i) was considered significant when $p < 0.05$. The regression coefficients and p-values for the DJND of the T_{20} and EDT parameters are presented in Tables 7 and 8.

Table 7. Regression coefficients and p-values for $D\text{JND}_{T_{20}}$.

No.	Surface group	S [m^2]	b_1	b_0	p-value
1	A:balcony ceiling	341.8	0.000	–0.208	0.998
2	A:ceiling	338.2	–0.002	–0.377	0.450
3	S:ceiling	371.8	–0.018	–0.516	**0.000**
4	A:walls	939.8	–0.019	0.295	**0.000**
5	S:walls	750.0	–0.015	0.088	**0.000**
6	A:front box barriers	111.1	–0.001	–0.216	0.854
7	A:floor	358.2	–0.008	0.136	**0.007**
8	S:floor	422.4	–0.006	0.131	0.090
9	Portal	84.9	–0.034	0.315	**0.019**
10	A:windows	22.0	–0.046	0.083	0.238
11	S:back curtain	327.5	–0.034	0.187	**0.000**
12	A:seats	567.8	–0.003	0.056	**0.000**
13	A:doors	31.0	–0.036	0.355	0.510
14	A:barriers	124.8	–0.010	–0.012	0.180

Table 8. Regression coefficients and p-value for $D\text{JND}_{\text{EDT}}$.

No.	Surface group	S [m^2]	b_1	b_0	p-value
1	A:balcony ceiling	341.8	–0.001	–0.297	0.505
2	A:ceiling	338.2	–0.005	0.173	**0.033**
3	S:ceiling	371.8	–0.017	–0.039	**0.000**
4	A:walls	939.8	–0.015	–0.076	**0.000**
5	S:walls	750.0	–0.023	0.125	**0.000**
6	A:front box barriers	111.1	–0.031	0.140	**0.001**
7	A:floor	358.2	–0.005	–0.108	0.303
8	S:floor	422.4	–0.021	–0.092	**0.000**
9	Portal	84.9	–0.016	0.067	**0.000**
10	A:windows	22.0	0.004	0.113	0.282
11	S:back curtain	327.5	–0.028	–0.032	**0.000**
12	A:seats	567.8	–0.004	0.101	**0.000**
13	A:doors	31.0	–0.002	0.078	0.392
14	A:barriers	124.8	–0.014	–0.245	0.105

The analysis shows that, for many surface groups with small areas, the results obtained were not statistically significant ($p > 0.05$). This implies that, for these areas, there is no linear relationship between changes in a parameter and changes in its acoustic absorption. Figure 5 presents the sensitivity indexes $S_{\text{param},i}$ that are statistically significant.

