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Optimization-based method for the calibration of geometrical acoustic models

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ABSTRACT

Uncertainty of the final results of room acoustic modelling is a result of uncertainties of many model input parameters, which have to be discovered and limited if possible. It can be done by model calibration. In this paper, a detailed procedure of room acoustic model calibration is proposed. It is based on detection and limitation of possible sources of discrepancies between measured and simulated selected room acoustic parameters defined in ISO 3382-1 standard. As independent parameters which describe the variability of the acoustic field in the room the most accurately, clarity C_{80} and early decay time *EDT* are suggested. Based on uncertainty analysis, sound absorption coefficients of all materials used in the interior and selected sound scattering coefficients as well as positions of the receivers are chosen to be input parameters adjusted in the model calibration process. Correction of these parameters is done using optimization algorithms in order to accelerate the procedure. Methods for choosing key ray-tracing simulation parameters are presented, according to which it is possible to obtain repeatable results in the shortest possible time. All analyses are done for five different interiors (three philharmonics and two churches). Correctness of sound absorption/scattering coefficients calculated in the calibration process is validated in the comparison of simulation and measurement results, using a different sound source position. Obtained results are specific for analysed rooms, but proposed methodology is universal for all kinds of room acoustic models.

1. Introduction

Modern design of an acoustically qualified room is based on numerical models. For complicated shapes analysed above Schroeder frequency [1], geometrical acoustic methods are usually used, since they provide reliable results with reasonable computational cost. An acoustic model includes information about geometry of the interior and acoustic properties of the materials on all surfaces, as well as physical conditions of wave propagation. By locating sound source and receivers with given parameters (coordinates, directional pattern) inside the room, it is possible to calculate acoustic properties of the interior. However, the uncertainty of input model parameters propagates to the results of the simulations. For existing objects, in order to increase the reliability of modelling results, the measured values of room acoustic parameters can be used for the calibration of the model. Model calibration is the process of adjusting model parameters within the range of their uncertainties in order to obtain a model representation that satisfies pre-agreed criteria [2]. Calibration is especially useful in renovation projects, where only chosen structures in existing rooms are replaced (for example chairs in a theatre). The better the agreement between the results of a simulation and measurements of an object's initial conditions, the more precise the prediction of the acoustic parameters of the room after renovation. Close matching of the model and reality is also important for auralization, where every single material can change impression of the listener [3–5]. Properly calibrated model is also crucial in inverse problem solving, where only close coherence of a real room with the model allows the calculation of sound absorption coefficients of materials [6].

The compliance of the model with the measurement can be achieved by recognizing discrepancies between model and measurement results and limiting their sources. Most of them are connected with uncertainty of modelling real objects' parameters and physics as a finite set of input parameters and algorithms which shape the acoustics of the modelled space, described by the output parameters. These output parameters (room acoustic parameters) used as a coherence criterion of simulation and measurement results should be sensitive to input parameters, repeatable and resilient to parameters not included in the analysis. Frequency dependence is also crucial, since most of the input parameters depend on a frequency. Sound absorption and sound scattering

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coefficients of materials are widely recognised sources of uncertainty in room acoustics modelling [7]. Another important factor is imperfect omnidirectional character of the sound source [8,9]. Atmospheric conditions and the way of analysis of the received signals should also be mentioned as a source of discrepancies between model and the measurements results [10]. Exact positions of the sound source and receivers, as well as their vicinity, can also impact the results [11]. Apart from parameters connected with the physical object, purely numerical parameters are also important. Setting unsuitable simulation parameters also leads to errors in results due to simplification of physical phenomena.

Having defined properly the input and output parameters of the model with uncertainties significantly influencing the modelling and measurement results, as well as validating room acoustic modelling algorithm, it is possible to achieve a set of input value corrections, which provide required consistency between model and measurement results. It is possible to be done by repeating simulations many times with a defined way of changing input parameters. Usually, the correction is done manually. Using optimization algorithms helps to automatize calibration process, which speeds up the procedure and allows obtaining better consistency between simulation and measurement results.

In the paper a detailed procedure of geometric acoustic model calibration is proposed. Analyses are made for selected room acoustic parameters defined in ISO 3382-1, based on variability of their spatial distributions and correlations with each other (par. 3.2 and 4.1). Optimization search space (model input parameters) is defined based on uncertainty analysis (par. 3.3 and 4.3). Modified outlier analysis is proposed to exclude receiver points biased with gross error. Calibration was done for five different rooms. Validation of the calibration results (set of the model input parameters best matching to the measurement results) was done by comparing objective functions calculated for measurement and simulation results obtained for another sound source position (par. 3.7 and 4.7).

2. Geometrical acoustic model

2.1. Uncertainty of model input parameters

Most important and problematic are the uncertainties of acoustic properties of surfaces in the model (materials). In room acoustics, two most important ones are: sound absorption coefficient defined by Sabine [12], and sound scattering coefficient defined by Mommertz [13]. In spite of more than 100 years of using sound absorption coefficient, it is still not accurate enough. Even laboratory measurements give wide spectrum of results while measuring the same material [7,14,15]. It is mainly caused by different geometries of reverberation chambers, with not perfectly diffused sound field. Jeong has even proposed a correction for reverberation chamber measurements of sound absorption coefficient in order to obtain a better consistency amongst different measurement facilities and with analytical calculations [16]. In real rooms, not perfectly diffused sound field impacts acoustic material performance even more. In diffuse sound field, the sound waves hit all the points of the structure with the same probability from all the directions and all the surfaces in the room are hit with the same probability. In reality, for low frequencies, where the modal density is not sufficient, the pressure distribution of an incident wave is not uniform. What is more, for complicated geometries, especially with many surfaces located on the way from the sound source to the receivers, the points located far from the sound source are hidden from the sound source and less sound waves hit them. Sound absorption coefficient depends, amongst others, on the size of the sample [17,18], the way of mounting [19] and the sound waves incident angle. ISO 354 standard measurement idealizes natural acoustic conditions in a room, so changing diffuse sound field in the reverberation chamber to non-uniform characteristics of in-situ conditions will induce changes to the performance of the material. Apart from that, the properties of materials used in rooms are changing over the years [20], so even if precise construction is known, sound absorption coefficient can be given only with a significant uncertainty.

Sound scattering coefficient and its influence on room acoustic parameters is much less recognized [6,21–23]. Most of the authors agree that scattering phenomenon should be modelled, while its influence on the results must be checked individually for every room.

Another source of discrepancies between the model and in-situ measurements results are the positions of receivers and sound source. Firstly, the coordinates of the receivers and the sound source are biased by measurement error. As it was shown in [11], even small change in receiver position (less than 0.5 m) can change sound clarity C_{80} above the threshold of perception. Moreover, in ray tracing simulations, where rays represent waves and specular reflection is simulated by one narrow ray, it is possible, that some rays which should hit the receiver, miss it slightly. Spherical receivers approximately twice as big as a human head (radius 0.31 m versus radius 0.18 m) are used in ray tracing simulations to reduce this problem. Nevertheless, it was observed that changing the position of the receiver slightly can improve the results [23]. As a result, it is possible that for each frequency a different position of the sound source and the receiver is required, only because of different reflection patterns for frequency-independent ray tracings.

Apart from the sound source position, its imperfect omnidirectional pattern can also introduce uncertainty of the measurement results, as it was described in [9,24]. In order to reduce this effect, ISO 3382 standard recommends averaging the values obtained for at least three different angles of a sound source. Exact angle position sequence, which helps to obtain the most representative averaging is suggested in [25]. The author suggested that the receivers closer to the sound source are susceptible to changes of the sound field connected with the angle position of the sound source. The highest variations were observed for C_{50} and C_{80}. In [8] the authors obtained small standard deviations for all parameters connected with reverberation, while in [25], significant variation of *EDT* was observed.

2.2. Ray tracing simulation parameters

In ray tracing modelling, the simulations must be conducted with high repeatability and without any systematic error. The most important random error decreasing repeatability is caused by simplification of physical phenomena due to insufficient number of rays in the simulations. Ray tracing method uses finite number of sound rays sent randomly in all directions from the sound source. Directional pattern of the sound source determines spatial probability of rays distribution. Rays generated in random direction from the sound source are reflected from surfaces in a specular way according to the Snell's law. Some part of the reflected energy is scattered in random direction according to the scattering coefficient fraction. This also decreases repeatability of calculations. For small number of rays and not highly diffused sound field, each calculation gives different results. The requirement suggested by Rindel, that all surfaces are hit by at least one ray [26] can be insufficient for analysing all receivers independently, especially for hardly scattering surfaces, where a lot of strong reflections hit the receivers.

