A way to investigate the soundscape of urban spaces: a case study on the example of city of Zabrze

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Abstract

The paper describes the concept of design research on the soundscape in selected places of the urban environment and presents the achieved results of the project related to that. The method of acquiring and processing information about the soundscape and its evaluation has been obtained by means of psychoacoustic tests realized in laboratory conditions. An important element of the carried out research was the development of an application that shares soundscape map information to users using mobile technologies. The application allows identification and assessment of city soundscape.

Introduction

The assessment of noise pollution in the outdoor spaces is one of the complex problems related to environmental assessment. In order to perform this kind of assessment the sound sources and parameters characterizing acoustic climate have to be investigated. Variability of these parameters is mainly due to the type and dynamics of sound sources over time and instability of meteorological conditions. The specificity of noise pollution lies in the complexity of human hearing and its subjective evaluation, in the high spatiotemporal variability and in the rich spectral content of noise generated by a variety of sources in the environment.

In terms of describing the acoustic environment and evaluating noise mitigation strategies, relevant noise indicators have to be used. Correct selection of appropriate noise indicators in the urban context and making decisions based on them is a necessary activity when it comes to the threat mitigation of noise sources.

Research on noise indicators has led to the conclusion that L_{Aeq} has been recognized as a basic descriptor for evaluating sounds, including fluctuating ones.

The L_{Aeq} indicator is critically evaluated in many respects, including:

- it is not the best indicator for assessing pleasant sounds,
- it covers only the energy dimension of noise, and therefore poorly distinguishes between sound environments.

It should be noted that the various energy indicators used for noise annoyance assessment do not take into account the evaluation of fluctuating sounds, which are commonly found in urban areas and which have a negative impact on noise annoyance [1].

According to the studies on the identification of the soundscape, its occurrence in human perception in the acoustic environment is considered as the basis for its existence [2]. The soundscape depends strongly on human perception in the context of a specific time, place and activity. The soundscape refers to the perception aspect of preferred sounds.

Attempts to correlate objective and subjective information obtained from environmental and laboratory studies are an important source of knowledge on the soundscape. In particular, the acquisition of objective information includes "in-situ" measurements of sound levels, binaural sound recordings and sound characteristics. The use of methods linking acoustic comfort to sound levels, mainly by means of L_{Aeq}, is increasingly important in the implementation of soundscape research work, particularly in the assessment of urban noise.

In the studies on the soundscape and its impact on people's daily lives as well as psychological and health aspects, three basic approaches can be considered, i.e. physical, psychophysical and perceptual:

- **the physical approach** adopts an objective assessment of the acoustic environment [3]. This approach utilizes the technology of acoustic mapping, which is a basic tool in the tasks of assessing and forecasting the acoustic environment of a large part of European countries. In this approach, acoustic impressions of sound perception are treated secondarily,
- **psychophysical approach**, includes the relationship between the acoustic environment and the impressions of sound perception. Objective acoustic parameters (i.e., most often in the form of sound levels) are linked to subjective impressions of acoustic evaluation. The complexity of this approach lies, among other things, in the direct consideration of varying sound characteristics (represented in the time and frequency domains) and personal or socio-demographic characteristics [4, 5].
- **The perceptual approach** has relatively recently begun to be taken into account, in this case the soundscape is treated mainly as a source of information and an element of the interaction between people and the environment.

Among the methods used to assess the soundscape the following are worth mentioning [6]:

- analysis of acoustic signals under laboratory conditions,
- the sound walk method,
- the survey research method.

Analysing acoustic signals under laboratory conditions, targeting the perception of the sound environment is one of the methods evaluating the soundscape that can be useful in obtaining more information when comparing to the typical environmental studies. This method provides exposure to the sound environment in established and controlled situations. The ability to use ambisonic technology allows for a relatively accurate synthesis of the sound field through the use of a multichannel listening system. Analyses from the resulting signals are used to search for coefficients that characterize the soundscape.

The sound walk method is used in soundscape analyses and evaluations, such as the study of locations on the pedestrian path. This method includes measurements of psychoacoustic indicators and evaluation of people's perceptions at the locations under study. One of the goals of using the sound walk method is to look for correlations of psychoacoustic parameters for each location, in order to determine the strength of the relationship between objective parameters and soundscape perception.

The survey research method uses a survey form consisting of two parts: *a questionnaire* and *a semantic differential test*.

The *questionnaire part* includes categories such as personal information, land use, compliance with expectations and evaluation of the environment in terms of examining pleasant impressions of the soundscape.

The *semantic difference test* is used to examine the quality of the soundscape environment. The pairs of adjectives that are used in the semantic difference test are selected according to the native language of the related community and the soundscape description aspects.

It should be noted that the focus of the research on developing the idea of soundscapes for environmental noise assessment can contribute to the understanding of human response to noise sources in both urban and non-urban areas.

In the 2021/2022 academic year, the research works portfolio of the *Silesian University of Technology* includes PBL [1] projects. In particular, a project entitled *"Designing the acoustic component of a smart city using the concept of soundscape and mobile technologies"*, which has been carried out by an interdisciplinary and an interdepartmental team of students and academics, in particular: the *Department of Organization and Management* and the *Department of Applied*

[1] Project Based Learning

Mathematics. The problem addressed in the project concerns aspects of designing the soundscape of urban spaces, with a particular focus on the interaction of the citizens with the acoustic stimuli present. The formulated title of the project is in line with the development and implementation of the *SmartCity 3.0* concept in the cities. Solving the problem requires the development of a method to study the city soundscape using appropriate models, procedures and tools for recording, collecting and accurate processing of the acoustic signal. The starting point for developing a soundscape creation method is the procedure of creating strategic noise maps using the concept of layered map implemented in GIS[2] and the latest international standards for soundscape identification and analysis [7, 8, 9].

In order to identify and assess the acoustic climate of the cities, the strategic noise maps are being created. Based on the current EU Directive 2002/49/EC the strategic noise maps are prepared for four classes of noise sources: road noise, rail noise, aircraft noise and industrial noise. It should be noted that strategic noise maps are prepared for the purpose of assessing and preventing noise pollution caused only by the above-mentioned sources. In reality, the problem becomes more complicated and complex, as urban spaces are also exposed to diverse sources with varying dynamics, both natural and anthropogenic sources. The concept of soundscapes, which is being developed in environmental acoustic research, includes various aspects and factors related to sound perception in particular. Reducing the assessment of life quality only to one criterion, which is the human perception of the particular place (including sound perception), consequently leads to the question: is it pleasant or unpleasant to be in this place?

The results of studies on the phenomenon of noise confirm that the psychoacoustic aspects of sound, the temporal structure of the signal, the formation of subjective characteristics of sound in the following domains: time, frequency, time-frequency, among others, have a significant impact on the perception of noise [10, 11, 12].

