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Formalization of the stages of conducting acoustic expertise when designing decision support systems

Victoria V. Usik[1)]
ORCID: https://orcid.org/0000-0002-3515-4849; viktoriia.usyk@nure.ua. Scopus Author ID: 59940385100
Bohdan P. Fedorchak[2)]
ORCID: https://orcid.org/0009-0003-7335-9276; fedorchakbogdan@gmail.com. Scopus Author ID: 59532264200
Oksana A. Povoroznyuk[2)]
ORCID: https://orcid.org/0000-0001-7524-564 ; povoks76@gmail.com. Scopus Author ID: 55817007400
Anna E. Filatova[2)]
ORCID: https://orcid.org/0000-0003-1982-2322; Hannah.Filatova@khpi.edu.ua. Scopus Author ID: 56448583600
Valerii V. Filatov[2)]
ORCID: https://orcid.org/ 0009-0007-7762-1517; Valerii.Filatov@khpi.edu.ua. Scopus Author ID: 59178850500
[1)] Kharkiv National University of Radio Electronic, 14, Nauky Ave. Kharkiv, 61023, Ukraine
[2)] National Technical University "Kharkiv Polytechnic Institute", 2, Kyrpychova Str. Kharkiv, 61002, Ukraine

ABSTRACT

Relevance. This work addresses the current scientific and technical problem of developing a functional model for conducting acoustic examinations of enclosed premises with different functional purposes as part of decision support systems. Different types of premises, including concert halls, conference halls, press centers, office spaces, and meeting rooms, have specific requirements for sound field characteristics, the sequence of examination stages, and the procedures applied at each stage. Consequently, the acoustic examination process for each type of premises is typically determined individually by a specialist based on professional experience. Therefore, there is a need to formalize the examination stages and develop a generalized functional model of the acoustic examination process for different types of enclosed premises as a basis for a specialized decision support system. **The purpose of the study** is to reduce the subjective component and improve the validity and reliability of acoustic examination results by developing a generalized functional model of the acoustic examination process for enclosed premises with different functional purposes. **Research Methods.**Statistical theory methods were used to calculate reverberation time. Geometrical acoustics was applied to analyze sound reflections from room surfaces and identify acoustic defects in rooms with complex geometries. **The following results were obtained** . A generalized functional model of the acoustic examination process was developed using the IDEF0 functional modeling methodology, followed by its decomposition. Four main functional blocks were identified: A1 – Auditoriums; A2 – Small Volumes with Predominantly Speech Content; A3 – Press Centers; and A4 – Special-Purpose Rooms. Each block was further decomposed into individual stages. The general approach to performing these stages was standardized while accounting for the specific sound field requirements of each type of premises. The functional model was tested during the acoustic examination of four meeting rooms. **Conclusions**. The relevance of developing a specialized decision support system for acoustic examination has been substantiated. As the first stage in developing such a system, the acoustic examination process was formalized through the development and decomposition of a functional model. The testing results confirmed the applicability of the proposed functional model. Future research will focus on developing the information, mathematical, and software and hardware components of the decision support system for acoustic examination.

Keywords: Acoustic expertise; stages of acoustic expertise; closed room; sound field; parameters; functional model; decision support; optimization of acoustic properties; sound content

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1. INTRODUCTION

The purpose of conducting acoustic examinations of different types of enclosed premises (concert halls, conference halls, press centers, office spaces, meeting rooms, etc.) is to analyze the characteristics of the sound field at the control points within the room and to develop recommendations for their optimization through construction and acoustic treatment measures, including the use of enclosing surfaces and sound-absorbing materials.

The acoustic properties of a room are determined by several factors, including its volume and geometry, the presence of furniture, the configuration of enclosing structures, and the type and distribution of surface treatment materials [1], [2], [3]. Depending on the functional purpose of the room and the characteristics of the sound content, specific requirements are imposed on the sound field characteristics, including sound quality, speech intelligibility, echo control, and noise reduction.

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The process of conducting an acoustic assessment usually includes the following stages [1]:

– verification of the existing architectural and construction solutions for the interior surfaces of the room (geometry and finishing materials);

– development of recommendations to ensure optimal reverberation characteristics (at the stage of developing technical specifications for the design of enclosing structures);

– room acoustic modeling using the recommended enclosing structures and finishing materials;

– measurement of the objective characteristics of the sound field in the room after implementation of the recommended measures to ensure optimal acoustic conditions.

In this context, an important stage is room acoustic modeling. This stage makes it possible to identify and correct acoustic problems in advance and to evaluate the effectiveness of enclosing structures and finishing materials before the commencement of construction and finishing works.

Specialized software packages are used for computer modeling of the sound field in enclosed spaces, including hybrid approaches and grid-based time-domain methods [4], [5]:

– EASE (Enhanced Acoustic Simulator for Engineers) is a software package for detailed three-dimensional modeling of the acoustic characteristics of rooms and sound systems. It is designed for various types of spaces, including concert and opera halls, theaters, meeting rooms, conference halls, university auditoriums, religious buildings (e.g., temples and cathedrals), and transport terminals (e.g., airports and railway stations), where the design of public address systems is of critical importance [6], [7];

– CATT-Acoustic is an established software tool for three-dimensional geometric modeling and prediction of sound-field parameters in rooms with complex geometries and diffuse surfaces. It enables detailed assessment of impulse-response characteristics and acoustic visualization [8];

– ODEON is a software package based on the hybrid ray-tracing method, which is widely used for the acoustic analysis of concert halls, theaters, complex architectural spaces, and industrial facilities, particularly for noise control applications [9].

Despite the wide range of tasks that can be addressed using existing acoustic modeling software packages, these tools do not provide decision support throughout all stages of acoustic assessment and require expert configuration of model parameters. In particular, when setting up a model for a specific type of room, the specialist must specify the type of dominant sound source, as well as the criteria for assessing the quality of the sound field to be calculated during the simulation.

In addition, the geometry of the enclosing surfaces and the sound-reflection and sound-absorption characteristics of the materials must be specified as input data. The selection of enclosing surfaces and finishing materials, taking into account the constraints on their use for specific types of rooms, constitutes a multicriteria decision-making problem that is currently addressed largely on the basis of expert judgment.

Thus, existing acoustic modeling software packages automate only one stage of the acoustic assessment process, namely, the modeling of the sound field in enclosed spaces and the calculation of its characteristics for specified architectural and construction solutions. All other stages of the acoustic assessment, including the development of recommended architectural and construction solutions to ensure optimal acoustic conditions, as well as consideration of the implementation requirements and constraints associated with performing the acoustic assessment for different types of rooms, are carried out manually by a specialist [1].

2. LITERATURE REVIEW AND PROBLEM STATEMENT

The acoustic assessment process is conducted in accordance with the applicable regulatory documents [10], [11]. The assessment of speech intelligibility and the perception of sound content by listeners under reverberant conditions are discussed in [12], [13], [14]. However, the specific sequence and scope of the aforementioned stages of acoustic assessment may vary depending on the functional purpose of the room, the type of dominant sound content, and geometric and structural constraints [15], [16]. Therefore, for each type of room, the acoustic assessment procedure is individually determined by a specialist based on professional expertise and experience.

Thus, the objective of this study is to automate all stages of the acoustic assessment process by developing a decision support system (DSS) that provides decision-making support throughout the assessment process and accounts for the specific implementation requirements and adaptation of the assessment stages to different types of rooms. This approach is expected to reduce subjectivity and improve the reliability of the results. Automated

decision support systems (DSSs) can minimize the influence of human factors and accelerate the selection of optimization measures for the acoustic correction of halls with different types and functional purposes [17], [18], [19].

Promising directions for the automation of construction and acoustic studies include the integration of BIM concepts [20], [21] and digital twins [22], [23], as well as the use of specialized information technologies for process planning [24].

The initial stage in the development of the DSS is the formalization of the acoustic assessment process through the development of a functional model [1].