For rooms where highly absorbing materials are used, the energy of a ray is dampened to a negligible fraction of the initial energy before reaching a receiver located far away from the sound source, so its energy can be ignored. On the other hand, when walls are highly sound reflecting and the geometry of the room is complex, there are highly energetic rays that hit the receiver after a very long time, without influencing any important parameters of the sound field in a given place. Tracing the "lost" rays with long paths is very computationally expensive and has no impact on the results. On the other hand, setting the ray truncation time to too short results in deleting important rays and reducing the acoustic energy in the second part of the impulse response and as a result introduces systematic error. ISO 3382 standard recommends using measurement signals longer than at least ¾ of estimated reverberation time. Commercial measurement software recommends values longer than reverberation time [27]. In ray tracing software, values from 2/3 [28,29] to 1/1 [30] of the longest estimated reverberation time are suggested.

2.3. Description of the acoustic field

There are many parameters describing the acoustic field in a room defined by acousticians. The most important ones are defined in ISO 3382-1 standard. In the model calibration process, only parameters sensitive to changes of model input parameters can be used. What is equally important, parameters describing acoustic field should be unambiguous: assuming no errors neither in numerical simulation, nor in the acoustic measurement methods, there should be only one set of model input parameters for which selected model's descriptors is equal to measurement results.

The simplest and most popular way of obtaining good consistency between model and measurement results is to compare mean value of reverberation time (averaged over all measurements point for each frequency separately [31]). This solution gives information about the total acoustic absorption in the room, but does not reflect the distribution of different materials over the room. The comparison of spatial distributions of measured and simulated room acoustic parameters gives better information and it was a basis for the most of the calculations in this paper. The model output parameter chosen for analysis should:

- be well defined and easily calculated from the impulse response/echogram without additional calibration or equipment required,
- be frequency-dependent,
- vary over the room (wide range of values over different measurement positions).

The output parameters should be also connected with the function of the room and the use of the model results. For auditorium, parameters defined for speech should be used (for example C_{50}, Table 1), while for a concert hall, parameters connected with music perception are more suitable (for example C_{80}). If the model calibration is done for renovation purposes, energetic parameters should be used (reverberation times, G, C_{80}). For auralization using binaural signals, interaural cross correlation IACC was suggested [32]. For industrial noise and classrooms, sound pressure level is important [22,33]. Apart from ISO 3382-1 parameters, different ones can also be used, like for example shape of a decay curve [6]. In this approach, the interpretation of results is more difficult, as just noticeable differences (JNDs) for decay curves do not exist.

If more than one parameters are used, they should be non-correlated. Averaging correlated values would decrease differences between measurement and simulation and could lead to overoptimistic results [35]. However, comparing the results for different parameters requires defining JND for each of them in order to unify the units.

Table 1
Room acoustic parameters used in the paper according to ISO 3382-1 with symbols and just noticeable differences (JND).

Parameter name	Symbol	Just noticeable difference (JND)
Reverberation time based on 10 dB evaluation range	*EDT*	5%
Reverberation time based on 20 dB evaluation range	T_{20}	5%
Reverberation time based on 30 dB evaluation range	T_{30}	5%
Clarity (speech)	C_{50}	1 dB
Clarity (music)	C_{80}	1 dB
Sound strength	G	1 dB
Speech transmission index	STI	0.03 [−] [34]
Interaural cross correlation	IACC	0.075 [−]

3. Methods used for the automatic model calibration

General algorithm of the model calibration procedure is presented in Fig. 1. All calculations were done in two environments: definition of the model and ray tracing were made in I-Simpa software. Then, the echograms were exported to Matlab for the calculation of room acoustic parameters (e.g. reverberation times T_{20}, *EDT*, clarity C_{80}). Matlab was also used for all the calculations connected with optimization process. I-Simpa is an open source ray tracing software [36]. Its main advantage is that it can be run from a command line with a given set of input parameters.

Data flow diagram of proposed calibration procedure includes model preparation, optimization and validation. Model input parameters, like geometry, acoustic properties of materials and locations of sound source and receivers were used to define the numerical model in I-Simpa. Based on uncertainty analysis of model input parameters the main part of the calibration started. Correction of the selected model input parameters was done in order to minimise the difference between simulation and measurements results. Automatisation of the main part of the procedure was possible thanks to optimization algorithms. From acoustic measurements results only C_{80} and *EDT* are used for final objective function because of the correlation and variation analysis. Results from the sound source position S1 are used for model calibration, while the second sound source position (S2) is used for the validation of calibration results (best sound absorption and scattering coefficients).

3.1. Analysed rooms

In order to check the proposed method, five different models were calibrated (Table 2) using the first sound source position S1. The geometries of the analysed rooms are presented in Fig. 2.

For all interiors, acoustic measurements were made according to ISO 3382-1 requirements [37]. Omnidirectional sound source B&K4292-L located 1.5 m above the floor was placed in two different locations characteristic for the sound sources used normally in analysed object. As receivers, GRAS 46AE microphones were used, placed 1.2 m above the floor in at least as many positions as pointed in Table 2. Receiver positions were equally distributed over audience area. For every sound source and receiver position the most important ISO 3382-1 acoustic parameters were calculated from impulse responses: reverberation time, early decay time, clarity and speech transmission index.

Numerical models of rooms reflect real interior geometries, absorption and scattering coefficients of materials and sound source/receiver positions. In the simulation the same ISO 3382-1 acoustic parameters were calculated from ray-tracing echograms.

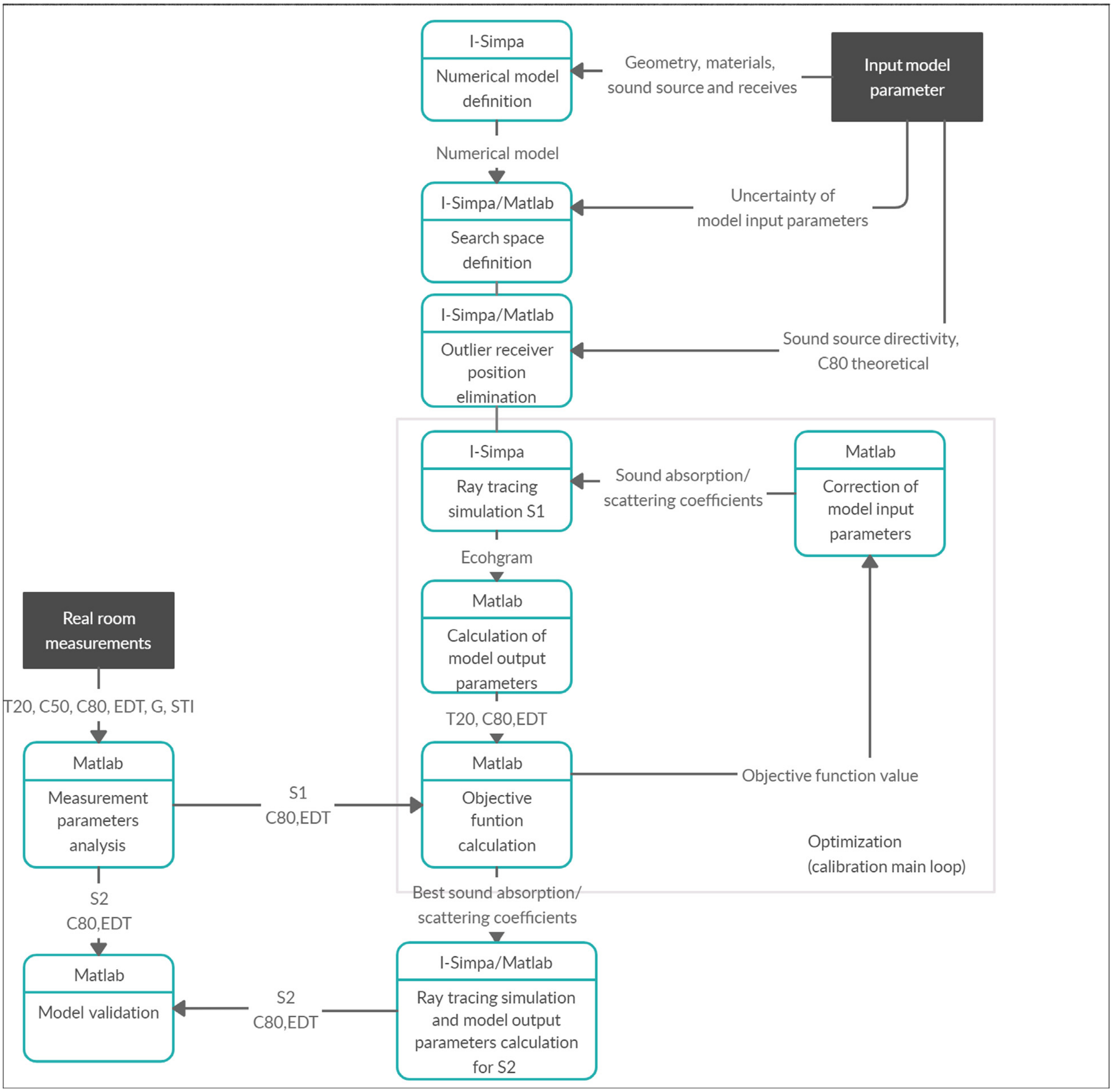

Fig. 1. Algorithm of the room acoustic model calibration procedure. Process boxes are supplemented with environment information (Matlab/I-Simpa).