It was assumed that the soundscape creation methodology can be created by means of designing two experiments:

- in an outdoor environment: recording and processing of the acoustic signal using specialized measurement equipment,
- in a closed room: evaluation of the acoustic signal using a listening booth and the psychoacoustic test method.

It should be noted that it is currently impossible to distinguish pleasant and unpleasant sounds using dedicated equipment, because there is a lack of such solutions both in the area of the use of appropriate measurement methods and the implementation of appropriate technologies.

Modern digital technologies in conjunction with appropriate modeling solutions make it possible to effectively support design tasks. The advantage of digital technology applications is the ability to support decision-making in both the short and long-term horizons with direct public participation. It therefore becomes crucial to develop a way of acquiring, collecting, processing and sharing digital information in the creation of smart solutions for the cities. Currently a Smart City is a city that uses advanced information and communication technologies more consciously, interactively and efficiently [13].

It was assumed for the implementation of the research that the collected acoustic signal measurement data set represents various sound sources of natural and anthropogenic origin.

The tangible result of the project was the development of an application for mobile devices, that allows users to identify and evaluate the soundscape for selected points on the city map.

1 Description of the research concept

The research area considered in the project can be identified with the help of relationships and interactions occurring among: the environment, sound source(s) and humans. The developed concept of soundscape, which is based on the identification and evaluation of sound perception, corresponds to contemporary challenges and needs of acoustic design of smart cities.

Taking into account the subjective aspects of evaluating different sounds with respect to (but not limited to): the place of residence, the activities carried out, the nature and duration of the acoustic stimulus, as well as other factors accompanying the perception of sound, are of key importance in the tasks of designing the city's soundscape.

In the adopted concept for the implementation of design tasks, it was assumed that soundscape research will use:

- acoustic and aural signals as sources of sound information of the environment,
- GIS models and tools as a way of representation and processing of sound information (the basis of the GIS spatial data model is a set of geometric elements in raster or vector form, i.e.: points, lines, surface objects, which are used to represent real world objects; geometric objects are stored on thematic layers, connected to tables containing descriptive attributes, characterizing them qualitatively or quantitatively),
- mobile application solutions that allow the acqui-

[2] Geographic Information System

sition and sharing of environmental sound information using mobile devices.

Known methods of digital acoustic/phonic signal processing use advanced models and techniques for its evaluation. They allow the study of the soundscape of urban spaces by means of physical features and auditory impressions of sound, fig. 1.

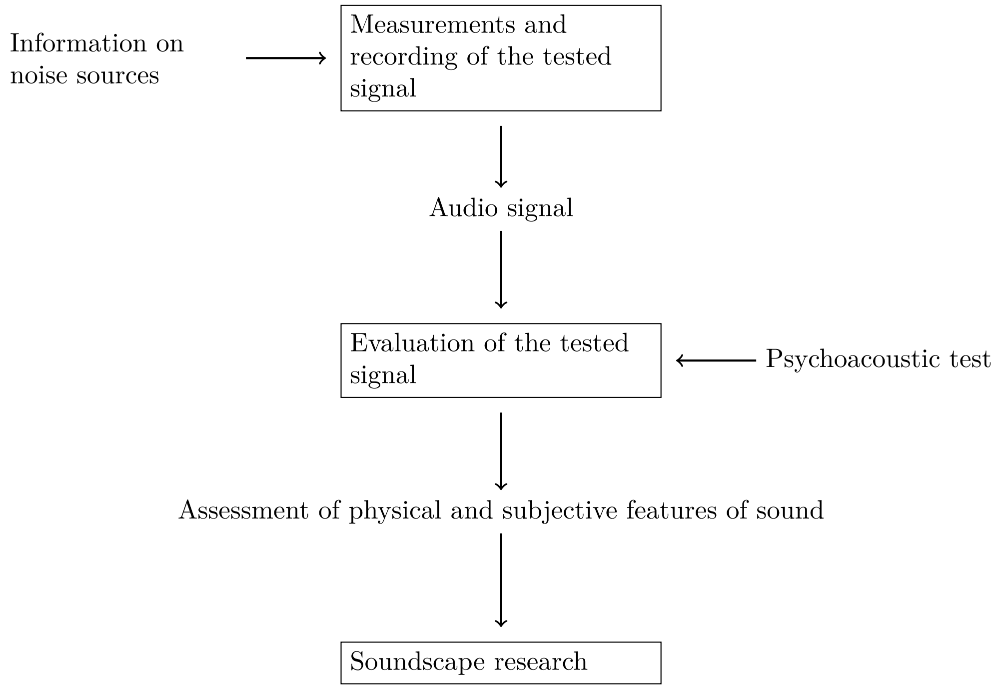


Figure 1: General scheme of information acquisition and processing for the study of the soundscape of urban spaces

For the soundscape study (Fig. 1), the following steps were taken:

- measurement and recording of the acoustic signal, which is the starting point for processing information about the characteristics of the acoustic and phonic signal,
- evaluation of the registered signal, involving methods and techniques that allow listeners to assess the annoyance/pleasantness of the sound of the registered signal, using the psychoacoustic test method.

The location of points where acoustic measurements are made and sounds are recorded, plays a key role in the study of the soundscapes. In order to properly map the measurement points, the project uses a layered model, implemented in geographic information systems (GIS). In the adopted model, the visualization part is a set of points located on a map base (raster layer), representing the locations of the measurements. In turn, the descriptive part of this layer contains a set of attributes characterizing aspects related to the acoustic measurements themselves (recorded equivalent sound level L_{Aeq}, temperature, humidity and atmospheric pressure at the time of the measurements). The descriptive attributes are stored in the database. At a given measurement point, they are available in the application based on their individual ID. In addition, this collection of points has been supplemented with photographs of the measurement sites and audio files of the audio recording made during the measurement. The `FastAPI` framework and the `React.js` library were used to create the interface of the mobile device application visualizing the information assigned to the surveyed points.

The data representation structure prepared in this way was the starting point for collecting data from measurements taking into account physical and subjective characteristics of sound.

2 Measurements and recordings of the acoustic signals as a source of information about the soundscape

A key aspect to the implementation of the listening study was the creation of the broadest possible base of sounds in the outdoor environment. To achieve this goal - sound registrations were carried out with simultaneous measurement of sound pressure levels.

To carry out the registration and acoustic measurements, 3 devices were used:

- SVAN 945A sound level meter,

- Two ZOOM sound recorders.