The main scientific contributions of this study are as follows:

– a systematic analysis of the specific requirements for sound-field characteristics and the constraints on their optimization for enclosed spaces with different functional purposes, which enabled the formalization of the acoustic assessment process through a standardized approach to the implementation of its stages, taking into account the identified requirements and constraints;

– the development of a generalized functional model of the acoustic assessment process, in which the established assessment stages are adapted to the requirements and architectural and spatial constraints of different types of rooms.

3. PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of this study is to reduce the influence of the human factor and improve the validity and reliability of acoustic assessment results by formalizing the assessment process for enclosed spaces with different functional purposes.

To achieve this objective, the following tasks are addressed:

– to formalize the acoustic assessment process by identifying the inputs, outputs, controls, and mechanisms of the functional model;

– to develop a functional model and perform its decomposition;

– to validate the functional model through an acoustic assessment of real-world spaces.

4. DEVELOPMENT OF A FUNCTIONAL MODEL

We present the functional model M_F using the IDEF0 functional modeling methodology [25], which provides a systematic hierarchical representation of processes through graphical blocks and logical relationships between them. The methodology also enables the detailed representation of processes through decomposition, thereby facilitating the analysis and understanding of the subject area.

To construct a context diagram representing the acoustic assessment process as a whole and its interaction with the external environment, it is necessary to define the inputs, outputs, controls, and mechanisms. The resulting functional model will make it possible to identify the main information sources and flows, as well as critical stages of information processing, thereby improving the efficiency of the acoustic assessment process.

The sound-field characteristics, three-dimensional room geometry, and room dimensions are considered as inputs. The outputs of the functional model M_F include recommendations for architectural and construction solutions, recommendations on the use of sound-absorbing materials, and optimized sound-field characteristics obtained after implementation of the recommended measures.

The required sound-field parameters for different types and functional purposes of rooms are specified in relevant legislative and regulatory documents.

According to ISO 3382 [10], [11], the key parameters used to assess acoustic quality include the reverberation time T_{60}, defined as the time required for the sound pressure level to decrease by 60 dB; Early Decay Time (EDT); Speech Transmission Index (STI) and the articulation loss of consonants (%ALcons), which characterize speech intelligibility; clarity indices C_{80} and C_{50}, which characterize the balance between early and late sound reflections for music and speech, respectively; and sound pressure level (SPL), which characterizes the sound level distribution throughout the room. The application of these acoustic quality indicators to different types of rooms is shown in the context diagram below.

Given that the acoustic assessment process depends on the type of room, the room type is also considered as a control.

In addition, the acoustic assessment is performed by an acoustic expert using a specialized measurement system [26] to record sound-field parameters at designated measurement points within the room, as well as by an architect responsible for developing architectural and construction solutions. The operation of the DSS requires a system analyst and a personal computer (PC) on which the DSS is deployed and used to enter, store, and process information. Thus, the main mechanisms identified

in the context diagram are the acoustic expert, architect, system analyst, measurement system, DSS, and PC.

Thus, based on the identified inputs, outputs, controls, and mechanisms, a context diagram of the functional model M_F for the acoustic assessment process was developed, as shown in Fig. 1.

The context diagram is decomposed into functional blocks. Taking into account the specific features of the acoustic assessment process, different types of rooms (concert halls, conference halls, press centers, office spaces, meeting rooms, etc.) have specific requirements for sound-field characteristics.

Furthermore, the assessment stages may differ in their sequence and implementation, leading to the identification of four main functional blocks:

A1 – Auditoriums; A2 – Small volumes with predominantly speech content; A3 – Press centers; A4 – Special premises.

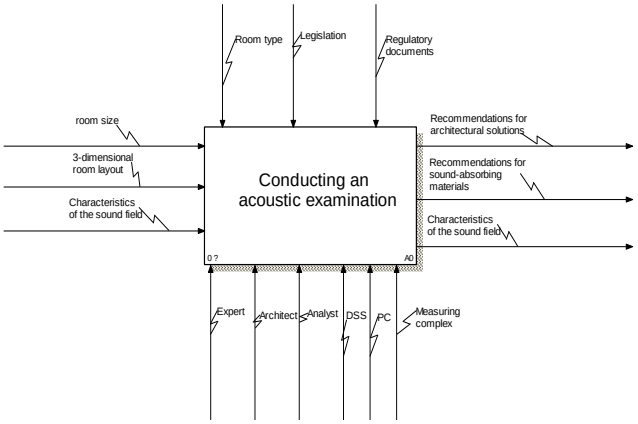


Fig. 1. **Functional model M_F conducting an acoustic examination**

***Source*: compiled by the authors**

Since only one of the identified functional blocks is executed for a given room, these blocks represent parallel branches of the diagram. The required block is selected using the control "Room Type", while all other inputs, outputs, controls, and mechanisms are inherited from the higher-level block A0. Due to the limited space available in the paper and the low informational value of this intermediate decomposition level, it is not presented. A more detailed decomposition is then performed, in which the main stages of the acoustic assessment process are identified for each of the specified room types.

4.1. A1 "Audience Halls"

For the decomposition of work A1 "Audience Halls", the following works were identified: A1.1 – Verification of architectural and construction solutions; A1.2 – Correction of acoustic deficiencies; A1.3 – Analysis of the frequency dependence of the reverberation time; A1.4 – Measurement of sound field characteristics [13]. The decomposition of the context diagram A1 is presented in Fig. 2.

Block A1.1 "Verification of architectural and construction solutions". The inputs to this block are the room dimensions and its three-dimensional geometric model. The output is a technical specification for the development of corrective architectural solutions.

At this stage, the geometric theory of sound propagation [2], [6] is applied, according to which sound is represented as a set of rays that propagate rectilinearly within the room and are reflected from surfaces in accordance with the laws of geometric optics. For this purpose, software modules are used to generate ray-tracing patterns on the plans and sections of the hall, including the verification of wall geometry on all floors, ceiling geometry, balcony railings, and other architectural elements. The primary purpose of this analysis is to identify acoustic defects, such as echoes and sound focusing, in rooms with complex geometries.

This analysis identifies surfaces that focus sound rays at specific locations within the room, thereby reducing the diffuseness of the sound field. It also identifies parallel surfaces that may create conditions for multiple sound reflections and the formation of standing waves at specific resonant frequencies.

Block A1.2 "Correction of acoustic deficiencies". The inputs to this block are the outputs of block A1.1, namely, the identified deficiencies in the sound-field characteristics and the technical specifications for developing corrective solutions. The corrective measures are aimed at addressing the acoustic deficiencies identified at the first stage. Recommendations are developed regarding the geometry of enclosing surfaces to increase the diffuseness of the sound field. By using different configurations of wall panels, the reflection angles of sound rays can be modified to eliminate parallel surfaces, thereby reducing the likelihood of standing waves. Another type of corrective measure involves analyzing the sound-reflection properties of surfaces and selecting sound-absorbing materials for their treatment to absorb sound energy and reduce the amplitude of reflected sound waves.

Thus, the outputs of this block are recommendations for architectural solutions and recommendations regarding the use of sound-absorbing materials.