Table 2
Main information about the analysed rooms.

Room name	Abbreviation	Volume, m^3	Number of different materials	Mean (500–1000 Hz) reverberation time T_{20} (measured), s	Number of receiver positions
Krakow Philharmonic	PK	6900	6	1.96	15
Podkarpacka Philharmonic	PP	7000	7	1.54	16
Lodz Philharmonic	PL	7600	9	1.57	26
Church in Tychy	CT	4700	5	4.53	6
Church in Warsaw	CW	16,200	6	7.19	12

Results from one of the sound source positions were used for the model calibration, while the second sound source position results were used for the validation of the obtained input model parameters.

In real rooms the number of different materials used in the tested interiors were usually higher than presented in Table 2. Two different ways of reduction of material number were proposed. Only the materials that cover a substantial area were included in the optimization process. What is more, if the sequence of different materials repeated in a room, the whole sequence was taken in the optimization process and was considered to be one material. For example, in case of Podkarpacka Philharmonic, the ceiling consisted of three different materials, but their distribution was homogeneous so they were treated as one material of aver-

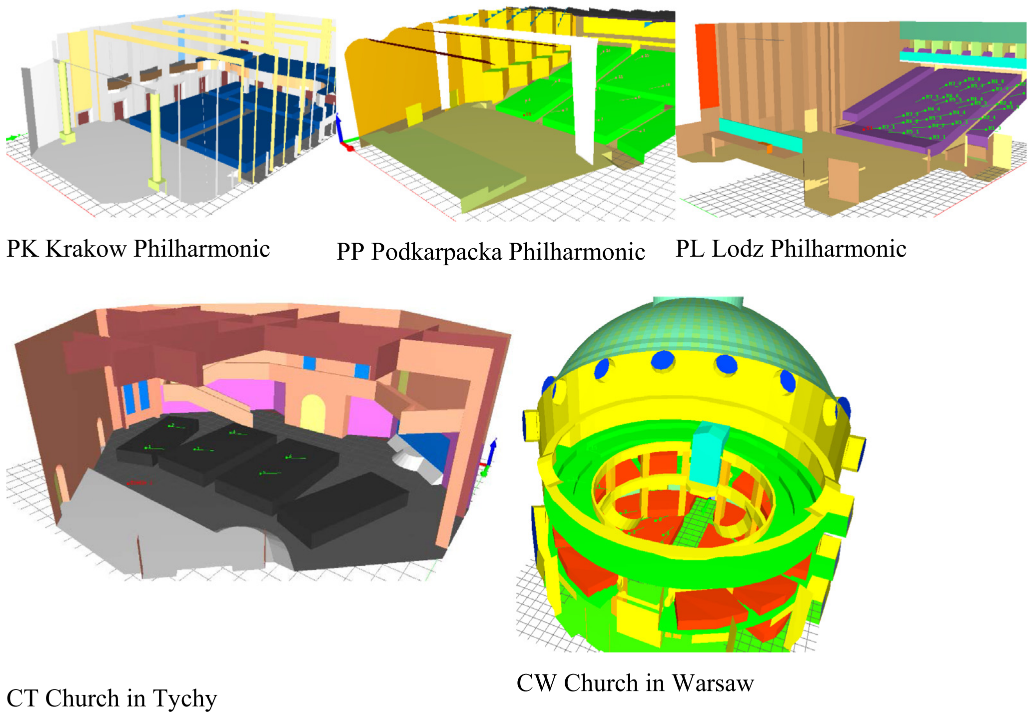

Fig. 2. Geometric acoustic models used for proposed procedure validation. Details of rooms are presented in Table 2.

aged acoustic parameters. It reduced the number of variables without decreasing the accuracy of the results. For Krakow Philharmonic, the total area of doors was insignificant, so it was omitted in the optimization process. As a result, the search space was reduced without changing the final results.

3.2. Selection of the room acoustics parameters

Choice of the measurements and simulation parameters describing acoustic field of the real room which is compared with the numerical model is one of the most important decisions that influence whole calibration procedure. These parameters should depend on the required accuracy of the model and its function: the calibration procedure proposed in the paper is conducted for the renovation purposes of rooms connected with music, so energetic parameters were proposed (see par. 2.3). Calculations were done for each frequency band independently, so frequency-independent parameters like STI were not considered.

In order to check the variability of parameter spatial distribution amongst different receiver positions, standard deviation for each frequency band was calculated for every acoustic measurement results. Parameter with the highest value were proposed to be used in the calibration procedure. Selecting only one room acoustic parameter can simplify the complexity of the acoustic field too much. It was proposed to use a second parameter, with low correlation with the first one and which also has significant variability over different receiver positions. In order to simplify operation on different acoustic parameters with different units, all results were converted to just noticeable difference (JND) scale according to ISO 3382-1 standard ranges given in Table 1.

3.3. Verification of sources of room acoustics parameters uncertainty

As it was stated in paragraph 2.1, there are many input model parameters whose uncertainties impact room acoustics (output model) parameters uncertainty. In order to simplify the calibration process, only parameters with uncertainty of substantial influence on simulation/measurement results have to be taken into consideration. Different factors create measurement and simulation uncertainty of results. Normally, in the ray-tracing method a perfectly omnidirectional sound source is used. However, in order to simulate the measurement conditions better, the sound source used in the simulations in this research had a directional pattern of a real sound source used for the measurements.

The calculations/simulations were performed for five different values of each input model parameter, spread equally in a reasonable range. During this computations all other parameters were locked. Maximum values of absolute differences between the results for a given parameter were calculated for every receiver. The change of a single output parameter (e.g. *EDT*) is multidimensional – for each room different values were obtained for every frequency band and every receiver. The values for all frequency bands and all receiver positions for a single room and single input parameter were treated as a one subset. All results were converted to the JND scale in order to unify the units. The parameter was included in the calibration search space for a given room if at least for 10% of receiver positions a change above 1 JND was observed.

Results simulated numerically or measured in some receiver points are biased with significant uncertainties caused by factors which cannot be defined in a specific range or cannot be defined at all. It was proposed to exclude those outliers from the calibration process.

The proposed procedure of search space definition can be done for all kinds of rooms. The ranges of input parameters proposed below should be set arbitrarily according to the type of a material and the experience of the measurement team.

3.4. Input parameters with defined range of uncertainty

One of the most important material parameters with significant uncertainty is sound absorption coefficient. It is directly connected with energetic parameters of the model by for example Sabine's equation [12], so it was supposed to have the most impact on the output model parameters. The uncertainty range for sound absorption coefficient (lower and upper constraints in model calibration) depends not only on a type of the material, but also on frequency. For low frequency bands, especially in case of audience, significant discrepancies are observed between the results of laboratory and in-situ measurements [38]. That is why in some cases lower and upper constraints should be set independently for each frequency band. Base values of absorption coefficients were taken from the literature. Ranges for different materials corrections were set by the following rules:

- for known materials with high absorption coefficients: +/−25%,
- for materials with low absorption coefficients (plaster, stone etc.): −50%, +200%,
- for chairs/banks/audience: +/−50% for 125 and 250 Hz, +/−25% for higher frequency bands.

On the other hand, the second most important material parameter – scattering coefficient is not directly connected with any of the output model parameters. The relation is individual for each geometry, sound and receiver positions and distribution of the materials. This is why for every model and every material, sensitivity analysis was performed individually. With scattering coefficients taken from the literature [39–41], for every room model $2n$ calculations were made, where n is the number of different materials used in the room. Every material's scattering coefficient was set independently to +/−50% of the base value for every frequency band.

Air temperature and its relative humidity influence air absorption parameters, so an error in the input value of temperature or relative humidity can cause uncertainty of the final results. From the base value (temperature: 20 °C, humidity: 50%) the following ranges were proposed: +/−2 °C and +/−5%.

Uncertainty of the receiver positions and uncertain influence of surfaces close to the receivers on the final results were included in the search space as a multiplication of every receiver in the close neighbourhood of the original position. 45 additional receivers around every original receiver were located on two spheres with the centre located 0.10 m higher than the original point with the radius 0.15 and 0.30 m (Fig. 3).

The uncertainty range of the sound source position was set to +/−0.50 m in three perpendicular directions (X,Y,Z) from the initial point. It was not possible to use a similar procedure like in the case of the correction of the receivers positions, because from every position of the sound source, the ray tracing has to be done individually.