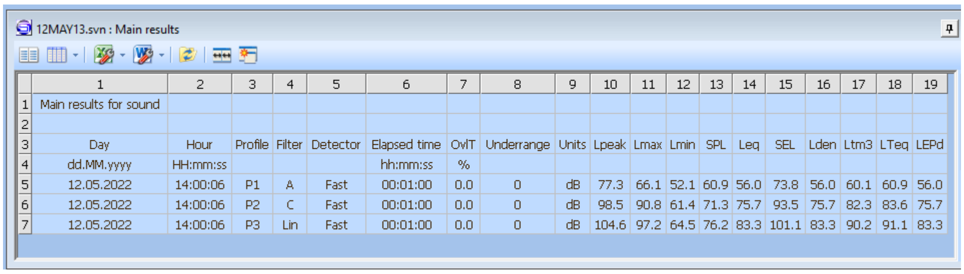
One of the sound recorders (ZOOM model H3-VR) has an ambisonic recording option thanks to the four microphones it contains, which allows recording surround sound from all sides simultaneously. The recordings were made with the AmbiX feature, as a result the audio can be played back in Ambisonics B format on four channels, which was also important for further psychoacoustic tests.

Measurement of sound pressure levels at selected points in the city was an important part of the research for the implementation of psychoacoustic tests. These values allowed calibration of the listening equipment involving re-measurement of sound pressure levels under laboratory conditions. Proper provision of sound levels during the listening tests in the amplification setting of the amplifier made it possible to adequately represent the immission of sound sources and provide acoustic conditions occurring during the implementation of measurements.

The sound recorders were the main tools for recording the audio signals under study. They were equipped with additional tripods, keeping the devices at a certain height, which made it possible to minimize the phenomena of reflection and absorption of sound by members of measurement team.

The sound recordings consists of 60-seconds of acoustic signal samples for each measurement point. The sampling frequency of the recordings was set at 44.1kHz. The frequency adopted is primarily due to the maximum frequency of human hearing - 20kHz, the Kotielnikov-Shannon theorem and the Nyquist frequency. On the one hand this frequency was a compromise due to the fact, that the evaluation of auditory impressions of sounds for most participants will not differ with increased sampling frequency. On the other hand, increasing the sampling frequency would significantly increase the amount of recorded data [14, 15].

Measurement of sound pressure levels at the test points were also carried out for 60-seconds. The obtained measurement value, recorded and saved in the application, was the L_{Aeq} value. The measurement was carried out with filter A and FAST characteristics on. Sample data recorded at a particular measurement point are shown in fig. 2.



12MAY13.svn : Main results

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	Main results for sound																		
2																			
3	Day	Hour	Profile	Filter	Detector	Elapsed time	OvlT	Underrange	Units	Lpeak	Lmax	Lmin	SPL	Leq	SEL	Lden	Ltm3	LTeq	LEPd
4	dd.MM.yyyy	HH:mm:ss				hh:mm:ss	%												
5	12.05.2022	14:00:06	P1	A	Fast	00:01:00	0.0	0	dB	77.3	66.1	52.1	60.9	56.0	73.8	56.0	60.1	60.9	56.0
6	12.05.2022	14:00:06	P2	C	Fast	00:01:00	0.0	0	dB	98.5	90.8	61.4	71.3	75.7	93.5	75.7	82.3	83.6	75.7
7	12.05.2022	14:00:06	P3	Lin	Fast	00:01:00	0.0	0	dB	104.6	97.2	64.5	76.2	83.3	101.1	83.3	90.2	91.1	83.3

Figure 2: Example data recorded at the measurement point

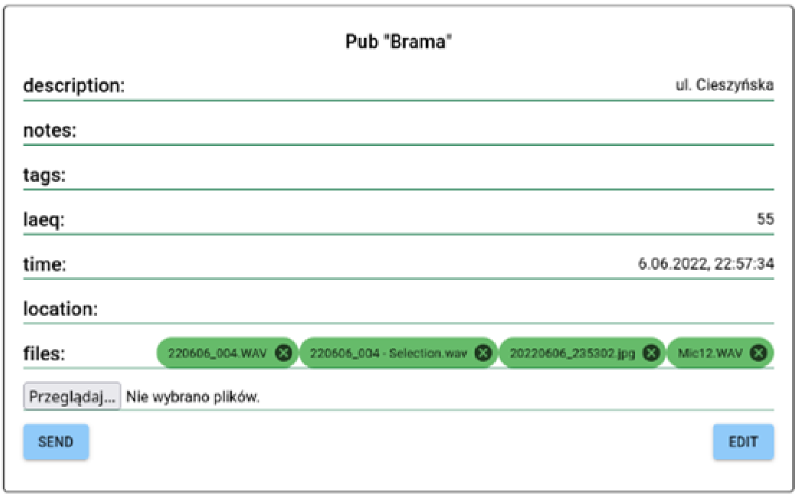


Figure 3: Example view from the measurement database

The dedicated mobile application was used for collecting measurement data and additional attributes directly in the measurement point, (Fig. 3). The developed application allows to capture the following information related to the measurement: the name and description of the measurement point, comments, tags, L_{Aeq} index values and a photo identifying the measurement point. The collected data at the measurement point are transferred to the measurement database, which is additionally supplemented with recorded sound sample files.

Additional information that is recorded during the measurements (Fig. 4) is the weather data including temperature, pressure and humidity. Although the values of these parameters did not fluctuate significantly, with careful analysis it is possible to study the relationship between this weather parameters and sound pressure levels and how the acoustic signal is evaluated by listeners [11].