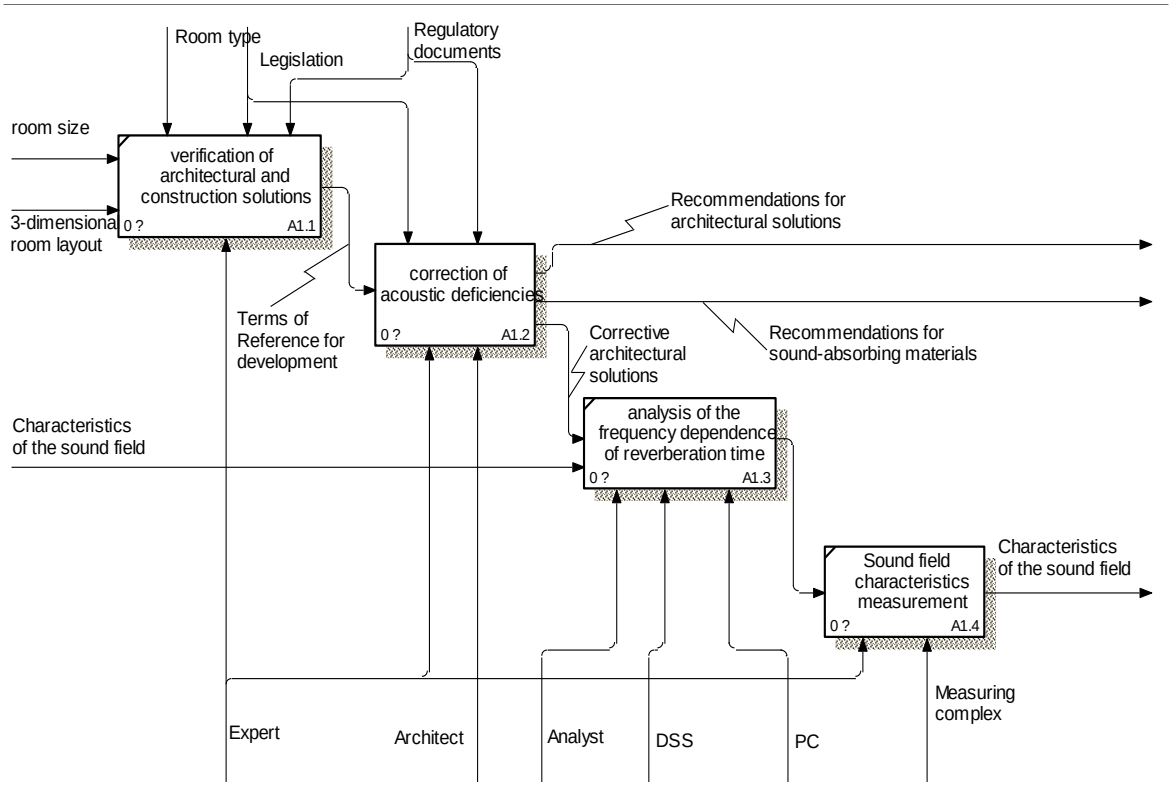


Fig. 2. **Decomposition of the context diagram A1 "Audience halls"**
***Source*: compiled by the authors**

Block A1.3 "Analysis of the frequency dependence of reverberation time". The inputs to this block are the outputs of block A1.2, namely, the design solutions for the geometry of wall and ceiling panels and the corresponding sound-field characteristics, in particular, the reverberation time T_{60}, which is a key indicator of room acoustic quality [2], [10], [11].

The main objective of this block is to perform acoustic modeling of the room while taking the proposed solutions into account. The acoustic model is constructed using mathematical modules of the DSS, which incorporates artificial intelligence techniques. The results of the computer simulation are used to analyze the frequency dependence of the reverberation time at the designated measurement points in the room. Based on the simulation results, the effectiveness of the proposed architectural and construction a solution is evaluated, and the solutions can be modified if necessary.

Block A1.4 "Measurement of sound field characteristics". This stage is performed after the completion of construction and finishing works. The objective sound-field parameters are measured at designated measurement points in the room. A hardware–software measurement system based on EASERA 1.1.3 [26] is used for these measurements.

4.2. A2 "Small volumes with predominantly linguistic content"

The decomposition of the context diagram A2 is presented in Fig. 3.

For the decomposition of work A2 "Small volumes with predominant speech content", the following works were selected: A2.1 – Checking the reflective capabilities of surfaces; A2.2 – Application of finishing materials; A2.3 – Analysis of the sound field at listening positions; A2.4 – Measurement of sound field characteristics. In this case, the general sequence of stages in diagram A2 remains unchanged compared with that of A1, "Auditoriums", but the content of the key stages differs [15]. This is due to the relatively small volume of these rooms and their typically rectangular geometry, in which the surfaces are predominantly parallel to one another. The results of the decomposition are discussed in greater detail below.

Block A2.1 "Checking the reflective capabilities of surfaces". As noted above, the small room volume and the parallel arrangement of the surfaces result in multiple reflections between parallel surfaces and the formation of standing waves, which can lead to echoes and increased reverberation time. At the same time, there are

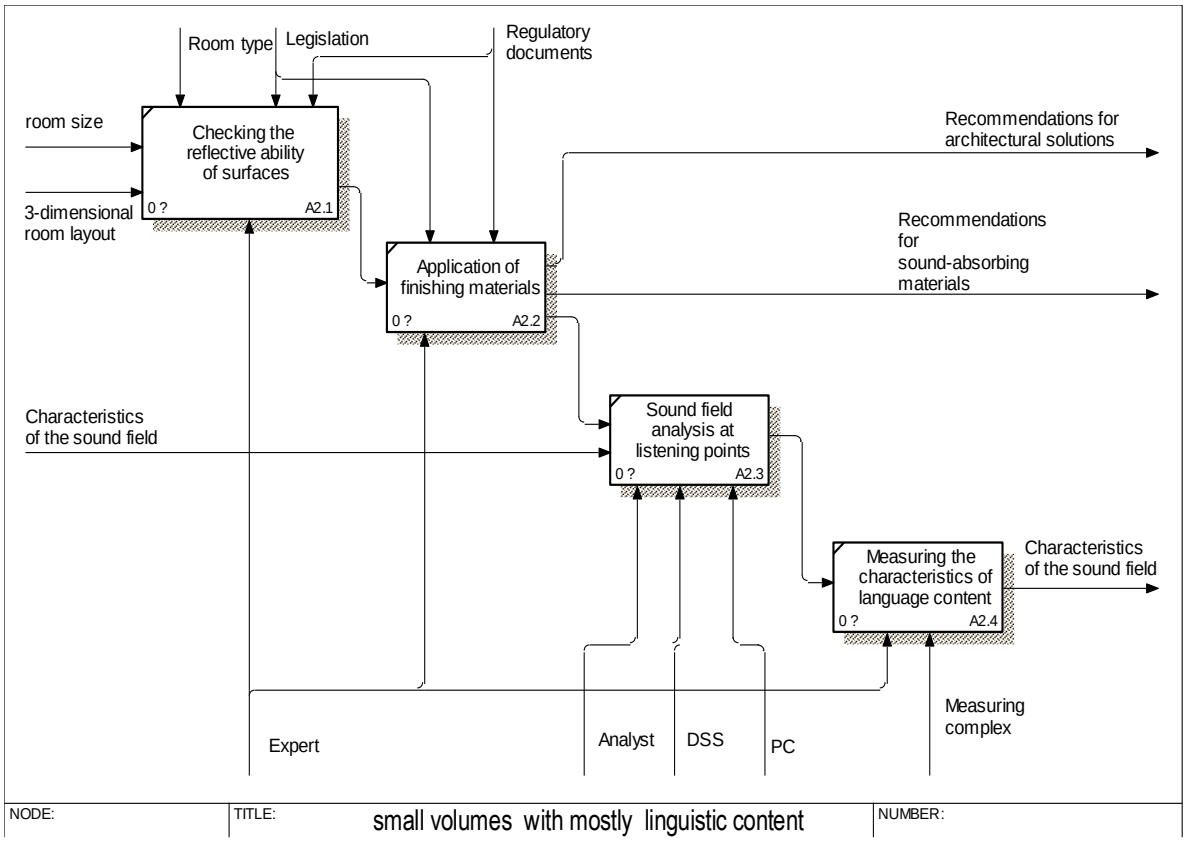


Fig. 3. **Decomposition of the A2 context diagram "Small volumes with predominantly linguistic content"**

***Source*: compiled by the authors**

constraints on modifying the surface geometry to reduce the number of parallel surfaces. In most cases, the surfaces are made of glass, which limits the possibility of modifying their geometry. Furthermore, because the room volume is small, the dimensions of the enclosing surfaces are significantly smaller than the acoustic wavelength, particularly at low frequencies. Therefore, geometric modifications can be effective only over a limited frequency range in which the acoustic wavelength is comparable to the characteristic dimensions of the room. In addition, large glass surfaces with a low sound absorption coefficient produce strong reflected sound fields. Consequently, the main objective at this stage is to assess the sound-reflection properties of the surfaces and determine the sound-field parameters over the frequency range relevant to speech content.

