

Synthesis of Uncorrelated Acoustic Quality Evaluation Indices of Buildings

K. KOSALA*

AGH — University of Science and Technology, Faculty of Mechanical Engineering and Robotics
Department of Mechanics and Vibroacoustics, al. A. Mickiewicza 30, 30-059 Krakow, Poland

Previous studies and analyses conducted up to now on the indicatory description of the acoustic quality of buildings concerned single value indices based on several selected acoustic parameters that are correlated with each other. Transformation of values, correlated into a new set of independent components for the purpose of their future synthesis, took place using the Singular Value Decomposition (SVD) technique. In this article, it is shown that SVD can also be applied to the determination of the single-value global acoustic quality index in the case where the decomposed index observation matrix contains partial indices that are not only correlated, but also uncorrelated. Alternatively, a statistical method used in econometrics, i.e. Comparative Multivariate Analysis (CMA), was adapted to obtain a single-value index from uncorrelated partial indices. Both proposed methods of synthesis have been verified using the example of a group of buildings – Roman Catholic churches.

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1. Introduction

The correct acoustic utilisation of the interior of a building is related to its function and purpose. Depending on function of the buildings, the scope of acoustic production may vary. Examples of public buildings with a narrow range of acoustic production are auditoriums and theatres or religious interiors such as synagogues, where speech signals are dominant. Another example is the group of buildings with acoustic conditions that are appropriate for playing and listening to music exclusively, which includes concert halls. A different specific group of buildings has multi-functional interiors with a wide range of acoustic production, including music and speech. These are buildings such as: opera houses, movie theatres and religious buildings, particularly Roman Catholic churches. Interiors of this type are a challenge for designers, because they require compromises of acoustic conditions.

The methods of Beranek [1] and Ando [2] are acknowledged methods of acoustic evaluation of concert halls and opera houses. The components of single-value ratings in these methods are uncorrelated with each other and describe various aspects of the acoustic field [3]. Acoustic evaluation of rooms may also take place using the more easily applicable impulse method. Acoustic parameters are calculated from the studied impulse response, which, in comparison with preferred values obtained from subjective studies, constitute the basis for acoustic evaluation. These parameters are correlated with one another; thus, it is difficult to use them to evaluate the acoustics of an interior in a complete way, e.g. by using one value, if even for the reason of certain information being duplicated during synthesis of these parameters.

Another approach to evaluation of the acoustic quality of buildings has been proposed – the global evaluation, based on partial indices related to the acoustic functions and purpose of a given building [4]. The global acoustic quality index of a building, W_G , is a function of many partial indices,

$$W_G = f(W_1, W_2, W_3, \dots, W_n), \quad (1)$$

where W_1, \dots, W_n are partial indices.

The global index is an approximated index and the general measure for evaluation. Partial evaluation indices give more accurate information on the acoustic properties of a building. All partial indices and the global index take values within the interval from 0 to 1. A value of 0 signifies bad acoustic properties of the building, significantly deviating from preferred values, and the value of 1 signifies good acoustic properties, in accordance with the preferred values of acoustic parameters.

The singular value decomposition (SVD) technique was applied to solve the problem of correlated acoustic indices in a single-value evaluation [5]. Up to this point, application of SVD for construction of a single-value index W_l from selected correlated partial indices took place by using the so-called full correlation [6] or decorrelation of the index matrix of observation [7].

This article shows the next step in studies on the index method of acoustic quality evaluation of buildings which is a synthesis of uncorrelated indices. Utilisation of two tools is proposed to fulfil this purpose – the SVD technique and the statistical method of comparative multivariate analysis (CMA). Here, the SVD technique will be applied for decomposition of the observation matrix of all partial indices used for evaluation that may be correlated or uncorrelated. The CMA method may be applied only in the case of uncorrelated indices. For this purpose, it is necessary to separate the partial indices taken for evaluation into strongly correlated and uncorrelated indices. The single value local index W_l will be created from strongly correlated indices using the SVD method

*e-mail: krzysztof.kosala@agh.edu.pl

which, together with other uncorrelated indices, will be a component of the global index W_G .

Both proposed methods of synthesis have been verified using the example of a group of buildings – Roman Catholic churches. It was verified which one of the global indices, W_{Gs} or W_{Gd} , was better correlated with the initial partial indices.