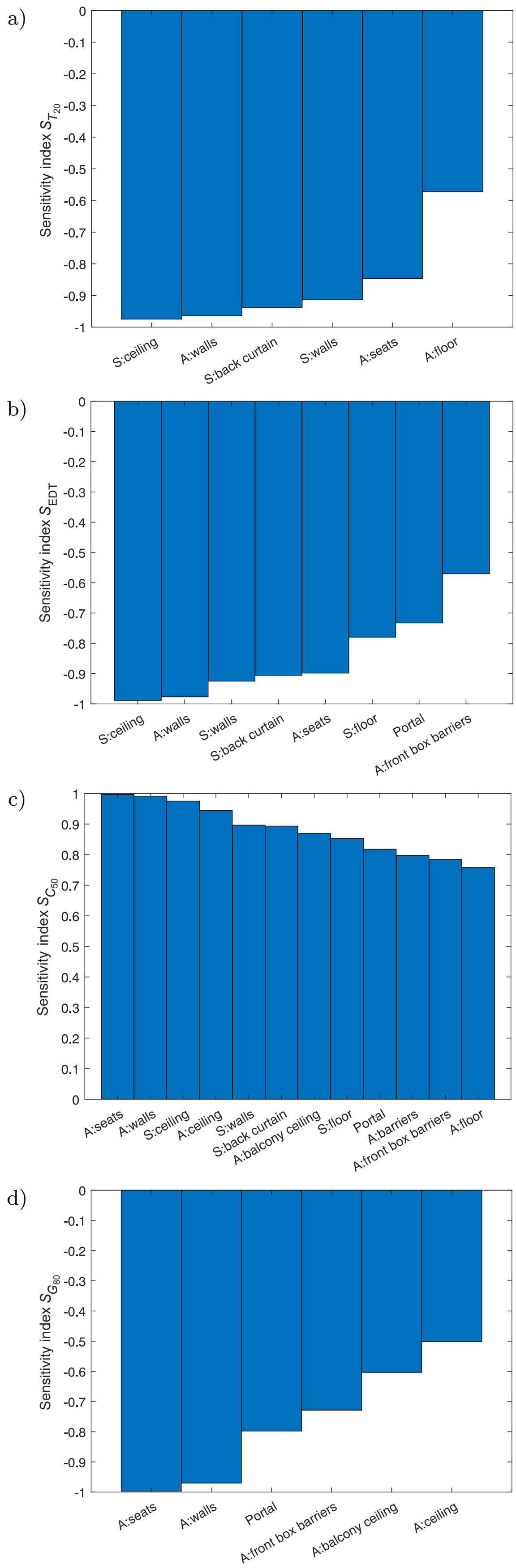

Fig. 5. Sensitivity indexes $S_{\text{param},i}$ for the: a) T_{20}, b) EDT, c) C_{50}, and d) G_{80}, all relative to JND.

Negative values of the sensitivity indexes S_{EDT}, $S_{T_{20}}$, and $S_{G_{80}}$ (Figs. 5a, 5b, 5d) indicate that the corresponding parameter is negatively correlated with changes in the acoustic absorption ΔA_i of the i-th surface. Higher absolute values of the sensitivity indexes indicate that a change in the sound absorption of a specific surface has a greater impact on the associated acoustic parameter.

The obtained sensitivity indexes S_{EDT}, $S_{T_{20}}$ show that the reverberation time is sensitive to changes in the sound absorption of large surfaces on the stage and in the audience area, particularly the stage ceiling (Figs. 5a and 5b). This confirms the measured values of EDT, where higher values were observed near the stage. This indicates that the stage volume and the presence of sound-absorbing materials significantly affect the reverberation characteristics of the hall. The analysis of C_{50} revealed that this parameter is particularly sensitive to changes in the sound absorption of surfaces located in the audience area, which is related to providing early reflections from nearby surfaces (Fig. 5c). Results obtained for the early sound strength G_{80} show that this parameter is particularly sensitive to changes in seat absorption and the walls surrounding the audience (Fig. 5d). However, the sensitivity indexes $S_{\mathrm{param},i}$ do not give any information on how much a change in the sound absorption of a given surface affects a specific acoustic parameter within the hall. The range of possible parameter changes is limited by the range of changes in the sound absorption coefficient of the given surface. Therefore, a qualitative analysis was carried out to determine the significance of potential changes in the acoustic parameters of the hall.

4.3. Qualitative analysis

A qualitative analysis was conducted in order to evaluate the significance of changes in acoustic parameters resulting from alterations in the sound absorption of a particular surface. Sensitivity analysis of the parameters related to JND was performed using unnormalized regression coefficients fitted to the model described in Eq. (4). In this particular analysis, the sensitivity index was represented by the unnormalized regression coefficient b_1. It was hypothesized that the coefficient b_0 would be zero, and that for an input $\Delta A_i = 0$, the change in output parameters would also be zero. An analysis was conducted to evaluate the maximum changes in the T_{20}, EDT, C_{50}, and G_{80} parameters relative to JND, in response to the modification of the absorption for individual values of A_i (see Figs. 6 and 7).

The most significant changes in $\mathrm{JND}_{T_{20}}$ (Fig. 6a) were observed in the change of the sound absorption