Block A2.2 "Application of finishing materials". At this stage of the acoustic assessment, finishing materials that are effective within the speech-frequency range should be selected. When glass is used for wall surfaces, the possibility of modifying their acoustic properties by applying conventional finishing materials is very limited. One option for increasing the sound absorption of glass surfaces is the use of curtains. Curtains can be made of specialized acoustic fabrics with appropriate sound absorption characteristics or of fabrics commonly used for stage curtains. Another option is the use of suspended sound-absorbing ceiling structures, such as frameless acoustic ceiling islands and/or vertical sound-absorbing panels (baffles).

Block A2.3 "Analysis of the sound field at listening positions". The room is acoustically modeled with the proposed solutions taken into account. The resulting sound-field parameters are evaluated within the speech-frequency range at the designated listening points.

Block A2.4 "Measurement of sound field characteristics" – is performed without fundamental changes, taking into account that the parameter being evaluated is speech intelligibility within the speech-frequency range.

4.3. A3 "Press Centers"

For the decomposition of work A3 "Press Centers", the following works were identified: A3.1 – Building a room model; A3.2 – Selection of finishing materials; A3.3 – Analysis of sound field parameters; A3.4 – Analysis of structures of

reverberation processes. The decomposition of the context diagram A3 is presented in Fig. 4.

In rooms such as press centers, there are stringent requirements for speech intelligibility, while significant modifications to the room geometry are generally not feasible because of the limited dimensions.

In addition, the following specific features must be taken into account when conducting the acoustic assessment:

– the functional purpose of the room, which determines the need to create specific acoustic conditions to ensure the required speech clarity and intelligibility;

– the presence of a projection screen, which implies the use of multimedia content and a sound reinforcement system and requires acoustic conditions that do not impair the reproduction of speech and musical content;

– the presence of built-in cabinets with glass front panels (display cases) located along the parallel side walls.

Taking into account the specific features of press center rooms described above, the formulation of tasks aimed at achieving optimal acoustic conditions is shifted toward the modeling and analysis of reverberation characteristics, where problematic parallel surfaces can be identified. Consequently, acoustic deficiencies that would normally be identified at the initial stage in models A1 and A2 are detected at a later stage in this case, resulting in a change in the sequence of stages beginning with the modeling stage.

Block A3.1 "Building a room model" – a room model is constructed that accounts for the existing architectural and construction features, the presence of furniture, and the sound-reflection properties of all surfaces.

Block A3.2 "Selection of finishing materials" – surface treatment materials are selected to achieve the required frequency-dependent reverberation time in accordance with the functional purpose of the room and the type of sound content presented.

Block A3.3 "Analysis of sound field parameters" – analysis of objective parameters characterizing the sound field in the room and their effect on the clarity and intelligibility of speech and musical content.

To assess speech intelligibility, the following indicators were used [14]:

%ALcons (Articulation Loss of Consonants), which represents the percentage of consonants lost during speech transmission and is directly related to speech intelligibility (maximum permissible value: 10 %);

STI (Speech Transmission Index), which quantifies speech transmission quality; and the speech clarity index C_{50}. Excessive reverberation time increases articulation losses because the reverberant sound from preceding signals acts as interference for subsequent speech signals, thereby reducing speech intelligibility.

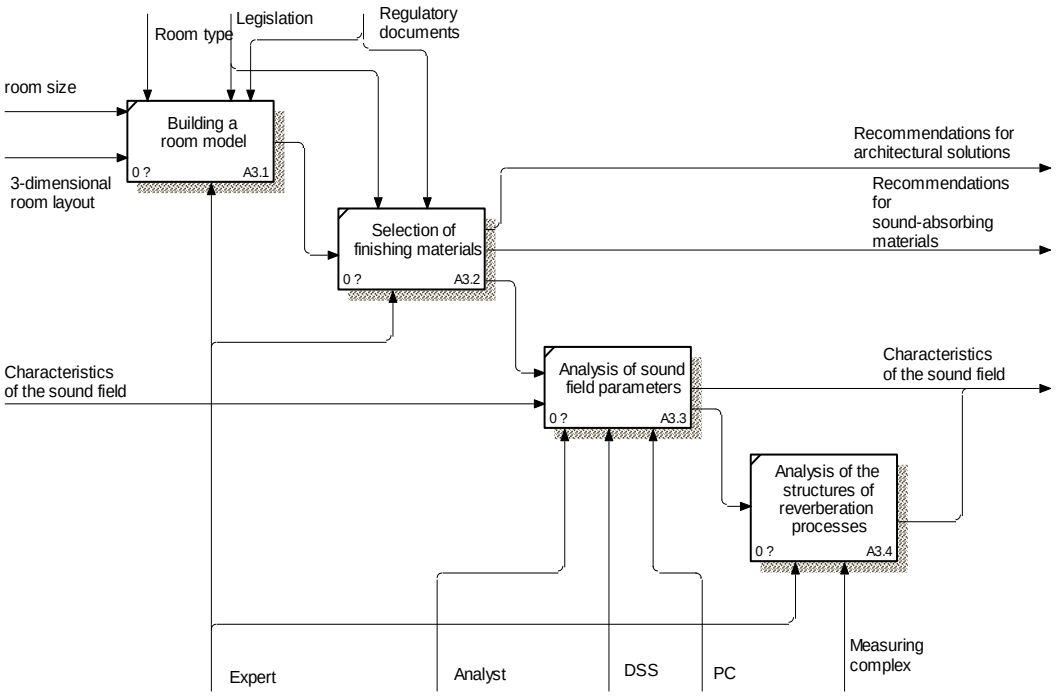


Fig. 4. **Decomposition of the A3 context diagram "Press centers"**
***Source*: compiled by the authors**

Block A3.4 "Analysis of structures of reverberation processes" – room impulse responses are obtained at the designated listening positions, and their analysis enables the assessment of the perceived acoustic characteristics of the room at each position. Recommendations are then developed to mitigate undesirable sound reflections.

4.4. A4 "Special premises"

When decomposing work A4 "Special premises", the following works were identified: A4.1 – Measurement of sound field characteristics; A4.2 – Correction of architectural and construction solutions; A4.3 – Replacement of Acoustic Surface Finishes; A4.4 – Use of sound reinforcement systems. The decomposition of the context diagram A4 is presented in Fig. 5.

Special-purpose rooms are subject to specific requirements for speech quality and may also be equipped with a sound reinforcement system. Therefore, a different sequence of assessment stages is proposed, beginning with the "final" fourth stage, which is treated as the initial stage in this case (see Fig. 5) [27]. This approach first involves defining the assessment conditions based on the specific characteristics of the room and the type of content, selecting an appropriate hardware–software measurement system and informative evaluation criteria, and only then processing and analyzing the measurement results.

Block A4.1 "Measurement of sound field characteristics". Since this stage is particularly important for this type of room, it is considered in greater detail through further decomposition.

Block A4.1.1 "Determination of research conditions". The basis for conducting an acoustic assessment of special-purpose rooms, such as meeting rooms, is typically unsatisfactory speech intelligibility, both when using an omnidirectional sound source and when using an existing sound reinforcement system. Therefore, the assessment conditions are defined by the requirements of relevant regulatory documents concerning speech intelligibility metrics, which are used to determine the measurement microphone layout.

Block A4.1.2 "Conducting field characteristics measurements". Sound-field measurements are performed using two types of test signal sources. For the acoustic measurements, an omnidirectional sound source is positioned at a height of 1.5 m above the floor along the longitudinal axis of the room, near the central seating position. For the electroacoustic measurements, the existing sound reinforcement system of the room, with the conference system switched on, is used as the test signal source.