2. Statistical method of synthesis of uncorrelated indices

The statistical method, i.e. CMA, adapted to construction of the global index W_{Gs} , is related to the analysis of complex phenomena. A complex phenomenon is understood as an abstract concept that illustrates the directly immeasurable qualitative state of real objects, described by a certain number greater than one of the so-called diagnostic variables. Multi-dimensional methods of statistical analysis used in econometrics [8] make it possible to present variables (building properties) in such a form so that they can be directly compared to one another. It is possible to construct a ranking of buildings in the light of multi-criteria evaluations. According to the assumptions of this method, clarifying (diagnostic) variables should be: characterised by high variability; strongly correlated with the clarified variable; and weakly correlated with each other. Acoustic parameters are the clarified variables, while partial indices are the clarifying variables.

Adaptation of the statistical method for the purpose of construction of a global index will be based on the use of a method for determining the weights of variables (uncorrelated partial indices) and a method of variable aggregation. It is proposed that property variability coefficients are used for calculation of measures of relative informational value which will be the weights ω_j of variables

$$\omega_j = \frac{V(X_j)}{\sum_{j=1}^s V(X_j)}, \tag{2}$$

for

$$V(X_j) = \frac{S(X_j)}{\bar{X}_j} \quad \bar{X}_j \neq 0, \tag{3}$$

where $S(X_j)$ is standard deviation of a property, X_j is the j -th variable.

Weights ω_j are called variance weights and are dependent upon the degree of variability of the property – the greater the variability of a property, the greater the weight of the assigned variable.

The last step in the construction of the global index W_{Gs} is based on conjugation of the transformed values; in this case, partial evaluation indices W_j and their weights ω_j . It is recommended to use an additive formula based on the addition of the products of normalised values of properties and their corresponding weights. The global single-value acoustic quality index of the i -th building is determined by the formula:

$$W_{Gs_i} = \sum_{j=1}^n W_{ij}\omega_j \quad (i = 1, 2, \dots, r) \quad \omega_j \in R_+, \tag{4}$$

where ω_j is weight of the j -th uncorrelated partial index.

3. SVD method of synthesis of building properties

The SVD method is a technique of calculation that is in wide use in numerical linear algebra [9, 10]. SVD is the decomposition of matrix into singular values. SVD decomposition is applicable in various fields of science such as diagnostics [11] and vibroacoustics [12, 13]. SVD is often selected as a method for solving linear problems of least squares [14]. The SVD method, similarly to factor analysis, and, in particular, the principal component analysis method (PCA) make it possible to transform the correlated data set into uncorrelated data without loss of any information.

The global acoustic quality index of a building W_{Gd} is related to the application of SVD to observation matrix \mathbf{A} of all indices, either correlated or uncorrelated with each other. As a result of $SVD(\mathbf{A})$, matrices \mathbf{U} , $\mathbf{\Sigma}$ and \mathbf{V}^T are obtained with information on the independent properties of the building. Matrix we \mathbf{A} can also be presented using the equation:

$$\mathbf{A} = \sum_{i=1}^n \mathbf{u}_i \sigma_i \mathbf{v}_i, \tag{5}$$

where \mathbf{U}_i is the i -th singular vector of matrix \mathbf{U} obtained from $SVD(\mathbf{A})$, \mathbf{v}_i is the i -th singular vector of matrix \mathbf{V}^T obtained from $SVD(\mathbf{A})$, and σ_i is the i -th singular value of matrix $\mathbf{\Sigma}$ obtained from $SVD(\mathbf{A})$.

The shares of information on independent properties obtained from singular values σ_i describing the variability of properties, are proposed to be used as weights of these properties. For this purpose, matrix \mathbf{B} , with uncorrelated components, is determined in the form of:

$$\mathbf{B} = \sum_{i=1}^n \frac{\sigma_i}{\sum_{i=1}^n \sigma_i} \mathbf{u}_i \mathbf{v}_i. \tag{6}$$

By adding the components b_{ij} of matrix \mathbf{B} , the single-value global index for the i -th building is obtained:

$$W_{Gd_i} = \sum_{j=1}^n b_{ij}, \tag{7}$$

where b_{ij} is uncorrelated partial index corresponding to the i -th row and j -th column of matrix \mathbf{B} .