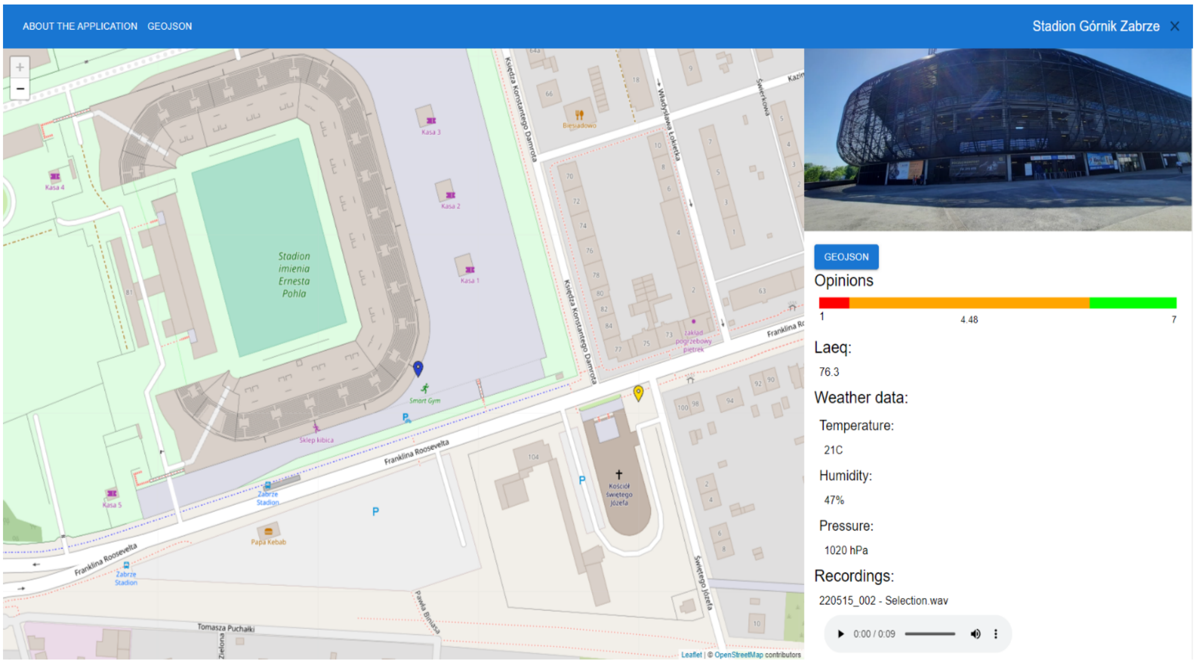


Figure 4: An excerpt from the map with sample information on the measurement point

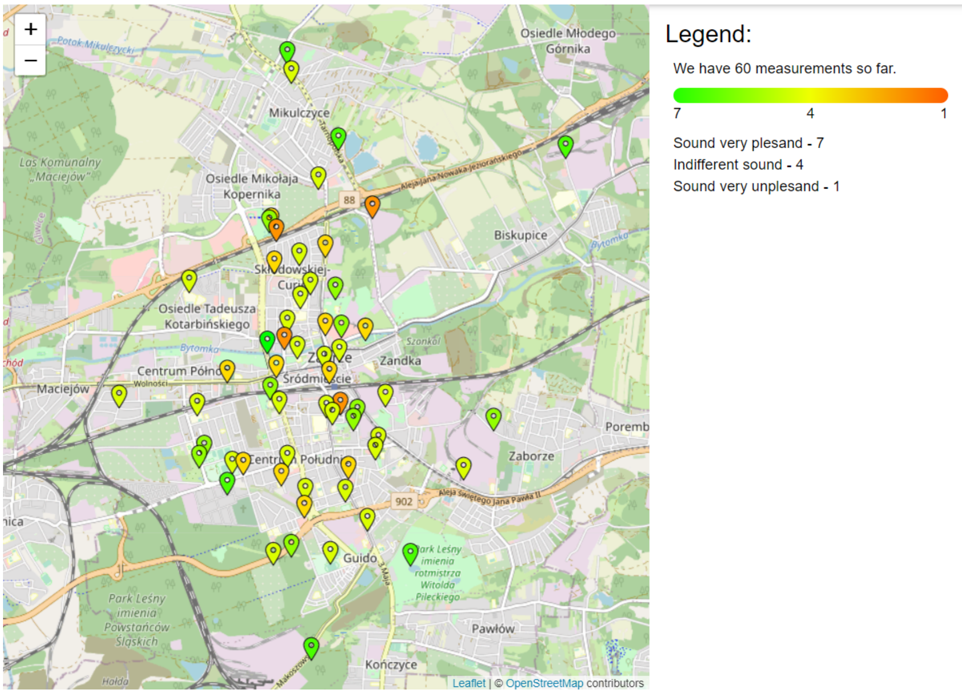


Figure 5: A section of the city area with the location of the measurement points

The application provides an automatic backup in the cloud functionality as well as allows to correct potential errors entered during the measurement process.

Sound measurements and recordings were carried out in 60 selected measurement points (Fig. 5, Fig. 6). The selection of measurement points has being determined by their spatial location, their proximity to particular buildings or elements of the surrounding area, and the likelihood of a characteristic sound in the area.

For example in the urban spaces intended for educational purposes - some characteristic sounds for such places are expected, i.e.: noise caused by increased traffic, the voices of students, the sound of school bells, etc. In the case of the industrial sector, the characteristic signals are noises coming from production halls, sounds of the operation of technological and construction machinery, and sounds generated by workers. The points marked on the map can be also identified by a color designation, which corresponds to the average rating of sound samples obtained during psychoacoustic testing. The lower values of this evaluation are marked with reddish colors, while the higher values correspond to greenish colors.

In the most cases, acoustic measurements were carried out during the day (from the morning to late evening hours), in order to capture characteristic sound sources in the studied urban spaces. It was assumed that increased sound levels would be observed during the afternoon hours, when traffic, school and industrial noise is more intense. Therefore, one of the criteria for the selection of measurement points was also the time period during which the measured signal could be most audible.

Name of place	Type of land use
Wesołe Miasteczko	Entertainment and recreation
Targowisko Miejskie Pod Ratuszem	Public space
Koksownia Jadwiga	Industry
Targowisko miejskie	Public space
Silesia Castings Workshop	Industry
Pomnik Bohaterów Monte Cassino	Park
Wieża Ciśnień	Park
Kościół św. Anny	Church
Zabrzański Kompleks Rekreacji	Sport
Pomnik Braci Górniczej	Park
Szpital kliniczny	Emergency services
Zespół Szkół Ekonomiczno-Usługowych	Education
Komenda Policji	Emergency services
Skwer z fontanną	Public space
Dom muzyki i tańca	Entertainment and recreation
Elektrownia Fortum Silesia	Industry
Przedszkole nr 1	Education
Osiedle domków ul. Zakopiańska	Residental areas
Szkoła Podstawowa nr 25	Education
Korty tenisowe	Sport
OSP Mikulczyce	Emergency services
Dzielnica przemysłowa	Industry
Plac teatralny	Public space
Rzeczka w parku	Park
Stadion GKS Walka Makoszowy	Sport
Mostostal	Industry
Hala MOSiR	Sport
Zespół Szkół Ogólnokształcących	Education
Parafia św. Andrzeja	Church

Type of land use	Number of appearances
Entertainment and recreation	8
Public space	9
Industry	9
Park	9
Church	5
Sport	7
Emergency services	4
Education	5
Residental areas	4
Total	**60**