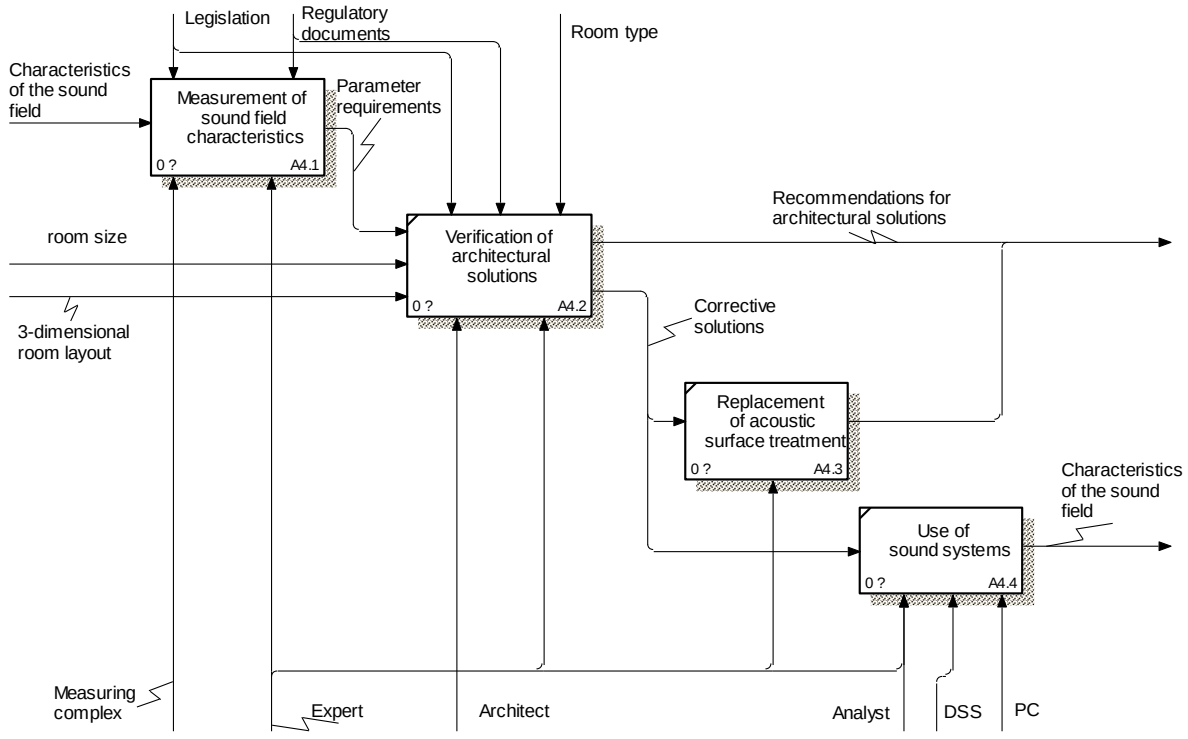


Fig. 5. **Decomposition of the A4 context diagram "Special premises"**
***Source*: compiled by the authors**

Block A4.1.3 "Determination of acoustics assessment criteria". The following acoustic parameters are used as criteria for assessing the quality of the sound content: reverberation time T_{30}, early decay time (EDT), speech clarity C_{50}, direct sound clarity C_7, %ALcons (Articulation Loss of Consonants), STI (Speech Transmission Index), and RASTI (Rapid Speech Transmission Index).

Block A4.1.4 "Analysis of results". The previously defined acoustic parameters are calculated at the designated measurement points, and frequency-dependent plots of T_{30} and the early decay time (EDT) are generated. The analysis results are used to identify specific locations within the room where correction of the sound-field parameters is required.

Block A4.2 "Correction of architectural and construction solutions". To improve the sound-field parameters, corrective designs for the enclosing surface structures are developed.

Block A4.3 "Replacement of acoustic surface finishes". Application of sound-absorbing materials for acoustic treatment of surfaces.

Block A4.4 "Use of sound reinforcement systems". To improve the acoustic properties of the room, corrective measures may involve not only modifying the geometry of the enclosing surfaces and applying acoustic treatment, but also installing or replacing the existing sound reinforcement system, including its type, suspension points, orientation angle, equalization, and signal-processing settings.

5. RESULTS OF VALIDATION OF THE FUNCTIONAL MODEL

The functional model was validated using four meeting rooms with the same functional purpose (hereinafter referred to as Rooms No. 1, No. 2, No. 3 and No. 4) [16]. The selected rooms are representative of typical acoustic conditions and are commonly found in modern office, administrative, and educational facilities.

The following features are common to all the studied rooms:

– small internal volume;

– speech is the predominant type of sound content;

– limited possibilities for modifying the architectural and spatial configuration due to the small geometric dimensions of the rooms and the large area of glass enclosing surfaces.

The studied premises belong to the functional model A2 "Small volumes with a predominance of language content" (Fig. 6).

At the first stage of testing, A2.1 "Checking the reflective capabilities of surfaces", acoustic modeling was performed for each of the studied rooms using EASE 4.3 to assess the sound-reflection properties of the interior surfaces [6], [7].

All seating positions are represented by measurement points, which is typical for rooms of this functional type and provides an acceptable computational load.

Analysis of the modeling results made it possible to identify the surfaces that are the main sources of multiple reflections and to assess their influence on sound-field formation. The obtained results served as a basis for selecting the surfaces requiring acoustic treatment at subsequent stages of the functional model. Fig. 7 presents examples of reverberation patterns for Room No. 2 (Fig. 7a) and Room No. 3 (Fig. 7b), illustrating multiple reflections of sound waves between parallel surfaces with low sound absorption. Analysis of the reverberation modeling results for all studied rooms showed that the initial portion of the reverberation process is characterized by relatively uniform attenuation of sound energy. In contrast, during the final portion of the reverberation process, the amplitude of the reflected waves decreases only slightly, resulting in an increase in reverberation time and, consequently, reduced speech intelligibility.

In addition, the presence of a significant number of strong reflections in the reverberation tail indicates multiple reflections between parallel surfaces with low sound absorption. Collectively, these factors contribute to the occurrence of echoes and confirm the need for acoustic treatment of the surfaces at subsequent stages of the functional model.

The obtained results confirm the correct operation of block A2.1 of the functional model and justify proceeding to the next stage, which involves the selection and evaluation of the effectiveness of acoustic surface treatment measures.

After identifying the surfaces responsible for the largest number of multiple reflections, the next stage of the functional model is the selection of an acoustic treatment method for the room, represented by block A2.2, "Application of finishing materials". The main objective of this stage is to reduce the intensity of sound reflections within the speech-frequency range by increasing the sound absorption of the enclosing structures [16].