4. Verification of index synthesis methods using the example of religious buildings

Acoustic parameters measured in six unoccupied Roman Catholic churches (reverberation time RT [s], speech intelligibility index $RASTI$, clarity C_{80} [dB], sound level of external disturbances L_Z [dB]) were the basis for the calculation of values, developed in [5], of partial evaluation indices (the reverberation index W_P , the music sound index W_M , the speech intelligibility index W_Z , and the external disturbance index W_{ZZ}). Acoustic measurements were based on measuring impulse responses of the interiors. The MLS signal generated in the DIRAC program was used for the room excitation. An omnidirectional sound source was placed near the altar, 1.5 m above the floor. The microphone was placed 1.2 m above the floor. For calculation averaging, a dozen or so

positions of the microphone (placed on the whole floor surface) were used. Measurements and calculations were carried out in accordance with ISO-3382 [15]. The levels of disturbing sounds L_Z were measured by a SVAN 945A sound level meter at measuring points located in the middle of each church, 1.2 m above the floor. During the measurements, the churches were unoccupied and their sound amplification installation was switched off.

The procedures of determination of partial indices relate to the preferred values of acoustic parameters. The reverberation index W_P as a function of reverberation time T_{30} [s], measured in church without congregation, is calculated from the equation:

$$W_P = \begin{cases} 0 & \text{for } T_{30} > T_P + 4.5, \\ -0.22|T_{30} - 0.24 \ln(V_S) + 0.24| + 1 & \\ 0 & \text{for } T_{30} \leq T_P + 4.5, \end{cases} \quad (8)$$

where V_S [m³] is church cubic capacity, and T_P [s] is the preferred reverberation time for Roman Catholic churches [4],

$$T_P = 0.24 \ln(V_S) - 0.24. \quad (9)$$

The music sound index W_M as a function of clarity C_{80} [dB] is calculated from the equation developed on the basis of the preferred values of this parameter [4]:

$$W_M = \begin{cases} 0 & \text{for } -15 < C_{80} > 15, \\ 0.04C_{80} + 0.6 & \\ & \text{for } -15 \leq C_{80} < -10, \\ 0.06C_{80} + 0.8 & \\ & \text{for } -10 \leq C_{80} < -5, \\ 0.1C_{80} + 1 & \text{for } -5 \leq C_{80} < 0, \\ 1 & \text{for } 0 \leq C_{80} < 5, \\ -0.12C_{80} + 1.625 & \\ & \text{for } 5 \leq C_{80} < 10, \\ -0.083C_{80} + 1.25 & \\ & \text{for } 10 \leq C_{80} < 15. \end{cases} \quad (10)$$

The values of the speech intelligibility index W_Z are within the range from 0 (bad speech intelligibility) to 1 (very good speech intelligibility) and are equal to the RASTI, which has values from the same range.

The external disturbance index of the religious building W_{ZZ} as a function of equivalent sound A level of external disturbance L_{Aeq} [dB] is given by the formula:

$$W_{ZZ} = \begin{cases} 1 & \text{for } L_{Aeq} \leq 30, \\ 3/(L_{Aeq} - 27) & \text{for } L_{Aeq} > 30, \end{cases} \quad (11)$$

Three partial indices, W_P , W_M and W_Z are strongly correlated with each other. Index W_{ZZ} is not correlated with the other indices. Linear correlation coefficients between the indices are shown in Table 1.

A single-value index, the so-called local index of selected acoustic parameters W_l , was constructed from three strongly correlated partial indices, W_P , W_M and W_Z . The local index W_l is strongly correlated with these three partial indices and not correlated with the outside disturbance index W_{ZZ} (Table I).

TABLE I
Linear correlation coefficients between partial indices and the W_l local index.

	W_P	W_M	W_Z	W_{ZZ}
W_P	1			
W_M	0.9488	1		
W_Z	0.9158	0.9827	1	
W_{ZZ}	-0.2280	-0.1950	-0.0464	1
W_l	0.9893	0.9848	0.9598	-0.2036

TABLE II
Local and global acoustic quality evaluation indices of Roman Catholic churches: St. Sebastian's Church in Strzelce Wielkie (SE), The Holiest Sacred Heart's Church in Cracow (NS), The Reformati Fathers Church in Wieliczka (RE), St. Clemens Church in Wieliczka (KL), The Jesuits Fathers Church in Cracow (JE), St. Paul Apostle Church in Bochnia (PA).

Church	Volume [m ³]	W_{ZZ}	W_l	W_{G_s}	W_{G_d}
SE	1102	1.00	1.00	1.0	0.84
NS	2750	0.39	0.72	0.60	0.56
RE	4450	0.37	0.72	0.59	0.55
KL	6380	0.58	0.67	0.64	0.58
JE	9120	0.58	0.18	0.32	0.38
PA	13740	1.00	0.00	0.36	0.37

Global index W_{G_s} values were determined from uncorrelated indices W_l and W_{ZZ} using the CMA statistical method. The weights ω_1 and ω_2 , related to the indices W_l and W_{ZZ} are equal to 0.64 and 0.36, respectively. The values of global index W_{G_d} were determined by using the method of decorrelation of partial indices W_P , W_M , W_Z and W_{ZZ} . A list of values of calculated partial and global indices is shown in Table II. The values of global index W_{G_d} only differ slightly from the values of index W_{G_s} (Fig. 1). The greatest differences exist in the case of the SE building. The linear correlation coefficient between indices W_{G_d} and W_{G_s} is equal to 0.9994.