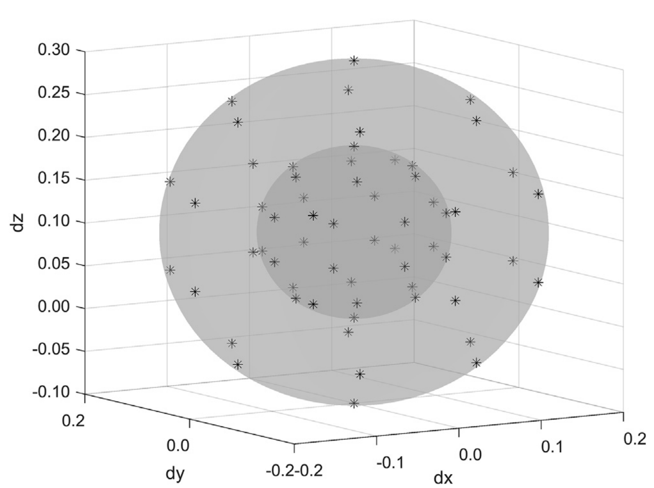

Fig. 3. Additional points created for every measurement position. The most complex case is presented (45 additional points located on two spheres with radius 0.15 and 0.30 m).

3.5. Other sources of uncertainty

It was impossible to describe and check the influence of all input parameters on the model results. It was important especially for singular receiver position analysis, where significant random error was probable on both simulation and measurement side. In order to help to protect the calibration process from this kind of errors, receiver positions with excessive uncertainty generated by parameters which cannot be included in the calibration search space were found and excluded from the measurement and simulation results.

Sound source not perfect omnidirectivity is a quite well defined source of uncertainty in the measurements of acoustic parameters. In order to check the uncertainty caused by non-omnidirectional character of dodecahedron, 3D sound source directivity characteristic of dodecahedron used in real room measurements was applied in the ray tracing simulations. The dodecahedron met ISO 3382-1 standard directional characteristics requirements. The simulations were repeated for 15 different angle positions of the sound source in the range of 0–72°. The reduction of this range was possible due to the symmetry of the sound source directional pattern. Standard deviations of single energetic room acoustic parameters (EDT, C_{50}, and C_{80}) were calculated for all receiver position separately (over all the angle positions of the sound source). Percentage of receiver positions for which standard deviations were above 0.5 JND were analysed. These values were calculated in order to compare obtained results with values from [8]. The mean value of energetic parameters (EDT and C_{80}) as a function of the distance from the sound source (expressed in a critical distance) was also investigated.

To exclude measurement outlier receiver points biased with a significant error caused by other factors, difference between measured sound clarity C_{80} and its theoretical value was proposed as an indicator. C_{80} theoretical values proposed for a perfectly diffuse acoustic field were calculated based on reverberation time T, distance from the sound source to the receiver r, and the volume of the room V [42]:

$$C_{80} = 10\log\left(\frac{d+e_r}{l}\right),$$

$$d = \frac{100}{r^2}, e_r = \frac{31200}{V}\exp\left(-\frac{0.04r}{T}\right)\left(1-\exp\left(-\frac{1.11}{T}\right)\right), \qquad (1)$$

$$l = \frac{31200T}{V}\exp\left(-\frac{0.04r}{T}\right)\exp\left(-\frac{1.11}{T}\right).$$

Medians of differences between theoretical and measured values were calculated for all receiver points in a given room. Results within six medians range (set arbitrarily in the reference to basic outliers analysis, where points outside six standard deviations range are excluded) were accepted for the model calibration.

3.6. Choice of ray tracing simulation parameters

The most important simulation parameters in the ray-tracing method are: the time of ray tracing (ray truncation time) and the number of rays sent from the sound source. Both of them impact the total computation time and the accuracy of the results (see par. 2.2). Average value of EDT and C_{80} differences between simulation and measurement results, selected based on par. 3.3, were chosen as an indicator of the model fidelity.

The analyses were done for ray truncation times between 30% and 100% of the longest measured reverberation time of a given room with 5% step. For each step, the calculations were repeated 15 times, which allowed the calculation of mean value and confidence interval. Differences between measurements and simulations were examined independently for each frequency band. Assuming that too short simulation time would cut echogram significantly and introduce systematic error to the results, the results obtained for too short truncation times were excluded. Finally, ray truncation time was set to the minimum percentage value of the measured reverberation time, according to the following criteria in the reference to the results obtained for the measured reverberation time:

- result averaged over all receiver positions cannot differ by more than 0.2 JND,
- confidence intervals of the results obtained in the subsequent calculations should match in at least 90%.

Finite number of rays used in the simulation introduces random error to output model parameters. Since in the calculations the results for all the points were important (not only the mean value), all points and all the frequency bands were verified. General criterion was applied that the number of rays should be enough to allow over 90% of receivers to have standard deviation (in 15 calculation repetition) below 0.5 JND. Points with high variability of results over successive calculations were excluded from the calibration process.

3.7. Optimization algorithms

The calibration search space defined basing on uncertainty analysis (see par. 3.3) was explored automatically using optimization algorithms. Output model parameters (room acoustic parameters – par. 3.2) are not linearly dependent on input model parameters. In geometrical acoustics this relation cannot be expressed by any equation like in statistical acoustics, so it cannot be differentiated. That is why a non-linear optimization was considered. Three different optimization algorithms were compared: Particle Swarm Optimization (PSO), Differential evolution (DE) and Genetic algorithm (GA). Acceleration coefficients for PSO c_1 and c_2 were set to 1.5 and 2.0 respectively, with inertial coefficient $w = 1.0$. DE algorithm was run with amplification factor $F = 0.8$ and crossover probability $CR = 0.7$. Optimization based on genetic algorithm was made with mutation probability $\mu = 0.3$ and crossover probability $CR = 0.7$. The parameters of algorithms were chosen according to literature suggestions. In the calculation freely available Matlab codes were used [43–45]. To accelerate the process, at one run of the ray-tracing algorithm, six different sets of values (acoustic parameters for each receiver) for six frequency bands were calculated, taking into account six different sets of absorption/scattering coefficients. The optimization codes were adapted to this process making parallel calculations for different frequency bands possible.

All optimization algorithms used are based on natural behaviour of animals and are designed for non-linear problems. The difference is mainly in creating a new population based on obtained results. The number of population members (sets of absorption/scattering coefficients for all materials) for all tested algorithms should be at least ten times the number of variables. Such a high number requires very long calculation time. This is why the possibility of reduction to two times the number of variables was analysed. In all cases, the number of iterations was the same as the number of variables.

3.8. Choice of the optimization objective function

The objective function was defined for the calibration procedure in order to translate selected model output parameters (according to par. 3.2) measured and simulated in many different receiver positions to a single-value indicator for a given frequency band.

In order to compare proposed calibration procedure with manual calibration made usually by acousticians, mean reverberation time T_{20} difference between simulation and measurement results was calculated:

$$J_1 = \frac{1}{n_r}\sum_{i=1}^{n_r}\left(\frac{T_{20}{}_{\mathrm{meas}}^{\,i} - T_{20}{}_{\mathrm{sim}}^{\,i}}{5\% * T_{20}{}_{\mathrm{meas}}^{\,i}}\right), \tag{2}$$

where n_r stands for number of receiver positions in the room, $T_{20}{}_{\mathrm{meas}}^{\,i}$ and $T_{20}{}_{\mathrm{sim}}^{\,i}$ for value measured and simulated in the room, respectively, in a given position i. 5% in the denominator was used to convert measurement and simulation results to just noticeable difference scale according to values given in ISO 3382-1 standard.

In the next step, the distributions of single output parameters (instead of averaged value) were checked. Squared differences between measurements and simulations were averaged over all measurement positions, for example:

$$J_2 = \sqrt{\frac{\sum_{i=1}^{n_r}\left(\frac{T_{20}{}_{\mathrm{meas}}^{\,i} - T_{20}{}_{\mathrm{sim}}^{\,i}}{5\% * T_{20}{}_{\mathrm{meas}}^{\,i}}\right)^2}{n_r}}. \tag{3}$$

In the last step, combinations of different parameters distributions were examined. For early decay time EDT and clarity C_{80} case, the results were calculated as follows:

$$J_3 = \left(\sqrt{\frac{\sum_{i=1}^{n_r}\left(\frac{EDT_{\mathrm{meas}}^{i} - EDT_{\mathrm{sim}}^{i}}{5\% * EDT_{\mathrm{meas}}^{i}}\right)^2}{n_r}} + \sqrt{\frac{\sum_{i=1}^{n_r}\left(C_{80}{}_{\mathrm{meas}}^{\,i} - C_{80}{}_{\mathrm{sim}}^{\,i}\right)^2}{n_r}}\right)/2 \tag{4}$$

where "meas" and "sim" subscripts stand for measurements and simulation results respectively. Just noticeable difference (JND) for EDT is the same as for T_{20} and introduces 5% to the denominator in the first sum, while JND for C_{80} is 1 dB (according to Table 1), so the conversion from dB to JND scale was done without any additional calculations. Root mean squared error (RMSE) of differences instead of average absolute value of differences was calculated to increase the objective function results of J_2 and J_3 for values above 1 JND, and decrease it for values between 0 and 1. Then, the errors which can be made when the chosen objective criterion is too easy to be fulfilled were analyzed. From the set of all objective function values J_3, a subset fulfilling the criterion usually set for a manual model calibration (value J_1 below 1 JND for every frequency band) was created. This subset was compared with J_3 values fulfilling the criterion proposed for automatic model calibration (J_3 values below 1 JND for every frequency band).