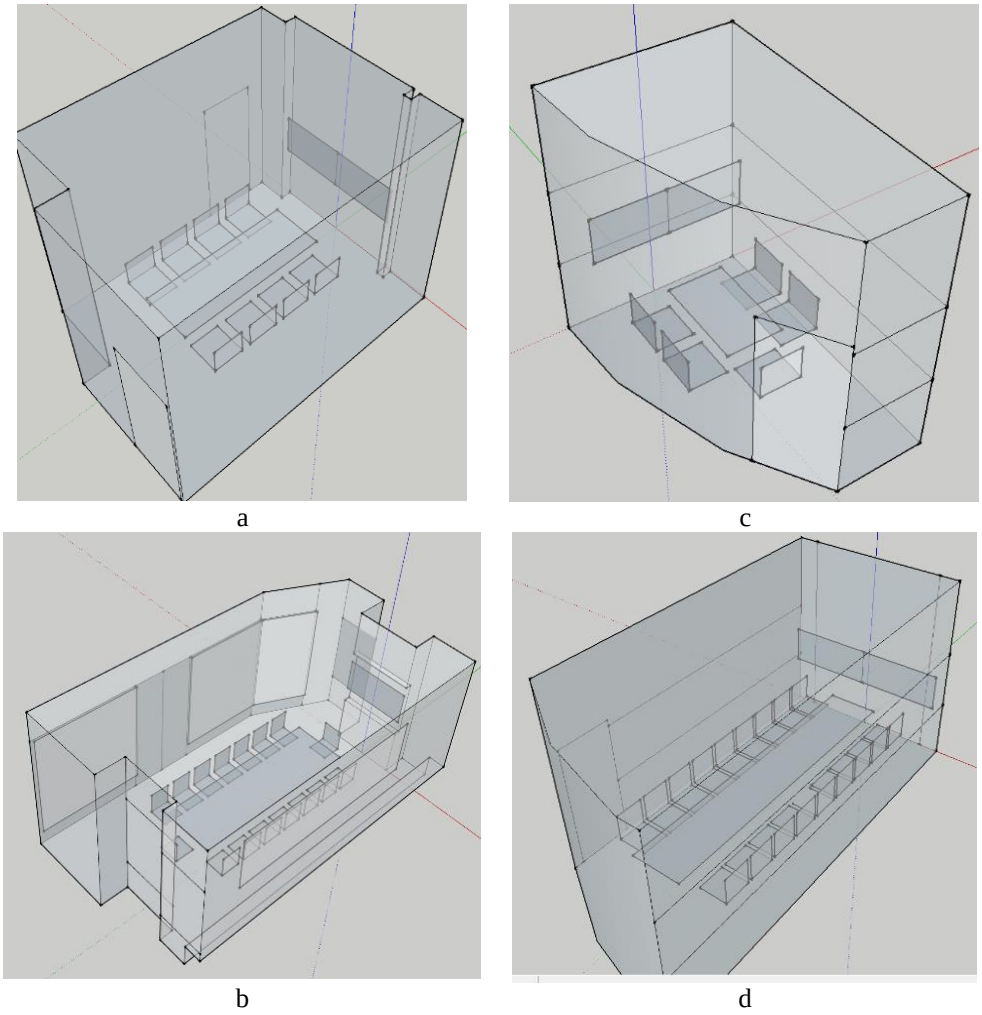


Fig. 6. **3D model of the investigated room:**
a – room No.1 with a volume of 45.5 m^3; b – room No.2 with a volume of 104.6 m^3;
c – room No.3 with a volume of 22.19 m^3; d – room No.4 with a volume of 67.64 m^3
Source: compiled by the authors

In general, the acoustic characteristics of a room can be corrected using two main approaches:

– modifying the finishing materials of the enclosing surfaces to adjust the frequency dependence of the reverberation time;

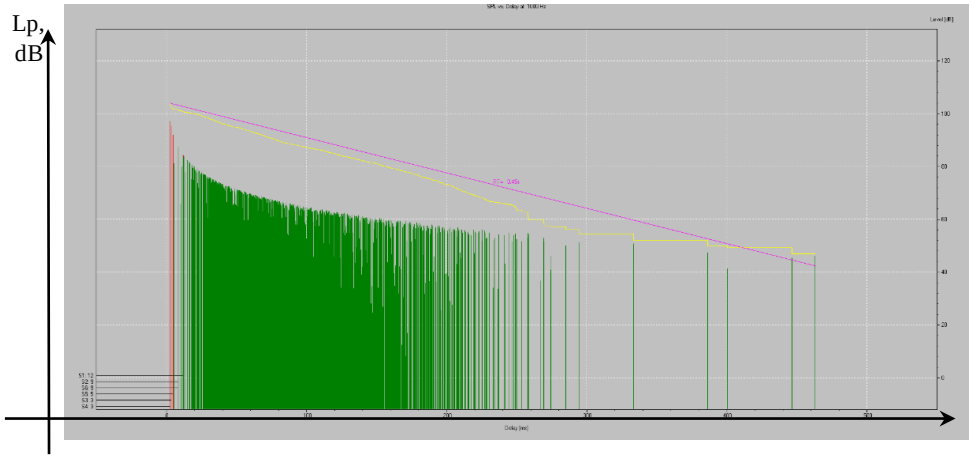
– modifying the geometry of the enclosing surfaces, followed by the selection of appropriate finishing materials to achieve the required acoustic characteristics.

However, for the studied rooms represented by functional model A2, "Small volumes with predominant speech content", modifying the geometry of the enclosing structures is impractical due to the limited room dimensions, the specific architectural and spatial configuration, and the need to preserve the existing interior design. Therefore, within the framework of testing the functional model, the use of additional sound-absorbing finishing materials was selected as the primary method of acoustic correction.

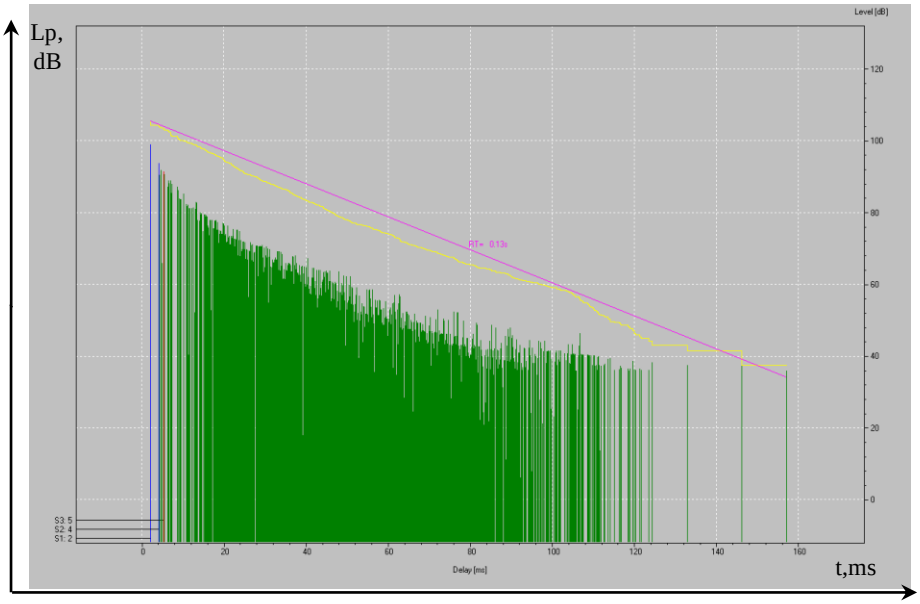
The materials were selected based on the results of the previous stage, which identified the surfaces contributing most significantly to multiple reflections. Particular attention was given to the acoustic treatment of glass surfaces, which are characterized by high sound-reflection coefficients and are a major source of undesirable reverberation.

The results of the selection of finishing materials for each studied room are given in Table 1.

The results of testing block A2.2 showed that, for all studied rooms, the primary acoustic correction strategy is to increase the sound absorption of the enclosing structures without modifying their geometry. Despite differences in the architectural and spatial configurations of the rooms, the functional model consistently identified the need to acoustically treat the glass surfaces and apply sound-absorbing materials to the walls and ceiling. These measures reduce the intensity of multiple reflections and reverberation time while improving speech intelligibility.



a



b

Fig. 7. **Structure of the reverberation process in the room: a – room No.2; b – room No.3**

***Source*: compiled by the authors**

Table 1. **Results of testing block A2.2 "Application of finishing materials"**

Room No.	Main problem surfaces (result of stage A2.1)	Suggested finishing materials	Expected result of acoustic correction
No. 1	Glass surfaces and parallel wall panels causing unwanted reflections	HERADESIGN Micro-SW profiled wall panels; sound-absorbing suspended ceiling; curtains on glass surfaces	Reduction of late-reflection amplitude; elimination of echoes and flutter echoes
No. 2	Longitudinal glass surfaces with a low sound absorption coefficient	HERADESIGN sound-absorbing wall panels; acoustic suspended ceiling; carpeting; acoustic curtains (or OpenAkustik) on glass surfaces	Reduction of reverberation time; increased speech intelligibility; reduced intensity of multiple reflections
No. 3	Large glazed areas and parallel surfaces	Use of sound-absorbing wall and ceiling materials; acoustic curtains on glass surfaces	More uniform decay of reflected sound energy and reduced influence of unwanted reflections
No.4	Parallel wall panels and glass surfaces	HERADESIGN profiled wall panels Micro - SW and KNAUF Perfpanel B 4-12/25 Q; sound-absorbing ceiling; carpeting; curtains on glass surfaces	Increased sound absorption; reduced reflection intensity; improved speech intelligibility

***Source*: compiled by the authors**

After selecting the acoustic treatment measures (block A2.2), the studied rooms were modeled again, taking into account the proposed finishing materials (block A2.3, "Analysis of the sound field at listening positions"). The purpose of this modeling is to evaluate the effectiveness of the acoustic treatment based on the sound-field characteristics at the designated listening positions. The reverberation pattern, spatial distribution of sound energy, and speech-perception quality metrics are analyzed.