Figure 6: The identification of measurement points

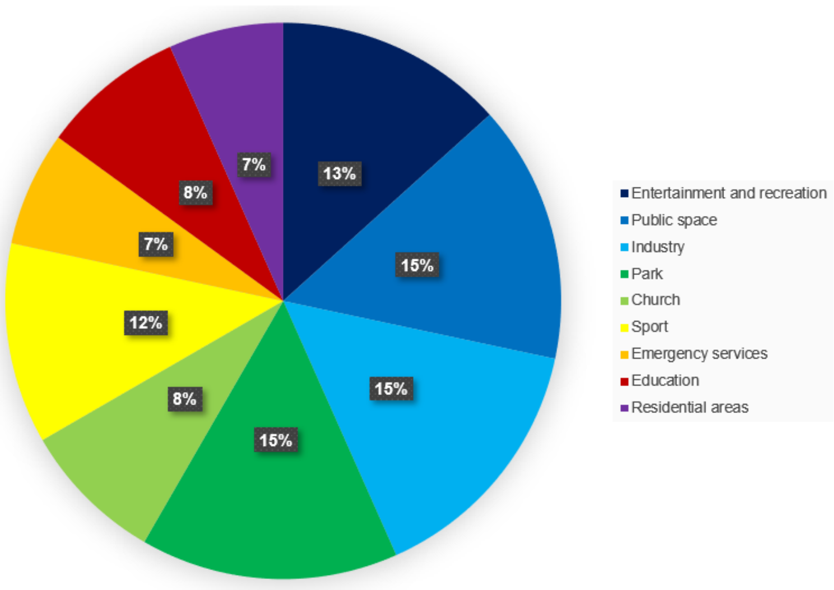


Figure 7: Share of land use types in the total number of measurements

Three main land use types dominate in the investigated area (Fig. 7): the Industry, the Public Spaces and Parks. This indicates some variation in the purpose of the city's places, which are accompanied by the emission of characteristic acoustic signals.

The smallest share occurred for the areas allocated to Services and Hospitals. This is due to the fact that these areas have relatively low sound pressure levels for most of the day. The main sources of sound outside buildings are vehicle's emergency sirens, which operate only in cases of danger to life and safety.

The results obtained from the soundscape study allow to identify the acoustic characteristics city Zabrze - it is an area with a dominance of industrial business, where public space and areas for recreation form small parks and squares along with fountains [16]. Probably these are not typical acoustic conditions of most cities in Poland. Therefore, it is reasonable to conduct this type of research in other agglomerations, which will allow to identify and assess the specifics of the soundscape. The information obtained from such studies can be used in local projects that will take into account people's behavior and their sound interaction with the environment.

3 Evaluation of sound impressions using the psychoacoustic test method

Psychoacoustic tests are used in many research works oriented toward subjective evaluation of sound. Among other things, they are used for: determining metrics of sound quality and rotorcraft noise annoyance [17], assessing the quality of telephone transmissions [18], or experimental studies of annoyance caused by acoustic signals from trams and buses [19].

In a study on determining metrics of sound quality and annoyance from rotorcraft noise [17], a psychoacoustic test was conducted on 40 people who listened to 105 differently modified, six-seconds long samples of helicopter sound. Based on a five-point rating scale, individuals determined the irritation caused by the sound of the rotorcraft. The conclusion of this research was that the subjects' irritation was influenced not only by the loudness of the rotorcraft sound but also by other subjective characteristics of the sound, such as: sharpness, tonality and strength of fluctuations.

The psychoacoustic test in the experimental study of annoyance, caused by car and bus noise, consisted of two parts. The first part of the experiment was based on 7 pairs of acoustic samples captured from cars and buses, each with a difference of 3dB. Research participants was listening to the samples and assessing of their annoyance reflected on an 11-point scale. In the second part the research participants were exposed to a 2-hour traffic scenario, during which they performed certain tasks. The result of the first test was that the noise of a car was described as equally annoying as the noise of a bus, which actually was 3 dB lower. The second part of the test concluded that both types of sounds had the same impact on task performance, with the noise signals from the car causing less annoyance during work.

In the project undertaken by the authors of this paper, the evaluation of sound perception was carried out, for the most part, on students of the Silesian University of Technology.

The choice of the auditory evaluation scale and the method of sound impressions testing

The method recommended by the ITU-T (Telecommunication Standardization Sector) for measuring the subjective evaluation of sound for 'listening-opinion' tests, is the ACR (Absolute Category Rating) method [20], which involves listening to a sample once and rating it according to a proposed scale.

Other commonly used methods for testing subjective sound evaluation are:

- **DCR** (Degradation Category Rating), which focuses on presenting samples in pairs, one of which is a reference and the other is subject to an evaluation of the degree of degradation relative to the reference sample,
- **Quantal - Response Detectability Method**, it presents the detectability or property of a sound as a function of an objective quantity,
- **CCR** (Comparison Category Rating), in which the listener is given two samples and compares them with each other.

Methods of subjective testing are standardized by the International Telecommunications Union (ITU) - recommendations are contained in recommendations published by the ITU.

The minimum sample size is specified in BS.1284 ITU-R Recommendation, which refers to conducting subjective tests. When the research group consists of non-experts, a minimum sample size of 20 participants is recommended. According to P.800 ITU-T recommendation, the entire session in which a single test is conducted should last from 20 minutes to maximum 45 minutes.

After recognizing the methods of conducting tests and taking into account the purpose of the research undertaken in the project, the method used to test the subjective evaluation of sound was the Absolute Category Rating method.

According to P.800 ITU-T Recommendation, the most commonly used scale in psychoacoustic studies is a scale with values from 1 to 5. It provides a relatively simple choice, as well as is easily understood by research participants. However, in case of the undertaken project due to the variety of sounds, it was decided to use a 7-point scale. It gives more opportunity for research participants to distinguish sounds from one another.

The final grade of sound perception for a given sound sample is the arithmetic average of the partial grades given by the research participants of the psychoacoustic experiment.

Rating	**Scale Interpretation**
7	Sound very pleasant
6	Sound pleasant
5	Sound rather pleasant
4	Indifferent sound
3	Sound rather unpleasant
2	Unpleasant sound
1	Very unpleasant sound

Table 1: Applied auditory rating scale for sounds

Figure 8: Created listening post for psychoacoustic tests

The way of sound impression research with the use of a constructed listening post

Before the start of the test, each research participant was informed about the rules of sound samples presentation and with the guidelines for answering (rating scale, interpretation of the scale, how to answer, etc.). Moreover each participant filled in a questionnaire about one's age, gender and the type of nuisance noise to which one is exposed at home. Psychoacoustic tests were conducted using loudspeakers configured in a 5.1 system, and in proper acoustic conditions provided by a system of sound-absorbing panels (Fig. 8).

A single session last about 10 minutes and it took place at the listening spot (Fig. 8). The session was based on the playback of 15 randomly selected sound samples (each 10-seconds long), which were representative of the one minute-long measurements taken. After each sound sample was played, the research participants rated their auditory impressions using an adopted scale. A total of 92 people took part in the tests, so that each sample was evaluated 23 times.

Results and analysis of the obtained data

The results of the tests were collected using a Google Forms and were then exported to a spreadsheet for statistical analysis. An excerpt of the collected results is shown in fig. 9.

