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Providing high-quality measurement data in analytical system of air pollution monitoring and their key importance for smart cities residents

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Abstract: *Providing high-quality measurement data in analytical system of air pollution monitoring and their key importance for smart cities residents*. The article presents selected, main elements of an air pollution automatic monitoring system with analytical subsystems concept in smart cities based on examples from Poland, implemented system in Pomerania, the concept of new system in Warsaw city and pilot research in Nowy Sącz city. All systems are the result of teamwork, ranging from design, development of new methodology and software to implementation in real-time air pollutants smart cities monitoring systems. Focused on the most neuralgic elements: data quality subsystems, new ideas of smart mobility measurement stations and their ability to use in future research and models. Special attention was paid to stochastic models and statistic methodology proposed and used in data diagnostics as analytical system engineering.

Key words: air pollutants, data quality analysis, data mining, exploratory methods, outliers, analytical software system, statistical analysis

INTRODUCTION

The direction in which follow modern society is the development and growing importance of urban industry-agglomerations – smart cities. It is essential that process proceeded in a way that ensures balances economic development as a consequence of providing a high quality of life for residents. In classical terms, the model concept of "smart city" environment is one of six main elements.

Automatic air pollutants monitoring (APM) systems are key part of the "nervous" smart city. They have to ensure a lot of functions, among others, such as reporting on the state of the air, weather warnings or ultimately control the emission determine the adopted solutions. Such system has to provide above all the credibility of measurements results. Obtained data allow to use them in key models impact of air pollution on health (Badyda et al. 2013a, Majewski et al. 2013). It is indispensable in the statistical methodology (Badyda et al. 2013b).

Taking into account several adverse health effects attributable to air pollutants (Badyda et al. 2015, 2016) it is necessary to provide much more dense air quality monitoring network, to expand the level of knowledge about potential exposure and thus to improve the activities undertaken to protect populations against air pollutants and their health outcomes.

The use of quantitative methods, including stochastic and exploratory techniques in environmental studies does not seem to be sufficient in practical aspects. There is no comprehensive analytical system dedicated to this issue, as well as research regarding this subject.

The aim of this work is to present selected aspects of the air pollution information systems in Poland with a particular emphasis on analytical subsystem Eco Data Miner (EDM), its idea, construction, implementation possibility and selected examples of the existing environmental information systems. The methodological accent was placed on data quality assessment in terms of using the proposed author's method – using harmonic models and robust estimators besides the classical tests of outliers with their iterative expansions.

The primary goal is to present the ideas of the most important parts of this type of systems: data quality assessment using exploration and stochastic models methodology. Similar subsystems are partly implemented in the Pomerania region. They were also started to be designed in Warsaw agglomeration and are being tested for the first time in the city of Nowy Sącz.

Ensuring data credibility can use these large-scale data including health impact models and warning systems, was synthetically presented.

THE IMPORTANCE OF AIR POLLUTION MONITORING SYSTEMS IN SMART CITY

A smart city is a city well performing in six "smart" characteristics, built on the "smart" combination of endowments and activities of self-decisive, independent and aware citizens: economy, mobility, governance, environment, living and smart people. A smart city is an urban development vision to integrate multiple information and communication technology (ICT) and Internet of things (IoT) solutions in a secure fashion to manage a city's assets. According to UNFPA (United Nations Population Fund), the world's population reached 7 billion people in 2011 (currently it is approx. 7.3 billion people). In the global scale, the urban population is over 50% of overall population. In Europe, it is almost 75%. Moreover, it is estimated that in 2030 among the world's population, which will then count approx. 8.3 billion people, 5 billion (over 60%) will live in the cities and in smart cities (WHO 2013).