3.9. Validation of the results

ISO 3382-1 standard requires the measurement of acoustic parameters for at least two sound source positions. Every ray-tracing simulation made from another sound source doubles the simulation time, so it was decided to use only one sound source position in the calibration process. Measurement results obtained in the second sound source position were used for the validation process. Using absorption and scattering coefficients (member) giving the best (the smallest) objective function value J_3 for the first sound source position, the calculations were repeated for the second sound source position. Theoretically, it is possible that some combinations of absorption and scattering coefficients giving low objective function for the first sound source position are not optimal for the second sound source position. In this case, the set of absorption/scattering coefficients of materials obtained in the optimization is not satisfactory. This is why at validation stage several calculations were done for each member giving local minimum in the main optimization loop. As a result of the whole calibration procedure, we chose sound absorption and scattering coefficients (member) which provided the best (the smallest) value of objective function averaged for sound source positions S1 and S2.

4. Results

4.1. Room acoustic parameters analysis

As it was stated in par 3.2, it is essential to use spatial distributions of parameters to calculate proper distributions of material properties. As different acoustic parameters are defined in different units, all of the measured and calculated values were divided by just noticeable differences (JND) defined in the ISO 3382-1 standard (Table 1), which enabled inter-parameter comparison and calculations.

The lowest standard deviation of the distribution was calculated for STI parameter (Fig. 4). The changes of this parameter over the room were very small, so it did not reflect properly the distribution of materials in the room. The highest standard deviations of distribution of parameters were calculated for C_{80} and G. Reverberation times T_{20} and T_{30} variabilities were comparable. Because sound strength G requires additional calibration, C_{80} was selected for the correlation analysis of different parameters (Fig. 5).

All values were converted to just noticeable difference (JND) values and averaged over frequency bands in 125–4000 Hz range. Clarity is mostly correlated with sound strength G, and speech transmission index STI. For all rooms, values were over 0.5 with maximum correlation 0.92 between C_{80} and G for Church in Tychy distributions. Parameters describing reverberation time have similar correlations with C_{80} – all values were in the range between 0.1 and 0.3.

Based on both variability of spatial distributions and correlation analysis, clarity C_{80} and early decay time EDT parameters were chosen as the most important indicators of the consistency between measurements and computer simulations. Mean value of these parameters calculated for every receiver position was an indicator for uncertainty analysis. Mean value of RMSE of this parameters was used as an objective function for final optimization algorithms (J_3).

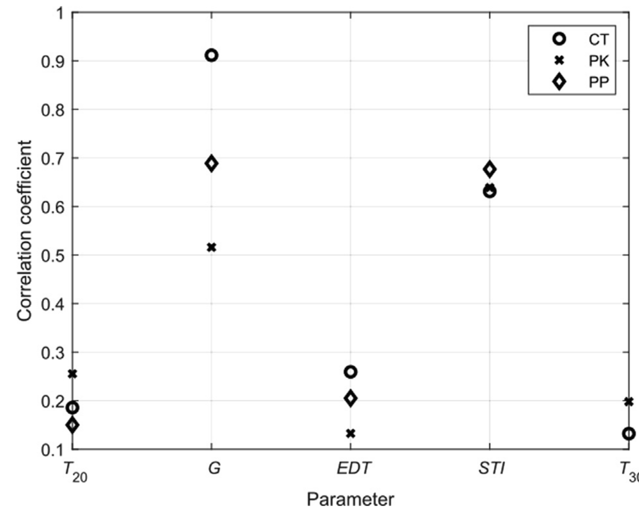

Fig. 5. Correlation of different acoustic parameters distributions (defined in Table 1) with C_{80} parameter averaged across 125–4000 Hz range for Krakow Philharmonic (PK), Church in Tychy (CT) and Podkarpacka Philharmonic (PP). Remaining rooms with similar values were excluded from the Figure for a better clarity.

4.2. Model sensitivity to input parameters uncertainty

Sensitivity of the room model to input parameter uncertainties was checked in order to include in the calibration process only those parameters whose uncertainties have substantial influence on the output model parameters. Results for three Philharmonics buildings are presented in Table 3. Median and 90th percentile of differences of mean value of C_{80} and EDT were calculated from the subset of all frequency bands and receivers positions (see par. 3.3). For two analysed churches the results were similar, but different acoustic materials were used there, so it was not possible to compare it with the values obtained for philharmonics.

Absorption coefficients of materials have the biggest impact on the output model parameters. Because of the biggest surface area and high uncertainty of absorption coefficients α of materials on the walls, the changes of this materials' α had the biggest impact on every analysed model's results. Ceiling, as the second biggest area located near the audience, also had a significant influence

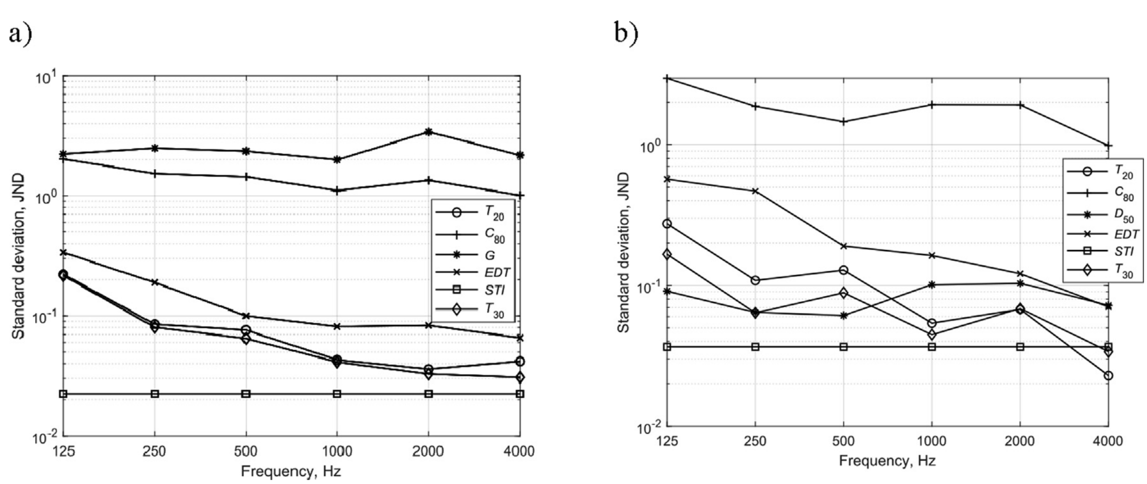

Fig. 4. Standard deviation of different acoustic parameters distributions for Krakow Philharmonic (a) and Church in Tychy (b). T_{20}, T_{30} – reverberation time, C_{80} - clarity, D_{50} – definition, EDT – early decay time, STI - speech transmission index. All values expressed in just noticeable difference (JND).

Table 3
Impact of input parameters changes on maximum change of mean value of C_{80} and *EDT*. Values above 1 JND are indicated in **bold**.

		Ranges of input parameter's changes	Krakow Philharmonic		Podkarpacka Philharmonic		Lodzka Philharmonic	
			Median	90th perc	Median	90th perc	Median	90th perc
Absorption coefficient	Walls	−50%/+200%	**9.14**	**10.26**	**9.96**	**17.19**	**16.38**	**18.93**
	Ceiling	−50%/+100%	**7.21**	**8.61**	**5.60**	**8.50**	**8.71**	**10.58**
	Audience	−25%/+25%	**4.28**	**5.40**	**5.89**	**7.53**	**4.01**	**5.00**
	Stage – floor	−50%/+200%	**3.19**	**4.27**	**4.51**	**6.08**	**3.81**	**4.96**
	Stage – walls	−25%/+25%	**1.89**	**2.45**	**1.25**	**2.20**	**1.36**	**1.70**
	Floor	−50%/+200%	**1.72**	**2.35**	**2.24**	**2.85**	**1.58**	**2.04**
Scattering coefficient	Walls	+/-50%	0.47	0.81	0.35	0.76	0.43	0.83
	Ceiling		0.31	0.64	0.96	**1.56**	0.33	0.64
	Audience		0.29	0.54	0.36	0.67	0.51	0.92
	Stage – floor		0.30	0.61	0.36	0.77	0.34	0.62
	Stage – walls		0.28	0.56	0.36	0.63	0.35	0.61
	Floor		0.34	0.57	0.30	0.67	0.31	0.58
Atmospheric condition		18–22 °C, 45–55%	0.51	0.87	0.83	0.97	0.47	0.72
Receiver position		+/-0.3 m	**3.22**	**7.02**	**6.30**	**13.48**	**4.90**	**11.14**
Source position		+/-0.5 m	0.47	0.74	0.53	0.86	0.54	0.98

on the results. Dividing the floor into the audience and the stage area revealed that stage material's α uncertainty impacts the final results uncertainty much more that audience floor material's α uncertainty. Sound source was located above the stage floor, what could influence the results.