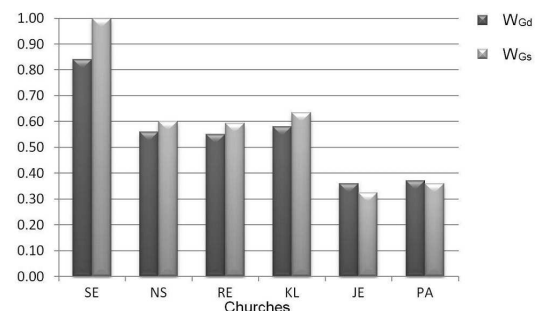


Fig. 1. Comparison of the acoustic quality of religious buildings using global indices W_{G_d} and W_{G_s} .

Table III shows the correlations of global indices with partial indices. The global index W_{G_d} is more strongly

TABLE III
Coefficients of linear correlation between partial and global indices.

	W_P	W_M	W_Z	r	W_{ZZ}
W_{Gs}	0.8900	0.8970	0.9376	0.9082	0.2168
W_{Gd}	0.8995	0.9088	0.9475	0.9186	0.1905

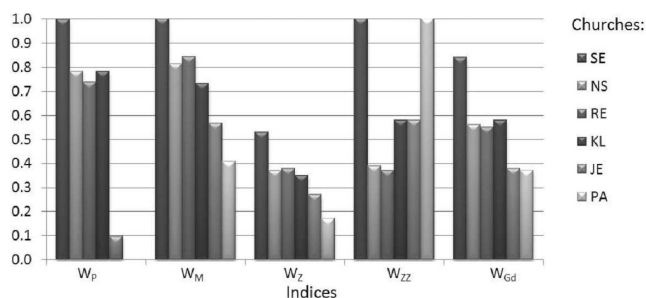


Fig. 2. Single-value evaluation of the acoustic quality of Roman Catholic churches.

correlated with partial indices W_P , W_M , and W_Z than index W_{Gs} . The average linear correlation coefficient r is greater for index W_{Gd} as compared to W_{Gs} .

Fig. 2 shows the single-value evaluation of acoustic quality using index W_{Gd} and partial indices W_P , W_M , W_Z , and W_{ZZ} . It results from Fig. 2 that the historic wooden church, SE, has the best acoustic parameters in terms of reverberation, intelligibility of speech, sound of music, and absence of external disturbances. The modern church, PA, based on an elliptical plan, has the worst acoustic parameters, excluding the level of external disturbances. The global index for this church is equal to 0.4. The second church in terms of bad acoustic parameters is the JE church. The excessive reverberation in the interior influences the bad intelligibility of speech and sound of music. Three of the studied churches among the six – NS, RE, KL – have global indices $W_{Gd} \approx 0.6$ which signifies rather good conditions for fulfilment of acoustic functions. The low values of outside disturbance indices W_{ZZ} are related to the location of these buildings near streets with bothersome noise from traffic.

5. Summary and conclusions

It was shown that the construction of a synthetic single-value index of uncorrelated partial evaluation indices may take place using the following methods: statistical – CMA and SVD. Verification of the proposed single-value evaluations was conducted on a selected group of buildings, namely Roman Catholic churches. Due to their nature, these buildings must resolve compromises between ensuring intelligibility of speech and articulation of music.

The problem of synthesis of correlated acoustic parameters and evaluation indices: of reverberation, intelligibility of speech, and articulation of music, was the subject of the author’s previous works. The single-value local index of selected acoustic parameters, along with an independent index of outside disturbances served in these

studies to provide a global evaluation index using the statistical method. The values of global evaluation indices obtained using the two methods discussed above are very similar and give identical results in terms of ranking of the acoustic quality of churches. However, due to the fact that the global index W_{Gd} obtained through SVD decorrelation, is better correlated with the initial partial indices than index W_{Gs} obtained using the statistical method, the evaluation conducted using index W_{Gd} is more reliable.

Further studies will be related to the application of indicatory evaluation methods for other public buildings and industrial buildings, as well as for a greater number of studied buildings.

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