The simulation results presented in Table 2 demonstrate the effectiveness of the proposed acoustic treatment. After the application of sound-absorbing materials, a decrease in T_{30} and EDT and an increase in C_{50} and STI were observed in all studied rooms, indicating improved conditions for speech perception and intelligibility.

The obtained results confirmed the improvement in sound-field characteristics following the acoustic treatment and justified proceeding to block A2.4 "Measurement of sound field characteristics", where the acoustic parameters in the speech-frequency range are quantitatively assessed.

The final stage of testing (Block A2.4 "Measurement of sound field characteristics") of the functional model is a quantitative assessment of the sound field characteristics after the implementation of the proposed acoustic correction. For each studied room, the main acoustic parameters at the listening control points in the speech frequency range.

The characteristics of the existing sound field were measured using a hardware-software measurement system. The system comprises EASERA 1.1.3 acoustic measurement software [26], a sound card, a test signal source, and an NTi Audio M2010/M2015 measurement microphone. The microphone is a 1/2-in omnidirectional measurement microphone with a flat frequency response and complies with the requirements of Class 1 specified in IEC 61672-1.

During the measurements, the test signal generated by EASERA 1.1.3 was transmitted through a sound card to a loudspeaker located in the room under study. An omnidirectional sound source positioned 1.5 m above the floor at the designated speaker position was used as the test signal source. The acoustic response of the room was recorded using an NTi Audio M2010/M2015 measurement microphone and transmitted through the sound card to EASERA 1.1.3 for further processing. The measurement points coincided with the corresponding simulation points and were located at the seating positions of all chairs in each room. The measurement conditions and the number of measurements at each control point were determined in accordance with the applicable requirements and implemented using the built-in software functions, including microphone calibration and generation of pulse signals with a specified duration and number of repetitions.

The measurement results are presented in Table 3 and were used to evaluate the effectiveness of the proposed solutions and validate the functional model.

Table 2. **Results of testing block A2.3 "Analysis of the sound field at listening positions"**

Room No.	Acoustic characteristics of the sound field before correction				Acoustic characteristics of the sound field after correction			
	T_{30}, s	**EDT, s**	**C_{50}, dB**	**STI**	**T_{30}, s**	**EDT, s**	**C_{50}, dB**	**STI**
No. 1	0.40	0.42	2.10	0.68	0.20	0.18	6.06	0.82
No. 2	0.70	0.74	-1.80	0.58	0.30	0.27	5.35	0.80
No. 3	0.25	0.27	3.40	0.75	0.15	0.14	4.37	0.78
No.4	0.37	0.39	2.70	0.69	0.19	0.17	5.48	0.82

***Source*: compiled by the authors**

Table 3. **Results of testing of block A2.4 "Measurement of sound field characteristics"**

Room No.	T_{30}, s	EDT, s	C_{50}, dB	STI	Conclusion
No. 1	0.21	0.2	6.2	0.81	Compliance with meeting-room requirements
No. 2	0.32	0.29	5.3	0.79	Improved speech perception
No.3	0.17	0.16	4.5	0.78	Recommended acoustic performance achieved
No.4	0.2	0.19	5.5	0.8	High speech intelligibility achieved

***Source*: compiled by the authors**

6. DISCUSSION OF RESULTS

The testing results confirmed the functionality of the proposed functional model for rooms of category A2, "Small volumes with a predominance of speech content" [16].

The control points covered the seating positions and enabled assessment of the spatial variability of the acoustic parameters in accordance with [10], [11]. The number of repeated measurements was determined to ensure the required repeatability of the results. For all studied rooms, the model enabled the identification of surfaces responsible for multiple reflections, the selection of appropriate acoustic treatment measures, and the improvement of the main acoustic parameters. The aggregated testing results are presented in Table 4 and confirm the applicability of the developed functional model to the acoustic examination of enclosed rooms.

Table 4. **Results validation functional models**

Room No.	Relative discrepancy, %			
	T_{30}	EDT	C_{50}	STI
No. 1	5.0	10.0	2.3	1.2
No. 2	6.3	6.9	0.9	1.3
No. 3	11.8	12.5	2.9	0.0
No. 4	5.0	10.5	0.4	2.5

***Source*: compiled by the authors**

A comparative analysis of the obtained values demonstrates good agreement between the modeling results and the experimental data, confirming the adequacy of the functional model.

Additionally, the proposed functional model was compared with the conventional acoustic examination procedure based on the following criteria: stage standardization, result reproducibility, validity of recommendations, and the influence of subjective factors (Table 5).

Thus, the proposed functional model provides a formalized and reproducible approach to acoustic examination and creates the prerequisites for reducing the influence of subjective factors. A quantitative comparison of the execution time with that of the conventional expert procedure requires a separate experimental study.

7. CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

The paper analyzes the specific features of acoustic examination for different types of rooms. It is shown that the content and sequence of the examination stages depend on the functional purpose of the room, the type of dominant sound content, and geometric and structural constraints, and are determined individually by the specialist for each object based on professional experience.

The relevance of developing a specialized decision support system (DSS) for acoustic examination is substantiated. The proposed DSS accounts for the specific implementation and adaptation of the examination stages to different room types, with the aim of reducing subjectivity and improving the reliability of the results. As the first stage in DSS development, the acoustic examination process was formalized by developing a functional model and its decomposition.

The functional model was tested in four A2-category rooms, "Small volumes with a predominance of speech content", and the results demonstrated the functionality of the proposed model. Quantitative assessment of the potential for improving result reliability and reducing the influence of the human factor through automation of the acoustic examination process will be possible during future testing and operation of the developed DSS.

Table 5. **Comparison of the conventional acoustic examination procedure and the proposed functional model**

Criterion	Conventional Expert Procedure	Proposed Functional Model
Execution sequence	Determined by the expert depending on the object	Formalized and standardized
Reproducibility	Depends on the expert's experience	Ensured by formalizing the examination stages
Validity of recommendations	Depends on expert judgment	Based on formalized stages and regulatory criteria
Subjective factor	Strongly dependent on the expert	Reduced through procedure standardization
Experimental verification	Depends on the specific study	Performed for four A2-category rooms

***Source*: compiled by the authors**

Prospects for further research include the development of mathematical and information models that will form the basis for the DSS architecture, comprising the following components: a common database for storing data from all stages of acoustic examination; a data management system; a knowledge base; and a user interface. The DSS software will support the implementation of the developed mathematical methods and algorithms, as well as the integration of existing acoustic modeling packages when required. The implementation of the DSS for acoustic examination will enable standardization of the examination stages for specified room types, reduce the influence of the human factor, and improve the efficiency of the examination process while preserving the possibility of expert intervention in nonstandard cases.