While the impact of sound absorption coefficient on the model output parameters is undebatable, the influence of sound scattering coefficient on reverberation time or sound clarity depends on many factors and has to be analysed individually for every room. For Krakow and Lodz Philharmonic, as well as for two analysed churches +/- 50% changes in scattering coefficient for any material did not significantly change the analysed room acoustic parameters for more than 90% of receivers. For these rooms the scattering coefficient of the materials was not included in the calibration process. For Podkarpacka Philharmonic, the changes of scattering coefficient of the ceiling caused over 1 JND change in the value of mean value of C_{80} and *EDT* for almost half of the receivers (median 0.96). For that room, scattering coefficient of the ceiling was included in the calibration process.

Atmospheric conditions change in ranges 18–22 °C and 45–55% influences noticeably less than 10% of receivers. The biggest change of the mean value of C_{80} and *EDT* was observed for the biggest philharmonic – Podkarpacka – no more than 0.97 for 90% of receivers.

Changing the positions of the receivers in the range of +/−0.3 m can cause big changes in model output parameters for all analysed rooms. The smallest median of the change of mean value of C_{80} and *EDT* was observed for Church in Tychy (about 2.2 JND, not presented in the table) and the biggest for Podkarpacka Philharmonic (6.3 JND). For all rooms in the calibration procedure, a point which matched the measurement results best was chosen from the generated "cloud of points".

Sound source position has smaller impact on final results – changing it in the range of +/−0.5 m results in changes below 1 JND of C_{80} and mean value of *EDT* for more than 90% of receivers in every tested room.

4.3. Receiver positions excluded due to gross error

4.3.1. Receiver positions biased with too high uncertainty due to non-omnidirectional sound source

Not perfect omni-directionality of the sound source influences clarity C_{50} parameter the most – for Lodz Philharmonic and Church in Warsaw, more than 50% of receivers have standard deviation of C_{50} above 0.5 JND (calculated over different angle positions of the sound source) for at least one frequency band (Fig. 6). Clarity C_{80} is similar, but 0.5 JND was obtained for about 20% less receivers than for C_{50}. Sound strength *G* has significant values of variation only for rooms with short reverberation times. For churches possible error in sound strength *G* connected with non-omnidirectional character of the sound source is much smaller. Parameters connected with reverberation time (T_{20}, *EDT*) were stable during the rotation of the sound source – for all receivers standard deviation was below 0.5 JND. Generally results are smaller than presented in [8].

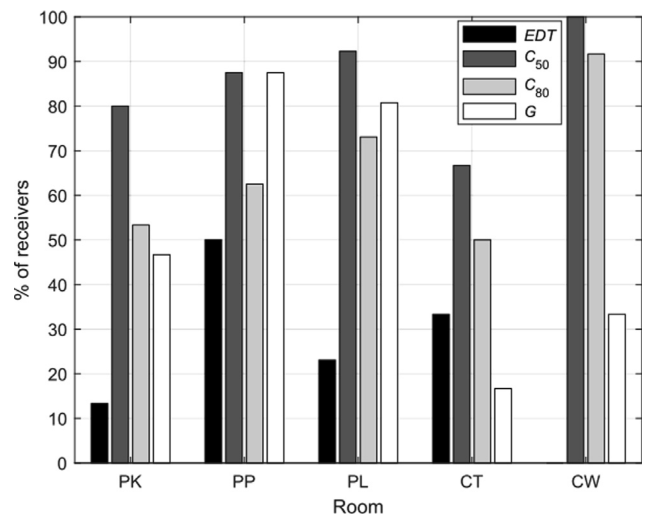

Fig. 6. Percentage of receivers for which standard deviation during rotation of the sound source was above 0.5 JND at least for one frequency band. Parameters used according to Table 1, rooms shortcuts according to Table 2.

The mean value of parameters C_{80} and *EDT* proposed as an indicator of model validity was also relatively stable. Amongst 75 receiver positions located in five rooms multiplied by six frequency bands, only twelve values (2.7%) were above 0.5 JND (see Fig. 7) and were excluded from the calibration process. The biggest values were observed for points close to the sound source. At the distance smaller than critical from the sound source in Lodz Philharmonic the standard deviation of the mean value of C_{80} and *EDT* was 0.83 for 2000 Hz. The same frequency band was problematic in Church in Warsaw for the receiver located 1.47 times the critical distance from the sound source.

4.3.2. Receiver positions with C_{80} far from theoretical values

For four rooms, differences in C_{80} between measurement and theoretical values calculated from eq. (1) were scattered around

0 dB point. According to the regression line for Krakow Philharmonic (Fig. 8, $R^2 = 0.54$), measured value of C_{80} = 0.5 dB corresponds to the theoretical value of 0 dB, with the slope 1.05. For the Church in Warsaw the differences were scattered around +1.7 dB. In this case, classic outliers analysis excluded too many points consistent with all points distribution. The applied criterion +/− 3 medians of the difference between measurements and theory was robust to this kind of results. It allowed exclusion of approximately 5% of receiving positions in every room.

4.4. Ray-tracing simulation parameters selection

The smallest number of rays providing repeatable results according do applied criteria (section 3.4) was obtained for Church in Tychy (Fig. 9). This room has a long reverberation time (T_{20} = 4.53 s) and a regular shape. On the other hand, in Church in Warsaw with even longer reverberation time (T_{20} = 7.19 s) and a spherical roof, it was very hard to obtain repeatable results for points near the half-sphere. Even for 1 000 000 rays, the results were still unstable and standard deviation for more than 10% of receivers did not converge linearly to zero like for the other rooms.

Comparing results of Krakow Philharmonic and Podkarpacka Philharmonic with similar volume and number or receivers, it can be concluded that long reverberation time helps to increase the repeatability of results. What is more, substantial number of receivers helps to reduce the influence of errors generated by single points (comparing results for Podkarpacka Philharmonic with only 16 receivers and Lodzka Philharmonic with 26 receivers).

With a number of rays providing repetitive results, minimum possible ray truncation time was calculated according to criteria given in section 3.4. In Fig. 10a and b, both criteria are presented – dash-dot line and solid line denote respectively mean and minimum value of results calculated for maximum ray truncation time. In case of the Podkarpacka Philharmonic (Fig. 10a) at 2000 Hz, ray truncation time shorter than 75% of measured reverberation time introduces systematic error – mean value of J_3 is lower than for a maximum analysed time. The 95% confidence range bar crosses the minimum line also. For high frequency band (2000 Hz), calculation can be done for much shorter time – only below 55% of the maximum measured reverberation time the influence is indicated. Similar trend can be observed clearly for Church in Tychy (Fig. 10b). Mean value at 1000 Hz decreases above 0.1 JND for ray truncation time equal to 75% of measured reverberation time,

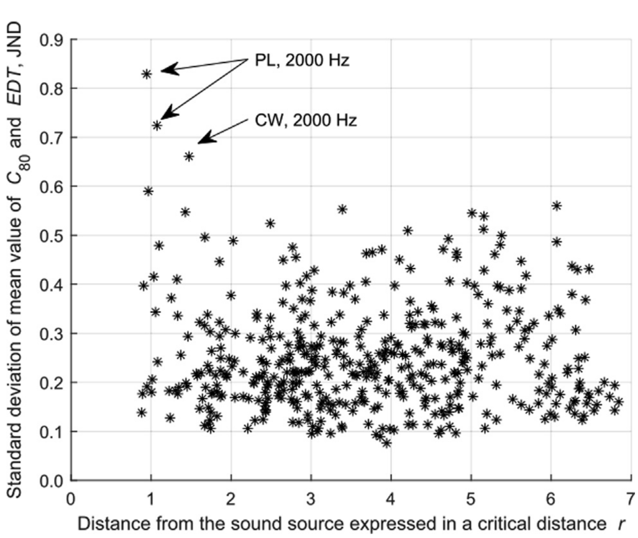

Fig. 7. Standard deviation of C_{80} and *EDT* combination as a function of critical distance *r* for five rooms and six frequency bands. Points with the highest values indicated.

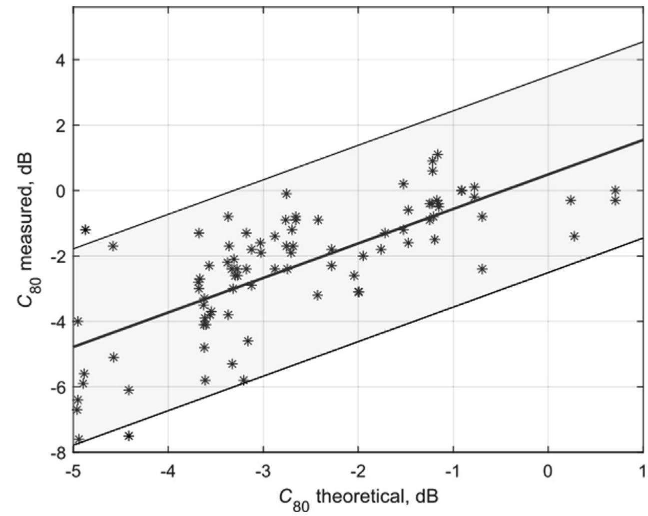

Fig. 8. C_{80} for all frequency bands measured in Krakow Philharmonic versus theoretical values calculated using Eq. (1). Range of +/− 3 medians of difference between measurement and theory is marked. Points outside the range were excluded from the calibration process.