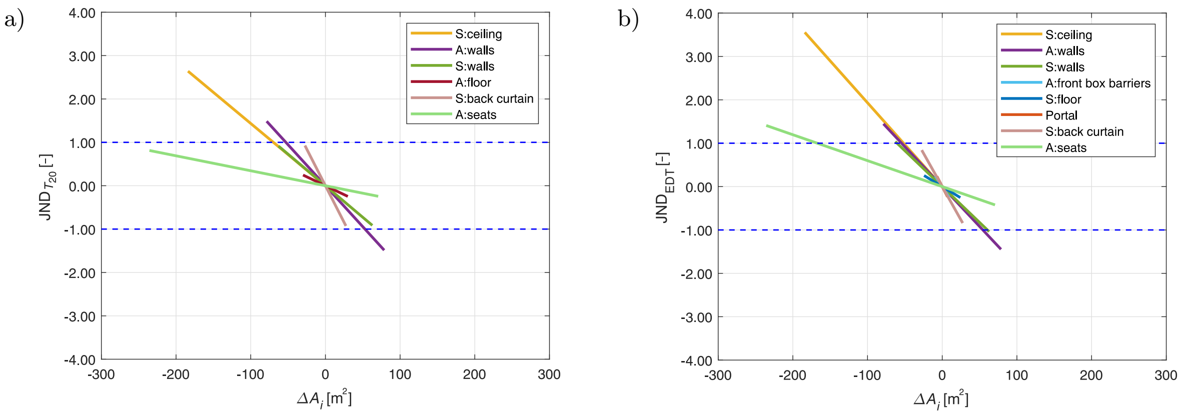

Fig. 6. Values of parameters related to the JND: a) T_{20} and b) EDT changes depending on the change in the sound absorption ΔA_i.

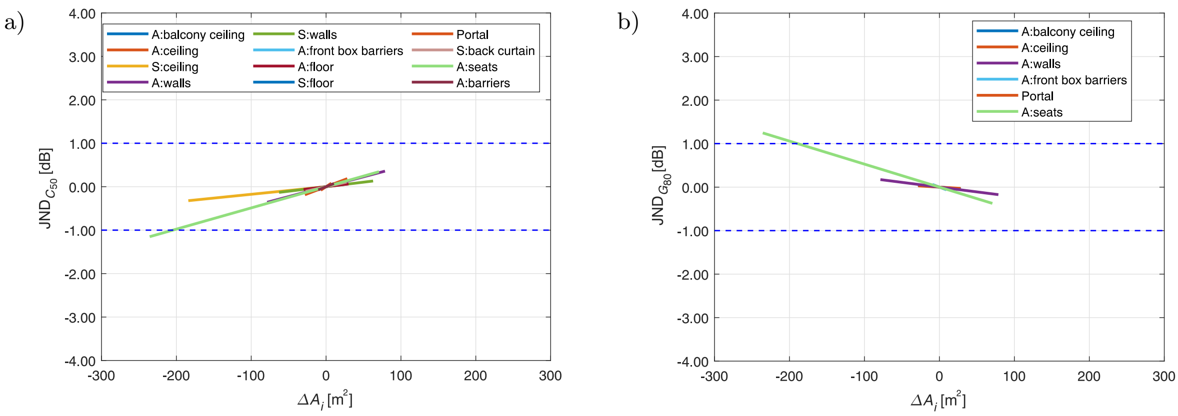

Fig. 7. Values of parameters related to the JND: a) C_{50} and b) G_{80} as a function of the change in the sound absorption ΔA_i.

of the auditorium walls and the ceiling above the stage. The range of potential JND changes for the stage ceiling is greatest, but only when absorption is reduced, leading to an increase in reverberation. This phenomenon can be attributed to the ceiling space above the stage being occupied by stage elements made of textile materials characterised by high sound absorption coefficients. Consequently, it is not feasible to achieve further increases in sound absorption. A similar effect is observed for the seating in the hall, where a substantial reduction in absorption results in an increase in reverberation time of approximately 1 JND. Conversely, modifying the sound absorption properties of the auditorium walls has the potential to either decrease or increase the reverberation time. A similar outcome can be achieved by adjusting the absorption of the rear stage curtain, although a change in the absorption coefficient of more than 50 % is required for this adjustment to significantly impact the acoustic parameters. It is important to note that enhancing the reverberation time in this hall is not desirable, particularly on stage, as it can result in a discrepancy between reverberation conditions on stage and in the audience areas. In order to achieve equal reverberation between the stage and the auditorium, consideration should be given to increasing sound absorption on the stage by increasing the absorption of the stage walls and the rear curtain.

The JND results for the EDT parameter (Fig. 6b) are consistent with those observed for T_{20}. The only significant difference is that it is possible to significantly increase the EDT time by reducing the absorption of the audience seating, for example, by using wooden seats instead of upholstered ones. However, as previously indicated, increasing the reverberation in the hall is not desirable and would not be a reasonable approach in terms of spectator comfort.