Timestamp	Age	Sex	What kind of annoying type of noise are you exposed to in your place of residence?	Wesołe Miasteczko	Targowisko Miejskie Pod Ratuszem	Koksownia Jadwiga	Targowisko miejskie	Silesia Castings Workshop	Pomnik Bohaterów Monte Cassino
6.9.2022 9:39:47	21	Man	Road	3	5	6	4	2	4
6.9.2022 9:45:10	23	Female	Road	5	4	7	3	6	1
6.9.2022 9:49:41	21	Man	Road	2	6	6	3	4	4
6.9.2022 10:11:05	21	Man	Road	3	6	7	3	4	6
6.9.2022 10:17:22	22	Female	Road	6	4	6	6	5	5
6.9.2022 10:26:11	23	Man	None	3	4	6	3	2	5
6.9.2022 11:39:25	23	Female	Road	6	4	5	3	5	5
6.9.2022 11:45:16	23	Female	Road	5	5	7	4	5	3
6.9.2022 12:03:38	21	Man	Rail	6	4	5	3	4	5
6.9.2022 12:10:08	21	Man	Road, Rail	4	6	7	4	5	4
6.9.2022 12:16:14	19	Man	Rail	7	4	4	2	3	5
6.9.2022 12:38:33	20	Female	Rail	5	4	4	3	5	6
6.9.2022 12:45:07	20	Female	Road	5	1	4	3	6	4
6.9.2022 12:53:32	19	Man	Road	6	2	4	4	3	2
6.10.2022 11:37:32	22	Man	Road	5	7	3	2	4	6
6.10.2022 11:55:50	21	Inna	Road	6	6	7	4	6	3
6.21.2022 17:26:45	30	Female	Industrial	6	5	4	4	3	6
6.21.2022 17:32:35	50	Man	Road	3	3	5	2	4	3
6.21.2022 17:47:33	20	Man	Industrial	2	3	6	5	3	5
6.22.2022 10:49:11	21	Female	Road	6	4	6	4	4	2
6.22.2022 11:01:03	22	Female	Agricultural	6	4	6	3	5	7
6.22.2022 12:08:48	24	Female	Road	2	4	5	2	3	5
6.22.2022 12:33:41	21	Man	Road, Rail	7	5	7	4	3	3

Figure 9: Excerpt from psychoacoustic test results collected with the form

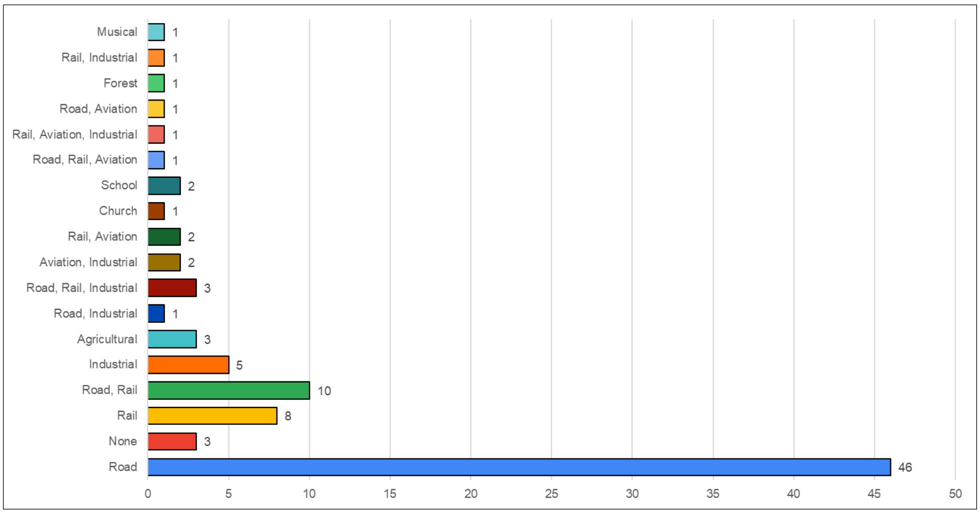


Figure 10: Dominant sources of noise in the respondent's domestic area

Name of place	Type of land use	Assessments																							Average	Standard deviation	LAeq
Wesołe Miasteczko	Entertainment and recreation	3	5	2	3	6	3	6	5	6	4	7	5	5	6	5	6	6	3	2	6	6	2	7	4,74	1,63	72
Targowisko Miejskie Pod Ratuszem	Public space	5	4	6	6	4	4	4	5	4	6	4	4	1	2	7	6	5	3	3	4	4	4	5	4,35	1,37	57
Koksownia Jadwiga	Industry	6	7	6	7	6	6	5	7	5	7	4	4	4	4	3	7	4	5	6	6	6	5	7	5,52	1,24	49,3
Targowisko miejskie	Public space	4	3	3	3	6	3	3	4	3	4	2	3	3	4	2	4	4	2	5	4	3	2	4	3,39	0,99	55,1
Silesia Castings Workshop	Industry	2	6	4	4	5	2	5	5	4	5	3	5	6	3	4	6	3	4	3	4	5	3	3	4,09	1,20	57,9
Pomnik Bohaterów Monte Cassino	Park	4	1	4	6	5	5	5	3	5	4	5	6	4	2	6	3	6	3	5	2	7	5	3	4,30	1,52	58,6
Wieża Ciśnień	Park	4	3	6	6	4	3	4	4	3	5	4	4	4	5	4	4	4	4	3	4	4	4	4	4,09	0,79	52,9
Kościół św. Anny	Church	4	6	5	5	7	6	5	5	4	5	6	6	4	3	1	1	3	6	6	2	5	5	6	4,61	1,64	47,4
Zabrzański Kompleks Rekreacji	Sport	2	1	5	2	1	1	1	1	1	3	1	1	3	1	4	1	1	2	2	1	1	1	1	1,65	1,11	64,4
Pomnik Braci Górniczej	Park	5	5	6	6	6	2	3	2	2	4	1	5	5	3	4	5	3	6	6	5	7	2	6	4,30	1,72	63,9
Szpital kliniczny	Emergency services	5	4	4	5	4	3	4	4	4	4	4	4	4	5	4	4	4	4	4	4	6	4	4	4,17	0,58	58,6
Zespół Szkół Ekonomiczno-Usługowych	Education	4	4	2	3	4	4	3	4	3	5	3	4	4	4	5	4	5	5	6	4	2	4	4	3,91	0,95	65,1
Komenda Policji	Emergency services	3	3	3	4	4	3	4	4	4	4	4	4	5	4	4	3	4	5	1	4	4	4	5	3,78	0,85	55,4
Skwer z fontanną	Public space	4	3	2	3	5	1	2	2	4	5	2	3	4	3	1	2	4	5	6	3	6	1	3	3,22	1,51	70,1
Dom muzyki i tańca	Entertainment and recreation	6	4	4	5	4	5	5	5	4	6	4	5	5	5	4	4	6	4	6	4	7	5	4	4,83	0,89	58,8
Elektrownia Fortum Silesia	Industry	5	4	4	4	4	4	4	4	4	4	4	4	5	4	7	7	6	4	5	6	6	6	4	4,74	1,05	54,1
Przedszkole nr 1	Education	2	2	3	3	3	3	3	3	3	3	3	3	4	1	3	4	3	5	2	1	2	1	6	2,87	1,18	63
Osiedle domków ul. Zakopiańska	Residental areas	4	2	4	5	4	5	4	5	6	4	3	2	4	5	6	7	4	7	6	5	4	4	3	4,48	1,34	58,1
Szkoła Podstawowa nr 25	Education	3	5	4	6	4	4	4	4	3	4	4	1	4	1	3	3	4	6	3	3	3	3	5	3,65	1,23	54,4
Korty tenisowe	Sport	6	4	5	7	4	6	5	4	4	6	5	4	4	3	4	7	5	6	4	4	5	3	6	4,83	1,15	51,8
OSP Mikulczyce	Emergency services	7	4	6	6	5	7	6	6	7	7	7	7	6	7	7	7	6	7	7	7	7	2	7	6,30	1,22	45,5
Dzielnica przemysłowa	Industry	2	6	1	2	2	3	3	2	2	2	2	1	4	1	3	3	3	1	2	3	1	4	3	2,43	1,20	58,5
Plac teatralny	Public space	1	3	1	3	5	2	2	4	1	6	6	4	5	5	1	3	3	5	1	1	6	5	2	3,26	1,84	65,1
Rzeczka w parku	Park	7	7	7	7	7	7	6	6	5	7	7	7	7	7	7	7	5	7	7	7	7	3	7	6,57	0,99	54,7
Stadion GKS Walka Makoszowy	Sport	4	4	4	4	4	6	5	4	3	4	4	3	4	1	4	5	5	5	3	2	3	4	6	3,96	1,15	57,2
Mostostal	Industry	2	4	4	2	2	4	2	3	1	4	2	4	4	4	2	2	2	2	5	3	2	3	2	2,83	1,07	65,2
Hala MOSiR	Sport	5	3	5	4	3	6	4	4	4	5	4	4	5	4	4	6	4	4	6	4	4	6	3	4,39	0,94	51,4
Zespół Szkół Ogólnokształcących	Education	3	2	4	3	4	6	5	3	4	4	4	3	4	1	3	4	4	5	4	1	3	4	6	3,65	1,27	51,3
Parafia św. Andrzeja	Church	2	6	2	2	1	2	2	3	1	6	2	1	4	5	1	2	3	5	5	2	1	4	2	2,78	1,65	70,6