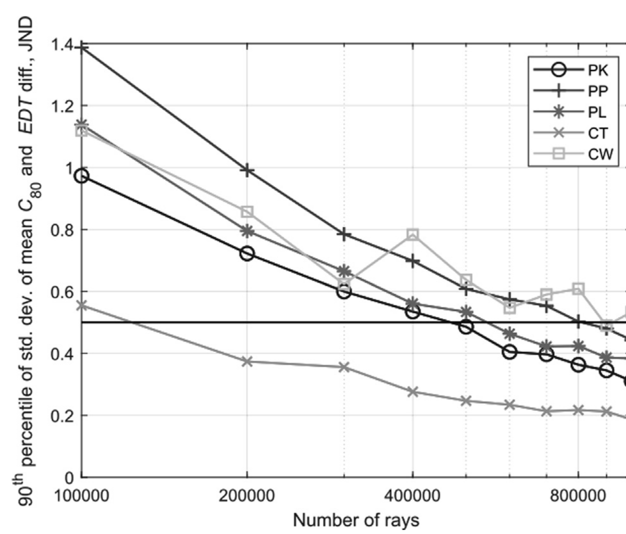

Fig. 9. 90th percentile of standard deviation of mean value of C_{80} and *EDT* difference between measurement and simulation results for Krakow Philharmonic (PK), Podkarpacka Philharmonic (PP), Lodz Philharmonic (PL), Church in Tychy (CT) and Church in Warsaw (CW) calculated for different number of rays used in ray-tracing simulation. Solid horizontal line denotes 0.5 JND criterion applied for ray number selection.

which implied further calculation with ray truncation time set to at least 4.36 s.

The final parameters of simulations used in validation process are presented in Table 4. For another rooms, if it is not possible to make above mentioned calculations, it is suggested to set ray truncation time for at least 90% of measured reverberation time for C_{80} and *EDT* calculation, to be sure that less than 10% of receivers are biased by a too short simulation time.

4.5. Objective functions analysis

Room acoustic parameters selected in par. 4.1 were used to calculate single number indicator of consistency between simulation and measurement needed for the optimization. Fig. 11 presents exemplary results for Krakow Philharmonic comparing different objective functions defined in par. 3.6. The best consistency

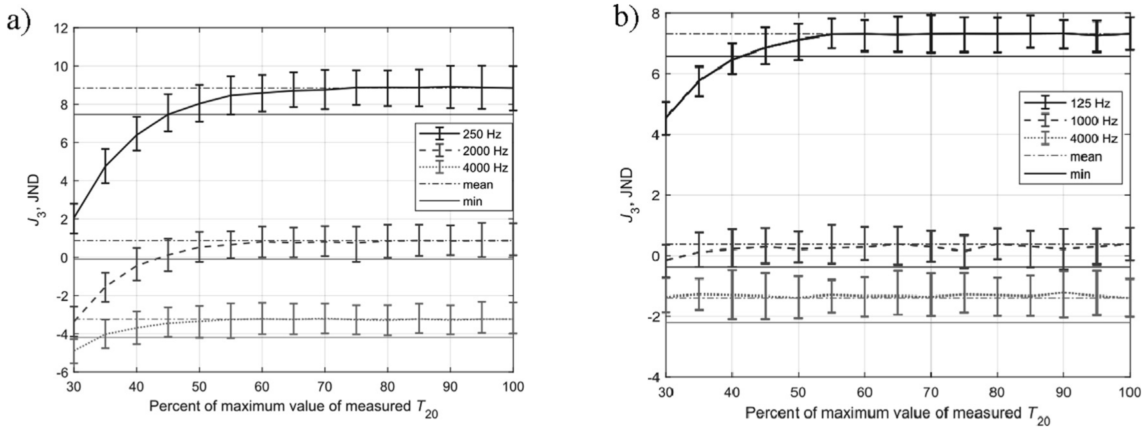

Fig. 10. Differences between measurement and simulation over time of ray truncation time expressed as a percent of maximum value of measured reverberation time in a given room. Bars denote 95% confidence range. Results presented for: a) Podkarpacka Philharmonic, b) Church in Tychy. Dash-dot line and solid line denote respectively mean and minimum value of results calculated for maximum ray truncation time.

Table 4
Parameters of simulation based on applied criteria. In second column percentage value of the longest measured value is given.

Room name	Time of simulation in seconds	Number of rays
Krakow Philharmonic	2.42 (90%)	500 000
Podkarpacka Philharmonic	1.35 (80%)	800 000
Lodz Philharmonic	1.62 (90%)	600 000
Church in Tychy	4.36 (80%)	200 000
Church in Warsaw	6.43 (85%)	800 000

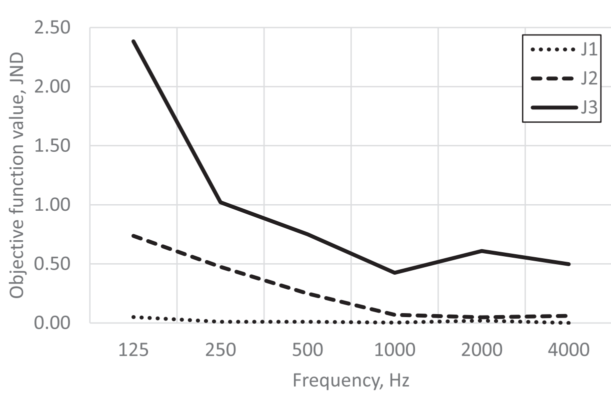

Fig. 11. Comparison of frequency characteristics of results obtained using automatic calibration for different acoustic parameters average values. Representative results for Krakow Philharmonic.

between measurement and simulation was observed for J_1 (spatially averaged value of reverberation time T_{20}). Taking into account the distribution of T_{20} (J_2) allows obtaining consistency below 1 JND for each frequency band. For an average of two parameters' RMSE (J_3), the results were the worst, but still most of them were below 1 JND for frequency bands above 125 Hz.

For all analysed rooms and objective functions, the biggest differences between measurements and simulations for the best combination of absorption and scattering coefficients of materials were observed for the low frequency bands. The differences between the measurement and simulation were even three times larger than for middle and high frequency bands.

The comparison between J_3 values calculated using manual and automatic model calibration criteria for Krakow Philharmonic is presented in Fig. 12. The ratio of mean values obtained for both criteria is about 1.8 (average for all rooms 1.95). Taking into account maximum values for both criteria, the ratio is 4.6 for Krakow Philharmonic (average for all rooms 5.0). This means, that calibration with an average reverberation time for all receiver positions as a consistency criterion, can lead to such a set of model input parameters (sound absorption/scattering coefficients, receiver positions) that another acoustic parameters, especially analyzed as distributions not as an averaged value, can be biased with a significant error.

4.6. Comparison of optimization algorithms

For three analysed optimization algorithms calculation of J_3 parameter was performed for every room and every frequency band (Table 5). Frequency averaged values are presented in Fig. 13. Mean value for all rooms is the highest for genetic algorithm (GA). Particle swarm optimization (PSO) and differential evolutionary (DE) algorithms gave similar results – mean value over all rooms is 0.91 for DE and 0.92 for PSO, while GA gave 0.97. Comparing PSO and DE algorithms in Table 5, it can be seen that much more "best results" (out of three algorithms) are obtained by DE than PSO algorithms. PSO has also the least number of worst val-

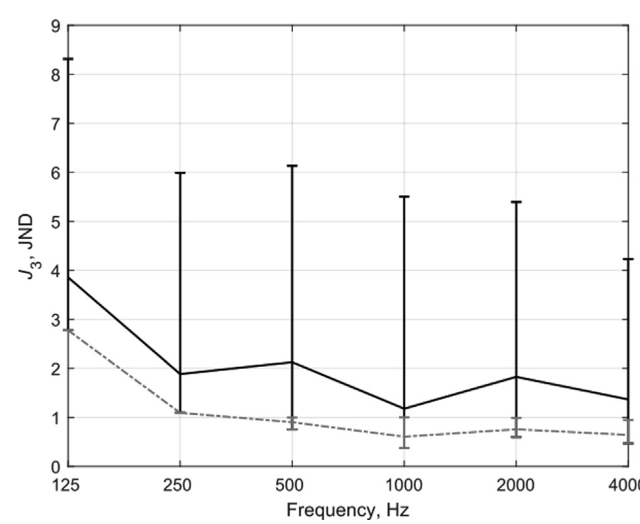

Fig. 12. Mean values of J_3 subsets fulfilling: manual model calibration criterion (J_1 < 1 JND – solid line), and automatic model calibration criterion (J_3 < 1 JND – dotted line). For frequency bands, where the second criterion was not fulfilled (125 Hz and 250 Hz), minimum values were taken. Error bars stand for minimum and maximum values from the subsets.