Analysis of changes in JND for the C_{50} clarity index (see Fig. 7a) reveals that a radical reduction in seat absorption can result in a significant decrease of C_{50}, potentially leading to a noticeable reduction in speech intelligibility. It has been demonstrated that alterations in the sound absorption of other surfaces do not have a significant impact on the C_{50} value. It is noteworthy that the highest sensitivity of $\text{JND}_{C_{50}}$ is observed for the auditorium ceiling, auditorium walls, and seats, which is related to the steep slopes of the lines. Nevertheless, alterations in the sound absorption for these surfaces do not result in any significant changes in $\text{JND}_{C_{50}}$. This sensitivity is associated with early reflections that reach the audience area; therefore, modifying the absorptivity of these surfaces can control early reflections and adjust the balance between early and late arriving energy.

The maximum increase in $\text{JND}_{G_{80}}$ (see Fig. 7b) is observed in cases where there is a decrease in sound absorption of the seats. As was stated in the preceding paragraph, this phenomenon is associated with early reflections reaching the seating area. It has been demonstrated that reducing seat sound absorption can result in an increase the level of early reflection, thereby increasing G_{80}. However, an increase in G_{80} results in a reduction in C_{50}. Within the context of a theatre, the acoustic parameter that appears to be of the greatest importance is C_{50}, given its correlation with speech intelligibility. For all other surfaces, altering the sound absorption results in negligible alterations to G_{80}.

4.4. Sensitivity analysis of changes in sound absorption of the audience and stage area

The subsequent stage of the research was to analyse the sensitivity of the acoustic parameters to simultaneous changes in the sound absorption of walls and ceilings in both the stage and auditorium. For this analysis, surfaces were grouped into walls and ceilings. The walls on stage comprised the side walls and the curtain on the back wall. The term 'walls' in the context of the auditorium refers to all wall surfaces and the fronts of the boxes. Similarly, the term 'ceilings' refers to the main ceiling and the ceilings beneath the balconies. The objective of this analysis was to evaluate the impact of simultaneous increases or decreases in sound absorption in each area on the key acoustic parameters. A comprehensive description of the configurations analysed is provided in Table 9.

Table 9. Description of analysed modifications of sound absorption in the stage and audience areas.

No.	Configuration	Description
1	S:↑w+c (−50 % - 0 %)	Increase the sound absorption coefficient of walls and ceilings on the stage from −50 % to 0 %
2	S:↑w (0 % - 50 %)	Increase the sound absorption coefficient of walls and ceilings on the stage from 0 % to 50 %
3	A:↑w+c (−50 % - 50 %)	Increase the sound absorption coefficient of walls and ceiling in the audience area from −50 % to 50 %
4	S:↑w (−50 % - 50 %), A:↓w (50 % - −50 %)	Increase the sound absorption coefficient of walls on the stage from –50 % to 50 % and decrease it in the audience area from 50 % to –50 %
5	S:↑c (−50 % - 0 %), A:↓c (50 % - 0 %)	Increase the sound absorption coefficient of ceilings on the stage from −50 % to 0 % and decrease it in the audience area from 50 % to 0 %
6	A:↓c (0 % - −50 %)	Decrease the sound absorption coefficient of ceilings in the audience area from 0 % to −50 %
7	S:↑w+c (−50 % - 0 %), A:↓w+c (50 % - 0 %)	Increase the sound absorption coefficient of walls and ceiling on the stage from −50 % to 0 % and decrease in the audience area from 50 % to 0 %
8	S:↑w (0 % - 50 %), A:↓w+c (0 % - −50 %)	Increase the sound absorption coefficient of walls on the stage from 0 % to 50 % and decrease it in the audience area from 0 % to −50 %