Figure 11: Presentation of sub-assessments of the sounds at the measurement sites

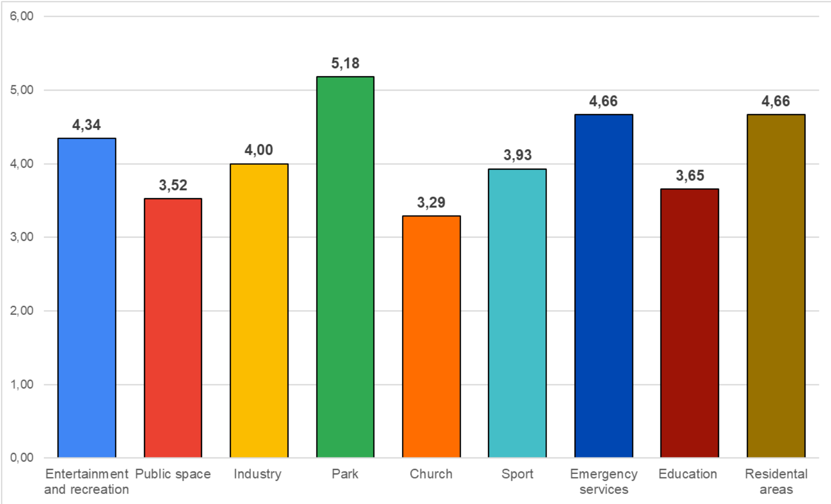


Figure 12: The retrieved average score of the psychoacoustic test for the investigated types of land use type

Analysis of the results revealed that the average age of the research participants was almost 23 years old. When it comes to the gender structure of the respondents – it was divided almost equally (51% males, 49% females). When asked what type of noise the surveyed person is exposed to in his place of residence, the most common answer was road noise. This was the answer marked by as many as half of the people surveyed. Detailed results are shown in fig. 10.

Based on the obtained sub-assessments of the sound samples, the average ratings and standard deviation were determined for each of the studied sites. In addition, each sound sample was completed with a measured L_{Aeq} value and the type of land use where the sound was recorded. Fig. 11 shows an excerpt of the results described above.

When it comes to the average scores of the psychoacoustic test related to the type of land use, the obtained results are shown in fig. 12.

Based on the aforementioned survey results, it can be concluded that, the places which received the highest ratings were Parks, with a mean of 5.18, Residential areas and Hospitals or Emergency services - these types of land use received a mean of 4.66. In contrast, the types of places that had the lowest mean, were Church (mean 3.29), Public space (mean 3.52), and Education related places (mean 3.65).

4 Technology stack used to create acoustic data collection and processing system

The project involved creation of a data collection and processing system (mobile app) based on classic frontend-backend architecture. The main goal that the development team set for itself was to develop such a system that, on the one hand, would guarantee the convenience and correctness of the data collection process, and on the other hand, would allow for a quick response from the IT-support side (for example in case of the need to modify the database).

The type of data collected during the measurements is:

- Location (geographic data).
- Weather data (temperature, humidity, pressure).
- Sound recordings.
- Photos taken at the measurement points.

The location of measurement points were identified based on the geolocation of mobile devices used by the measuring team. The advantage of this solution was the ability to use mobile phones, which are in the possession of every person. The disadvantage of this solution was the need for a permanent connection to the Internet. Due to the possibility of distortions associated with incorrect or inaccurate location readout, the possibility of manual correction was also implemented in the application.

The developed application has implemented several services to facilitate infrastructure management [21]. For the project purposes the following programming languages, tools and technologies has been used:

- Programming languages:
  - Python
  - TypeScript
- **React** - Library for creating UI.
- **FastApi** - Framework for creating the backend application.
- **Dramatiq** - tool for background task scheduling, it had access to the **FFmpeg** and **ImageMagick**

programs for transcoding files, was also responsible for retrieving weather information from the **OpenWeatherMap** service.

- **ImageMagick** - tool for converting, editing and composing digital images.
- **FFmpeg** - Audio transcoding utility.
- Databases:
  - **PostgreSQL** - Main database used for storing the measurement data
  - **Redis** - Supplementary database for caching.
- **PgAdmin** database management.
- **Git** - version control.
- **Docker Hub** and **Github Actions** for continuous integration
- The **NGINX** service - acted as a reverse proxy to the backend service and it hosts static files for web applications and administration pages as another service.
- External service **Open Weather Map** - a service that provides weather data.