Table 5
Objective function J_3 results for all rooms (see Table 2) for three optimization algorithms. Best values (out of three optimization algorithms) for a given room and frequency are written in **bold.** Worst values are in *italics* and grey background.

	Freq, Hz	125	250	500	1000	2000	4000
PSO	PK	2.38	1.02	0.75	0.42	0.61	*0.50*
	PP	2.16	1.11	0.82	0.81	0.85	0.86
	PL	2.11	**0.96**	0.58	**0.79**	**0.94**	**0.87**
	CT	1.00	*0.54*	0.38	0.36	*0.36*	**0.19**
	CW	*1.48*	1.02	0.51	1.21	0.94	1.06
DE	PK	**2.36**	*1.03*	0.74	**0.39**	**0.58**	*0.50*
	PP	**2.10**	1.13	0.84	**0.75**	**0.82**	**0.85**
	PL	**2.09**	0.98	*0.61*	*0.85*	*0.96*	0.91
	CT	*1.04*	0.48	0.39	*0.38*	0.32	0.25
	CW	**1.42**	*1.05*	**0.54**	**1.12**	**0.92**	**0.95**
GA	PK	*2.44*	0.99	*0.80*	*0.48*	*0.66*	**0.47**
	PP	*2.55*	*1.15*	*0.93*	*0.85*	**0.82**	*0.96*
	PL	*2.12*	*1.00*	0.53	0.83	**0.94**	*0.97*
	CT	1.03	0.49	*0.40*	**0.35**	0.33	*0.35*
	CW	1.44	1.04	*0.59*	*1.50*	*1.00*	*1.12*

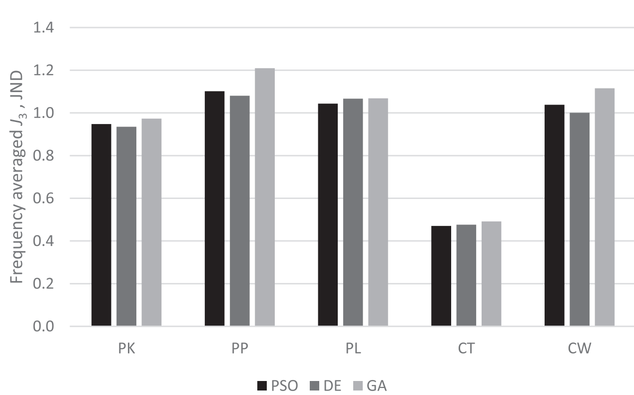

Fig. 13. Comparison of frequency bands averaged (125–4000 Hz) objective function J_3 results for different rooms and different optimization algorithms. PK, PP, PL, CT and CW – described in Table 2.

ues, what suggests that this algorithm was too "conservative" in exploring search space. For final calculation, DE algorithm was used, although PSO algorithm was almost equally good.

4.7. Validation of the optimization results

Calibration for every room was done for one sound source position S1 in order to accelerate the calibration process. Simulation and measurement results from sound source position S2 were used in order to validate optimization results. Fig. 14 presents comparison between objective function J_3 calculated during calibration (sound source position S1) and validation (sound source position S2). For most of the rooms and frequency bands, S2 gave bigger J_3 values. For Philharmonic in Lodz and Church in Warsaw, J_3 for mid frequency range was below 1 JND. The worst result was calculated for Philharmonic Krakow. While for low and high frequency bands the results of J_3 obtained for S1 and S2 positions are comparable, for the mid frequency bands, J_3 for S2 is much bigger than for S1 with 3.02 JND as a local maximum for 1000 Hz. For this case, calibration procedure should be repeated looking for another set of absorption coefficients giving local minimum of J_3 from S1 with a smaller J_3 for S2 sound source position.

5. Conclusions

In this paper, a method for the calibration of geometrical acoustic room model was presented. The method was used and validated for five acoustically different rooms. Different acoustic parameters described in the ISO 3382-1 standard were analysed. Since those rooms were designed for music, spatial distribution of sound clarity (C_{80}) and early decay time (*EDT*) were proposed as a criterion of simulation and measurement results similarity (objective function J_3). These parameters were selected because of their high variability of spatial distributions and low cross correlation.

The sources of discrepancies between measurement and simulation results were analysed. While changing absorption coefficients in the range adjusted to the type of material, changes of the mean value of C_{80} and *EDT* between 1.70 and 18.93 JND (for at least 90% of receivers) were observed. 90th percentile of the change of mean value of C_{80} and *EDT* caused by changing the position of the receivers in the range of +/−0.3 m was observed

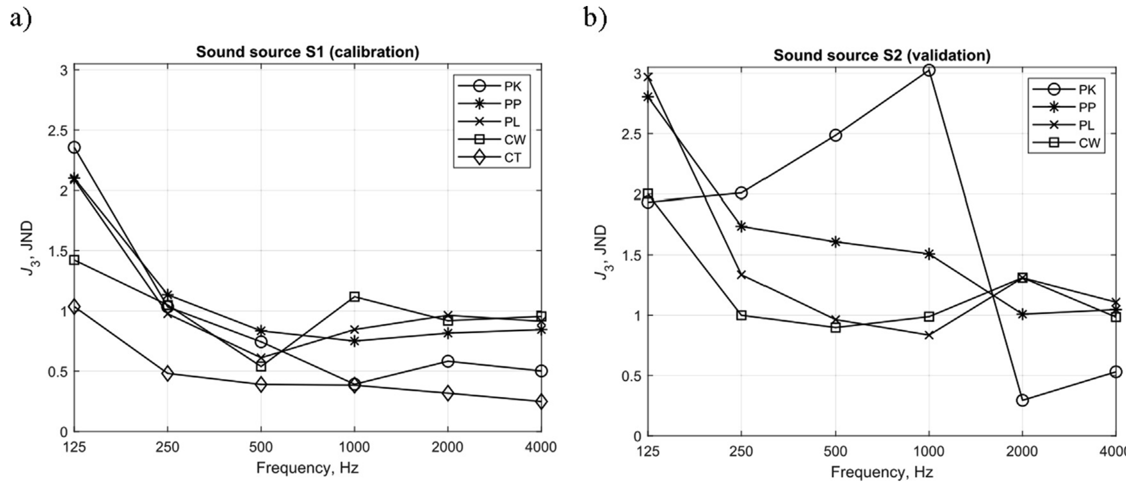

Fig. 14. a) Objective function values J_3 calculated in the calibration procedure (sound source position S1) compared to b) objective function values J_3 calculated in the validation process (sound source position S2).

between 7.02 and 13.48 JND. +/−50% changes in scattering coefficient significantly changed the analysed room acoustic parameters only for one material in one analysed room. These parameters were selected as the most important sources of uncertainty influencing room acoustic parameters and therefore they were selected to be corrected in the calibration process. Because of the possible random errors in both measurement and simulation results for singular receiver positions, the calibration was preceded by a selection of the receivers. Two criteria were proposed: difference between theoretical and measured C_{80} smaller than three medians of error, and checking if the values were not biased significantly by directionality of the sound source.

The criteria for ray truncation time and number of rays selection were described. Setting ray truncation time according to the proposed criterion allowed the decrease of systematic error to less than 0.1 JND. Ray truncation time above 90% of measured reverberation time did not introduce significant error in ray-tracing simulation. Using sufficient number of rays allowed the decrease of random error in the model to below 0.5 JND for at least 90% of receivers. Depending on the diffuse level in analysed room, required number of rays was set between 200 000 and 800 000.

Automatic correction of input model parameters based on differences between simulation and measurements was done for three different optimization algorithms. Differential Evolutionary algorithm (DE) was chosen to be the best.

Proposed calibration procedure was checked for five different rooms – three philharmonics and two churches. For all rooms, we found sets of absorption and scattering coefficients and exact receiver positions which gave objective function $J_3 < 1$ JND for middle and high frequency bands for each room. To check the obtained absorption and scattering coefficients, validation for another sound source position was conducted. The difference between the results of measurements and ray tracing simulations with absorption and scattering coefficients found before increased, but for two of the analysed rooms it was still below 1 JND for middle frequency range which confirmed the correctness of the results.

The sources of the worse compliance for low frequency bands as well as discrepancies observed for the second sound source position for Krakow Philharmonic should be analysed in further studies.

CRediT authorship contribution statement

Adam Pilch: Methodology, Conceptualization, Software, Investigation, Validation, Writing - original draft, Writing - review & editing, Supervision.

Declaration of Competing 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.

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