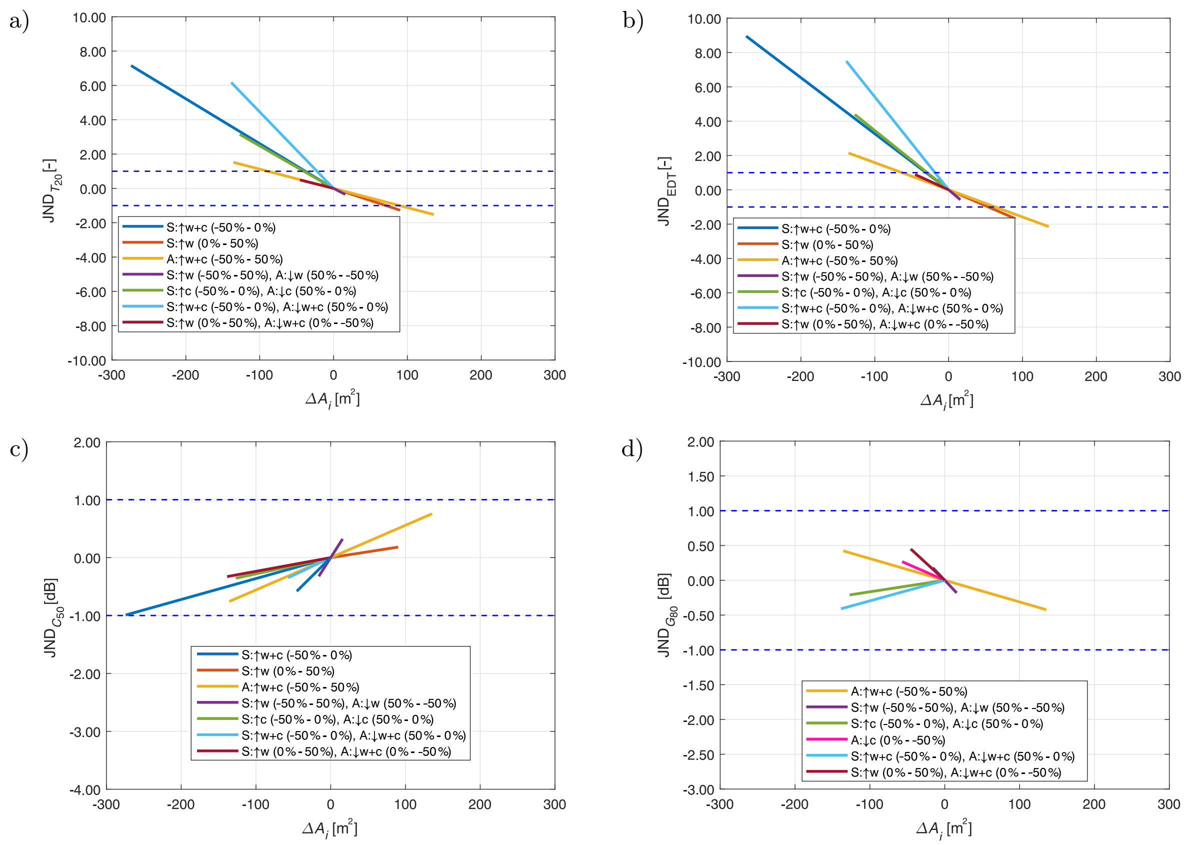

Fig. 8. Values of parameters related to the JND: a) T_{20}, b) EDT, c) C_{50}, and d) G_{80} depending on the change in the sound absorption ΔA_i.

Sensitivity analysis was performed to assess the impact of variations in acoustic parameters related to JND at specific locations, either on the stage or within the auditorium (configurations 1–3). Conversely, for configurations 4–8, the impact of sound absorption changes on the parameters was examined in both the stage and the auditorium areas (see Fig. 8). The arrows used in the descriptions are intended to indicate the direction of change in the sound absorption coefficient: an upward arrow indicates an increase in the sound absorption coefficient, while a downward arrow indicates a decrease. In the case of a stage ceiling characterised by a high sound absorption coefficient, the analysed changes in its absorption coefficient were carried out in the range from −50 % to 0 %.

The most significant changes in the T_{20} and EDT parameters relative to JND were observed for configurations 1, 5, and 7, where sound absorption on the stage walls and ceiling was reduced (see Figs. 8a and 8b). The increase in reverberation time in these configurations ranged from 4 to 10 JND. Conversely, a substantial decrease in reverberation time values, of approximately −2 JND, was observed when the sound absorption of the auditorium walls and ceiling or the stage walls was increased (configurations 2 and 3). In addition, it should be noted that increasing the sound absorption of the stage walls enables a significant reduction in reverberation time on stage and, consequently, throughout the entire hall, thereby achieving balanced reverberation conditions on stage as well as in the auditorium area.