Relatively large emission of air pollutants into the atmosphere in Poland results in regular exceedance of limit values of air pollutants concentrations including such as: PM_{10} (particles with aerodynamic diameter less than 10 μm) and $PM_{2.5}$ (particles with aerodynamic diameter less than 2.5 μm), benzo(a)pyrene (BaP) and locally nitrogen oxides (NO_x)

and ozone (O_3). The principal pollutants in the transport sector are (data for 2013): emissions of NO_x (39.4% in the EU; 31.7% in Poland), emissions of CO (22.4% in the EU; 20.2% in Poland), as well as emissions of PM_{10} (11.7% in the EU; 8.7% in Poland) and $PM_{2.5}$ (12.9% in the EU and in Poland) (WHO 2013).

A fundamental challenge facing modern society consists in reducing emissions of harmful substances, so as to minimize the impact of e.g. transport or municipal and households emission on air pollution and health. Problems of the air quality are particularly important in urban areas, due to the concentration of many sources of emissions on relatively small areas, both in large cities and in small and medium size towns. Air pollution significantly influences the condition of ecosystems and human health, causing numerous respiratory and cardiovascular systems disorders. Civilization diseases, caused most frequently by environmental pollution, result finally in economy in diminishing number of labor force which is provided by households

Data quality in APM systems – Eco Data Miner subsystem

Study regarding Eco Data Miner project started back in the late 1990s. This was a new concept of a dedicated analytical system that was created. It was going to allow both to make fundamental quantitative analysis and to implement dedicated solutions into the existing and future database systems of information on the environment. The system had to comply with a number of assumptions (Czechowski 2013, Czechowski et al. 2013), but its fundamental task was to enable to conduct analysis, often unconventional, both in operating regime and in research tasks, which is a difficult objective, regarding such a vast amount of data.

It must be mentioned that the objective this kind of system is not only collecting data, although it appears an important and necessary task. The phenomenon of air pollution is connected with the continuous development of a society. Urban areas, smart cities, are inhabited by a vast number of people and as a consequence industry and transport are highly developed. It makes them territories degradation of natural environment. Pollution emitted this way imposes hazards on people's health, which is a kind of feedback. The costs of development, borne by citizens of these urban-industrial areas, should be appropriately minimalized by the suitable management of environmental protection in a given region, taking into account the protection of the social environment, as well as natural environment.

Issues under investigation, represent a new aspect of the use of statistical methods and models, often their development. The concept of data quality is closely related to modeling and forecasting – it is an interdisciplinary problem.

Modeling with the use of stochastic and exploratory techniques seems to be a perfect complement to balance models in operation activity of automatic networks monitoring conditions of the atmosphere. There are at least two areas where this research proves to be useful: automatic concentration monitoring combined with forecasts warning against an excessive increase in pollution level and current analysis of quality of data, coming from monitoring network. Both these aspects, supported by a complex mathematical system, might become a mutually complementary, new area of use for quantitative methods, familiar and widely used in other areas, also dedicated to environmental engineering.

AIR POLLUTION MONITORING INFORMATION SYSTEMS

In Poland, similarly as in the entire Europe, the quality of air is shaped primarily by communal-living sources and road transport (Rogula-Kozłowska et al. 2014). The problems of appropriate air quality are especially important within the urban zones, due to the concentration of many sources of emission on relatively small areas in both large cities and smaller and medium towns (Majewski and Rogula-Kozłowska 2016). Due to the steadily increasing participation of the urban population in the general number of population, the issue of providing clean air will over the years become a more significant problem for human health, and therefore a stronger incentive to intensify research (Rogula-Kozłowska 2016).

Clean air in smart cities as one of the elements of the environment is essential for the health of residents in terms of the direct impact of pollutions, as well as indirect by providing high quality and food safety. It also helps to reduce future costs associated with treatment, including civilization diseases.

In Poland, the environmental monitoring is carried out by the provincial administration and the technical supervision exercised by the agency of the Ministry of the Environment – Chief Inspectorate of Environmental Protection. Besides them, there are institutions established by regions (agglomerations), together with scientific purpose monitoring and research. One of the most active organizations in Poland is the ARMAAG Foundation and created its 2013 project AirPomerania system and subsystem data quality assessment Eco Data Miner (EDM).