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Формалізація етапів проведення акустичної експертизи при проектуванні систем підтримки прийняття рішень

Усик Вікторія Валеріївна[1)]
ORCID: https://orcid.org/0000-0002-3515-4849; viktoriia.usyk@nure.ua. Scopus Author ID: 59940385100
Федорчак Богдан Петрович[2)]
ORCID: https://orcid.org/0009-0003-7335-9276; fedorchakbogdan@gmail.com. Scopus Author ID: 59532264200
Поворознюк Оксана Анатоліївна[2)]
ORCID: https://orcid.org/0000-0001-7524-5641; povoks76@gmail.com. Scopus Author ID: 55817007400
Філатова Ганна Євгенівна[2)]
ORCID: https://orcid.org/0000-0003-1982-2322; Hanna. Filatova@khpi.edu.ua. Scopus Author ID: 56448583600
Філатов Валерій Володимирович[2)]
ORCID: https://orcid.org/0009-0007-7762-1517; Valerii.Filatov@khpi.edu.ua. Scopus Author ID: 59178850500
[1)] Харківський національний університет радіоелектроніки, просп. Науки, 14. Харків, 61023, Україна
[2)] Національний Технічний Університет "ХПІ", вул. Кирпичова, 2. Харків, 61002, Україна

АНОТАЦІЯ

Актуальність. Робота присвячена вирішенню актуальної науково-технічної задачі побудови функціональної моделі проведення акустичної експертизи замкнених приміщень різного призначення при проектуванні систем підтримки прийняття рішень. Відмічені специфічні вимоги щодо необхідних властивостей звукового поля, послідовностей етапів експертизи, та особливостей проведення кожного етапу для різних типів приміщень (концертні зали, конференц-зали, прес-центри, офісні приміщення, переговорні кімнати, тощо). Таким чином, для кожного типу приміщення процес проведення акустичної експертизи визначається фахівцем індивідуально, спираючись на свій професійний досвід. Тому актуальним завданням є формалізація етапів та розробка функціональної моделі процесу акустичної експертизи різних типів замкнених приміщень при розробці структури спеціалізованої системи підтримки прийняття рішень. **Мета та завдання дослідження** полягає в зменшенні суб'єктивної складової, підвищенні обґрунтованості і достовірності результатів акустичної експертизи шляхом розробки узагальненої функціональної моделі процесу акустичної експертизи замкнених приміщень різного функціонального призначення. **Методи дослідження.** Методи статистичної теорії застосовано для розрахунку часу реверберації. Геометрична теорія розповсюдження звуку застосовується для аналізу структури відбиттів від поверхонь та виявлення акустичних дефектів у складних за формою приміщеннях. **Були отримані наступні результати**. Розроблено узагальнену функціональну модель процесу акустичної експертизи за допомогою методології функціонального моделювання IDEF0 та виконано її декомпозицію. При декомпозиції було виділено чотири основні функціональні блоки: А1– Глядацькі зали; А2 –Малі об'єми з переважно мовним контентом; А3 – Прес-центри; А4 – Спеціальні приміщення. Для кожного з вказаних блоків виконана подальша декомпозиція, в результаті якої виділені етапи, в яких стандартизовано загальний підхід до реалізації етапів, але враховані специфічні вимоги до характеристик звукового поля кожного типу приміщення. Виконано апробацію функціональної моделі при проведенні акустичної експертизи чотирьох переговорних кімнат. **Висновки**. Обґрунтована актуальність розробки спеціалізованої системи підтримки прийняття рішень при проведенні акустичної експертизи. В якості першого етапу побудови системи виконана формалізація етапів проведення акустичної експертизи шляхом розробки функціональної моделі та її декомпозиції. Результати апробації підтвердили працездатність запропонованої функціональної моделі. Перспективами подальших досліджень є розробка інформаційного, математичного та програмно-апаратного забезпечення системи підтримки прийняття рішень при проведенні акустичної експертизи.

Ключові слова: акустична експертиза; етапи акустичної експертизи; замкнуте приміщення; звукове поле; параметри; функціональна модель; підтримка рішень; оптимізація акустичних властивостей; звуковий контент

ABOUT THE AUTHORS



Victoriya V. Usik -andidate of Engineering Sciences, Associate Professor, Professor at the Department of Media Engineering and Information Radio Electronic Systems.Kharkiv National University of Radio Electronic, 14, Nauky Ave Kharkiv, 61023, Ukraine
ORCID: https://orcid.org/0000-0002-3515-4849; viktoriia.usyk@nure.ua. Scopus Author ID: 59940385100
Research field: architectural acoustics, room acoustic modeling, acoustic assessment, digital signal processing, computational acoustics, artificial intelligence applications in acoustic modeling

Усик Вікторія Валеріївна - кандитат технічних наук, доцент, професор кафедри Медіаінженерії та інформаційних радіоелектронних систем. Харківський національний університет радіоелектроніки, просп. Науки, 14. Харків, 61023, Україна
***Галузь досліджень*:** архітектурна акустика, акустичне моделювання приміщень, акустична експертиза, цифрова обробка сигналів, обчислювальна акустика, застосування штучного інтелекту в акустичному моделюванні



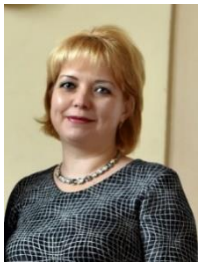
Bohdan P. Fedorchak - PhD student of the Department of Multimedia and Internet Technologies and Systems, National Technical University "Kharkiv Polytechnic Institute", 2, Kyrpychova Str. Kharkiv, 61002, Ukraine
ORCID: https://orcid.org/0009-0003-7335-9276; fedorchakbogdan@gmail.com. Scopus Author ID: 59532264200
Research field: room acoustics, acoustic modeling and assessment of enclosed spaces, digital signal processing, computational acoustics, sound field analysis, room acoustic optimization, speech intelligibility assessment

Федорчак Богдан Петрович - аспірант кафедри Мультимедійних та інтернет технологій і систем. Національний Технічний Університет "ХПІ", вул. Кирпичова, 2. Харків, 61002, Україна
***Галузь досліджень*:** акустика приміщень, акустичне моделювання та оцінювання замкнених просторів, цифрова обробка сигналів, обчислювальна акустика, аналіз звукового поля, оптимізація акустики приміщень, оцінювання розбірливості мовлення



Oksana A. Povoroznyuk - Candidate of Engineering Sciences, Associate Professor, Computer Engineering and Programming Department. National Technical University "Kharkiv Polytechnic Institute", 2, Kyrpychova Str. Kharkiv, 61002, Ukraine.
ORCID: http://orcid.org/0000-0001-7524-5641; povoks76@gmail.com; Scopus Author ID: 55817007400
Research field: information security, artificial intelligence, neural networks, signal processing, database design, decision support systems

Поворознюк Оксана Анатоліївна - кандидат технічних наук, доцент, доцент кафедри Комп'ютерної інженерії та програмування. Національний Технічний Університет "ХПІ", вул. Кирпичова 2. Харків 61002, Україна.
***Галузь досліджень*:** інформаційна безпека, штучний інтелект, нейронні мережі, обробка сигналів, проєктування баз даних, системи підтримки прийняття рішень



Anna E. Filatova - Doctor of Engineering Sciences, Professor, Computer Engineering and Programming Department. National Technical University "Kharkiv Polytechnic Institute", 2, Kyrpychova Str. Kharkiv, 61002, Ukraine.
ORCID: https://orcid.org/0000-0003-1982-2322; Hanna.Filatova@khpi.edu.ua. Scopus Author ID: 56448583600
Research field: information technologies, intelligent decision support systems, mathematical modeling, digital signal and image processing, artificial intelligence and fuzzy logic methods, computer-aided diagnostics.

Філатова Ганна Євгенівна - доктор технічних наук, професор кафедри Комп'ютерної інженерії та програмування, Національний Технічний Університет "ХПІ", вул. Кирпичова, 2. Харків, 61002, Україна
***Галузь досліджень*:** інформаційні технології, інтелектуальні системи підтримки прийняття рішень, математичне моделювання, цифрова обробка сигналів і зображень, методи штучного інтелекту та нечіткої логіки, комп'ютерна діагностика



Valerii V. Filatov - PhD, Senior Lecturer of Computer Engineering and Programming Department. National Technical University "Kharkiv Polytechnic Institute", 2, Kyrpychova Str. Kharkiv, 61002, Ukraine
ORCID: https://orcid.org/0009-0007-7762-1517; Valerii.Filatov@khpi.edu.ua. Scopus Author ID: 59178850500
Research field: radio engineering and information-measuring systems, digital signal and image processing, mathematical modeling of technical systems, intelligent data analysis, fuzzy logic and clustering methods

Філатов Валерій Володимирович - PhD, старший викладач кафедри Комп'ютерної інженерії та програмування, Національний Технічний Університет "ХПІ", вул. Кирпичова 2. Харків, 61002, Україна
***Галузь досліджень*:** радіотехнічні та інформаційно-вимірювальні системи, цифрова обробка сигналів і зображень, математичне моделювання технічних систем, інтелектуальний аналіз даних, методи нечіткої логіки та кластеризації