The analysis of the C_{50} parameter (see Fig. 8c) demonstrates that a reduction in the sound absorption properties of the walls and ceiling in the stage area (configuration 1) can result in a substantial decline in speech intelligibility. Conversely, enhancing speech intelligibility can be accomplished by increasing sound absorption in the walls and ceiling of the audience area (configuration 3). Within the range of sound absorption variations examined, which not exceeded 50 %, the alterations did not rise above 1 JND. It is evident that in order to achieve a substantial modification in the C_{50} parameter, it is necessary for the change in the sound absorption coefficient to exceed 50 %.

The analysis of the G_{80} parameter demonstrates that the main factor in the alteration of early sound strength (G_{80}) is the modification of the sound absorption properties of the audience wall and ceiling (see Fig. 8d). For instance, alterations in sound absorption on the stage are not statistically significant (configuration 1), and there is no correlation between G_{80} and sound absorption. This finding serves to emphasise the negligible impact of alterations in sound absorption on the stage in terms of shaping the G_{80}

parameter. It is also important to note that even alterations in sound absorption exhibited by both surfaces do not result in a substantial change in G_{80}.

5. Conclusions

This paper presented the findings of a sensitivity analysis of selected acoustic parameters relevant to theatres halls. The surfaces and groups of surfaces that significantly influence the acoustic parameters of the hall were identified as the stage ceiling, the stage walls with curtains, the audience walls, and the seats.

The surfaces with the greatest influence on the EDT and T_{20} reverberation parameters were the stage walls and ceiling, where the majority of the sound-absorbing materials are located. The auditorium seating and side walls also had a significant impact on EDT changes. This finding indicates that EDT exhibits enhanced sensitivity compared to T_{20} in response to variations in early reflections from nearby surfaces due to modifications in sound absorption.

A substantial enhancement in speech intelligibility, characterized by the clarity index C_{50}, could be achieved by increasing the absorption of the auditorium walls and ceiling. Conversely, a significant reduction in C_{50} could be achieved by reducing the sound absorption of the seats, e.g., by removing upholstery. It is noteworthy that other surfaces, despite their relatively high sensitivity, do not have a significant effect on clarity.

In a similar manner, the value of early sound strength G_{80}, which is responsible for the perception of proximity to the sound source and also serves to assess the amplification of natural sound by the room, can be primarily influenced by reducing the absorption in the audience area, including seats, walls and ceilings.

The sensitivity analysis of the parameters also revealed that the clarity index C_{50} and the sound strength G_{80} were significantly less sensitive to changes in acoustic absorption compared to the reverberation parameters T_{20} and EDT. Increasing acoustic absorption on several surfaces did not result in a substantial improvement of these parameters. This phenomenon can be explained by the fact that there are already many existing absorbing elements in the hall, such as stage curtains or upholstered seats, which already introduce very high absorption into the hall. Consequently, the addition of absorption to the remaining surfaces results in a relatively small change in the total absorption and, therefore, does not result in a significant change in the acoustic characteristics. The potential for improving these parameters, particularly G_{80}, could be achieved by modifying early reflections, e.g., with appropriately placed reflective panels and scenery elements.

In conclusion, it is also worth noting that the research results obtained for the Maria Zankovetskay Theatre in Lviv can be generalized to other theatres with classical stage and auditorium layouts. This is especially applicable to theatres with a tower stage, which is characterized by a much larger volume than the auditorium area. In such theatres, the primary challenge in shaping the reverberation of the interior is to ensure a balance between the stage and auditorium areas. Conversely, when evaluating the parameters of speech intelligibility and the amplification of sound transmission within the auditorium, proper management of early sound reflections becomes important.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contribution

The authors contribution is as follows: Jarosław Rubacha – conceptualization, methodology, data analysis, writing the manuscript; Adam Pilch – development of a numerical model, numerical data analysis; Roman Kinasz – supervision, research organization, funding acquisition, manuscript review; Wojciech Binek – measurement and data analysis, verification of the numerical model; Tadeusz Kamisiński – supervision, results analysis, manuscript review; Mykhaylo Melnyk – measurement and data analysis. All authors reviewed and approved the final manuscript.

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