At the moment it is created in cooperation with Gdynia Maritime University, Warsaw University of Technology and other research centers, another system AirVarsovia. Pilot studies for the new system are carried out, among others, in the northern part of Poland in Gdańsk agglomeration and in the southern part in Nowy Sącz city and neighboring municipalities. The pilot study is designed to test new concepts of construction new portable, smart meters air pollutants and mathematical modeling using field measurement new concept.

AirPomerania system

Agency of Regional Air Quality Monitoring in the Gdańsk metropolitan area was founded in 1993 by the following municipalities: Gdańsk, Gdynia, Sopot and Tczew. This foundation was founded to create the regional monitoring network (Fig. 1). Within the air monitoring system continuous measurements of the air quality are taken in several “representative” points and in so-called hot points, where the concentrations of pollutants are the highest one. The data from the automatic monitoring network in Gdańsk metropolitan area enables: identification of the area and reason of air pollution problems, verification of the criteria evaluate the air quality, evaluation of long-term tendencies, modeling processes, evaluation of recommendation effectiveness.

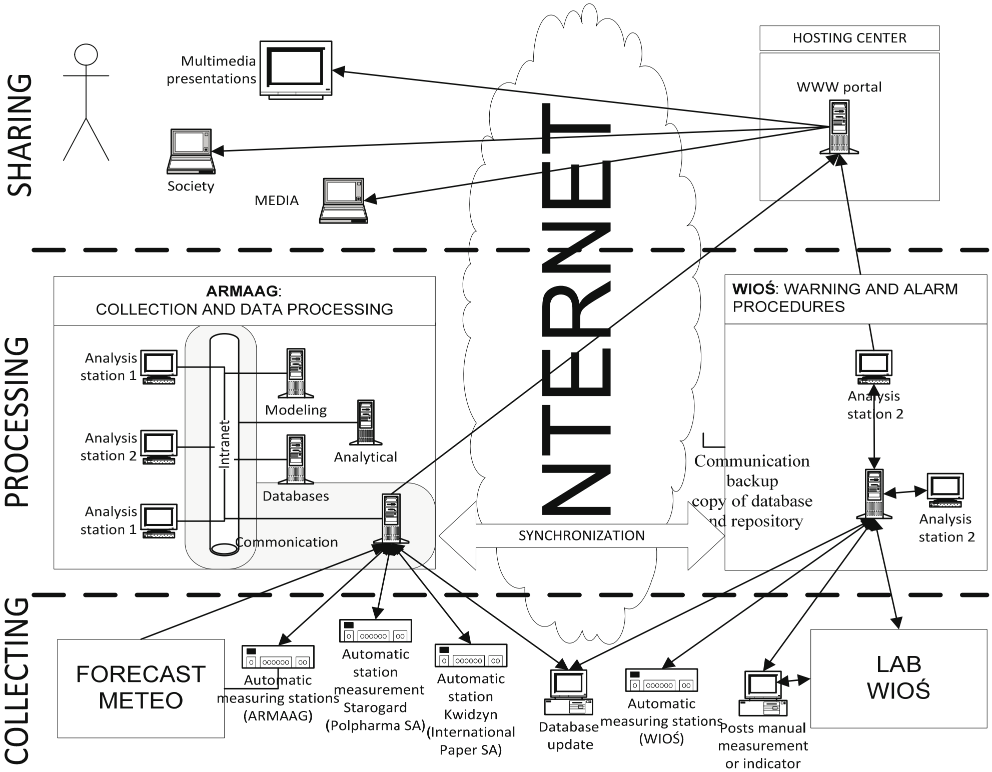

FIGURE 1. AirPomerania air monitoring system structure

AirVarsovia system

The current state of actions to helped design a network for monitoring air pollution (in particular transport) and build a forecasting system based on stochastic models in order to inform the residents of Warsaw, on the state of air quality in areas exposed to high concentrations of pollutants.

The concept of the information system of air quality in Warsaw AirVarsovia implies that it will consist of subsystems organized as shown (Fig. 2).