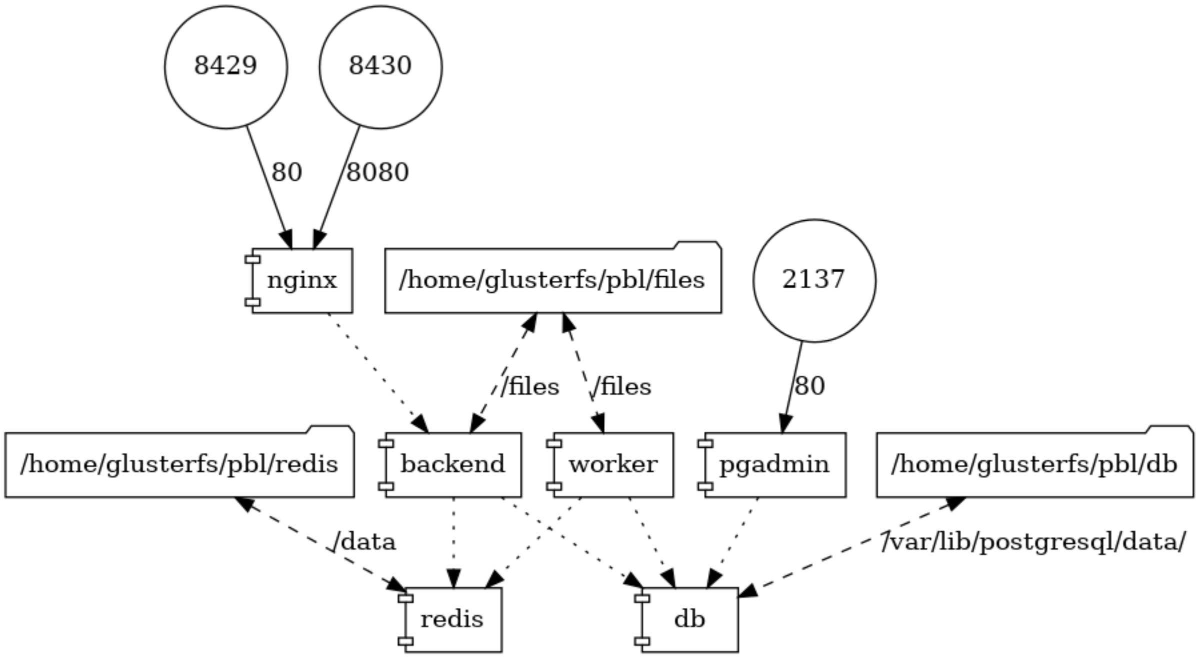


Figure 13: A diagram of the micro-services architecture

Fig. 13 shows the interconnection of services through network communication and file storage volumes.

File exchange between services was implemented by mounting the `/home/glusterfs/pbl/files` volume to the `/files` path to the backend and to worker services. In addition, the database services had their own volumes for storing data.

Communication with services was established via networks managed by the `docker-compose` tool. This makes uncontrolled access to internal services (such as databases) impossible. Communication with the outside environment was possible over ports:

- Port 8429 - public backend API and applications
- Port 8430 - backend API administration and administration pages.
- Port 2137 – pgAdmin administration site.

The application was tested by the members of measurement team, who received their accounts on a test instance of the application. As a result of the tests, the accuracy that could be achieved from the mobile phones was identified as a significant disadvantage of the application. The solution to this problem was to force greater accuracy, which resulted in higher power consumption and longer response times than in the case of one-time location query. Through testing, it was also possible to verify the system's performance in terms of user experience (UX). An example of a solution introduced after testing was sorting locations by the number of files entered, which had the effect of displaying locations without measurement files at the very beginning. A simple method of editing coordinates was also introduced, which is important in case a location would be downloaded incorrectly, which happened when there were problems with the internet connection.

5 Summary and conclusions

The results of the project are in the nature of pilot and development studies. The proposed approach to acoustic studies of urbanized areas, which consists of taking into account the evaluation of sound impressions of noise sources immission, meets public needs and expectations. The use of information about the evaluation of sound impressions in areas with mixed types of land use, combined with modern information technologies, makes it possible to create the digital sound layer of the city. In particular, the possibility of users' subjective sound evaluation and providing direct access to such information, makes it possible to comprehensively study urban spaces and also manage them sustainably. The acquired information about the subjective sound assessment and impact of sound sources related to that, can be used in design work of urban planning and development, the use of noise barriers or the formation of the acoustic climate in urban spaces.

In the further steps of the research, it is assumed to use recorded sound samples for extraction and subsequent evaluation of subjective sound characteristics, i.e. loudness, sharpness, roughness, strength of fluctuations in the dimensions of time, frequency and time-frequency. The extracted information will significantly extend the results obtained from psychoacoustic tests and can be used in the construction of a model for evaluating sound impressions.

Based on the results obtained from the psychoacoustic survey, it can be concluded that the sounds recorded in parks were by far the most pleasant, while the ones registered near churches, places of education and public spaces were considered as the least pleasant by the respondents. The collected information regarding the evaluation of sound impressions can be a premise for using measures to improve the quality of sound impressions of the studied places, for example, by creating green gardens with trees that would reduce some of the unpleasant sounds. Such an assessment probably comes from the observation that sounds from the natural environment are more pleasant for people and more relaxing than those in typically urbanized spaces.

It is worth noting that the average standard deviation of the evaluations of the tested sounds with a study sample of 92 people took the value of 1.17, which is relatively high considering that the evaluation of the sound was made on a seven-point scale. It can be assumed that an increase in the relevant test sample, as well as a decrease in the evaluation scale, would result in an increase in the accuracy of the obtained results with a decrease in the value of the standard deviation.

It should be noted that the respondents taking a part in the psychoacoustic tests were mostly young people, as their average age was 23. Therefore, it can be presumed that the results obtained from the evaluations of sound impressions were strongly related to the tastes of such a research group.

The developed application for mobile devices can be useful for carrying out research on the soundscape of cities. Its architecture allows for relatively simple modifications in the creation of subsequent versions. The application can also be made available to city residents via a registration panel. The problem for such a solution is the verification of personal data and sound recording parameters. After creating a proper account, residents can participate in the process of creating and developing a sound map of a given city. Each user is free to add sounds and photos from the studied place. The sound pressure level measurement and sound registration on the mobile device owned by the user should be verified. In this project, sound files were captured from professional sound recorders. The sound layer developed in the project was made available on the web platform after verification by team members. The information made available on this layer makes it possible to determine in which areas of the city people may be exposed to unpleasant sounds and which places are attractive in terms of perceived positive sound impressions.

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