The proposed system in its target shape will allow the following features:

1. The layer collection and archiving of data:
   - Making measurements of selected indicators of air quality and the size of the basic meteorological network dedicated monitoring station and transfer them to a central database.
   - Sharing the collected measurement data processing applications and forecasts through a centralized database – Warsaw Data Repository Monitoring Air Quality.
2. The layer of data processing and information sharing:
   - Making stochastic modeling and statistical analysis of measurement data and making forecasts of selected indicators of air quality for the next day.

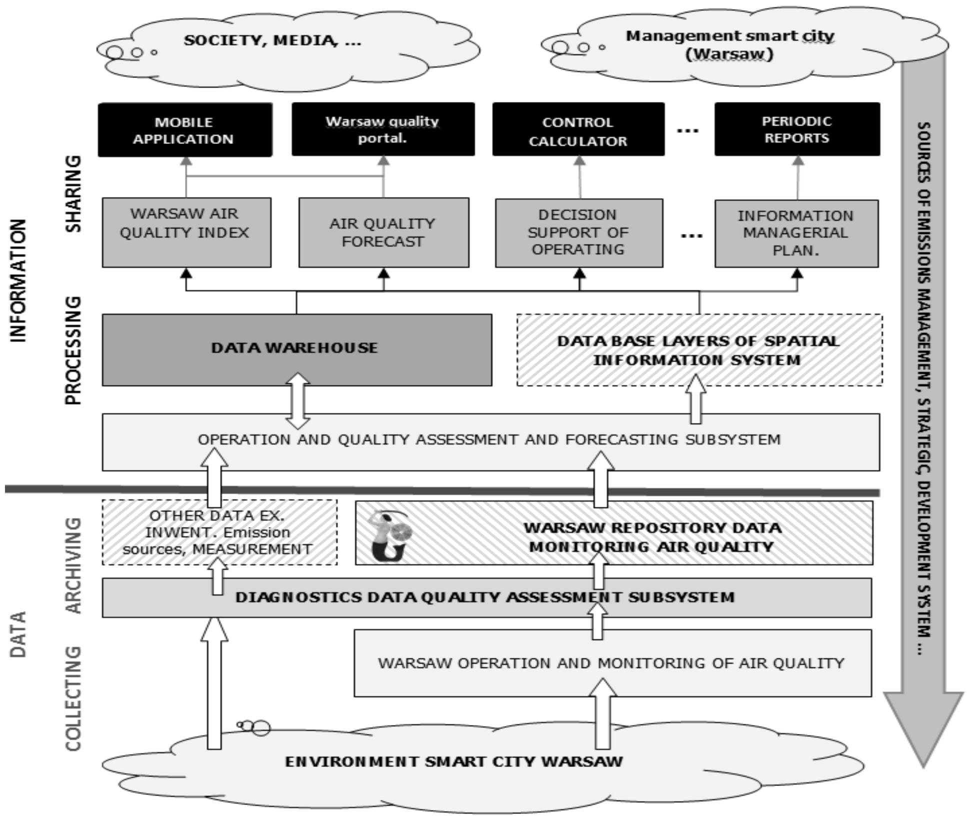

FIGURE 2. AirVarsovia projected air monitoring system structure

- Announce publicly available, the dedicated website of the City Hall and in the mobile application current and projected value of the Warsaw air quality index, as well as the measured and predicted selected air quality indicators.
- Processing of measurement data to a form suitable for decision support services of the City Board on the use of operational activities that reduce emissions.
- Information processing and preparation of periodic reports to the City Board in order to support the construction of a strategy to improve air quality.
- An assessment of the reliability and completeness of information in order to plan the development of the system and optimize the cost of its operation.

Pilot study of smart mobility stations in Nowy Sącz

Starting from 2016 are implemented new pilot study designed smart mobile devices measuring air pollution. The construction of these devices is to create so-called air pollution field measurement. Many devices will communicating with each other and the server will allow making precise measurements involving areas. With the measurement results instead of data from spatial modeling with high errors, it will be possible accurately inform the public about pollution in selected point of the city and preparation area forecast without interpolation.

The mobile monitoring stations (Fig. 3) are implemented support sensors up to 16 selected measured values. Each station is marked with an individual identifier that allows identifying the stations in the network. Types of measured values can be set individually for each position. Stations have the ability to make measurements of specific amounts of nominal frequency, local archiving measurement data, pre-processing of data and voice communications (GSM).

The first results of comparisons five smart mobile measuring station with reference measurements are shown on the graph (Fig. 4). The differences in the runs are associated with the location of the station.

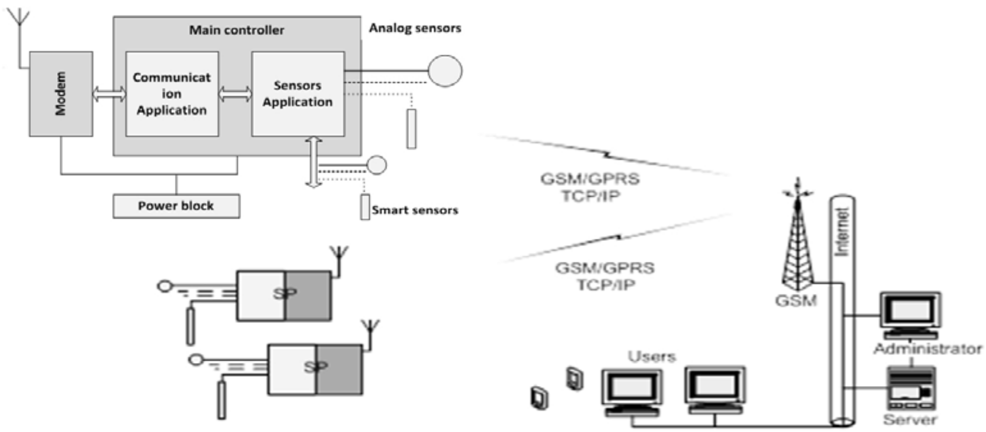

FIGURE 3. Nowy Sącz smart mobility measurement station and system project

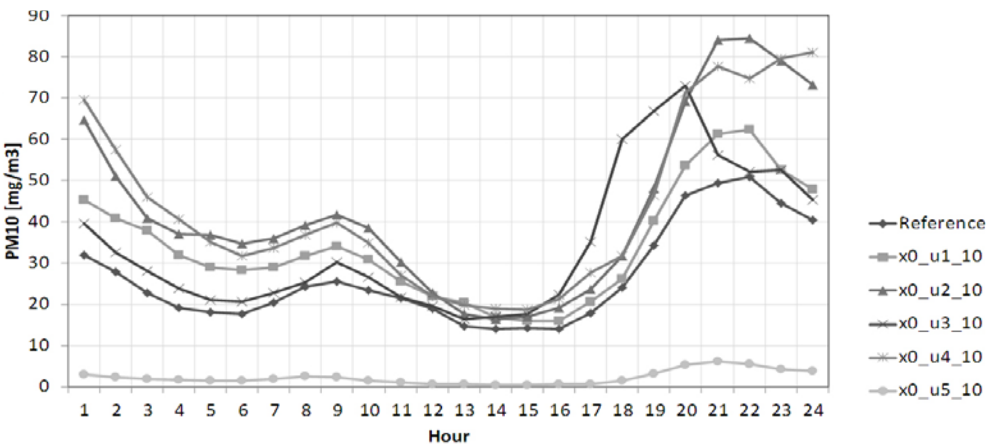

FIGURE 4. Average values of PM_{10} in 24-hour cycle from five smart stations and from reference; pilot series measurement results from Nowy Sącz (27.09–20.10.2016)

SELECTED MODELING STOCHASTIC KEY ELEMENTS IN AUTOMATIC SMART CITY AIR POLLUTION MONITORING SYSTEM

Analytical subsystem Eco Data Miner structure overview

The system is a dedicated analytical platform, which "natively" uses local data received from atmospheric conditions monitoring networks and allows integrating the data with the data from mesoscale systems. It operates in urban--industrial areas using research dedicated to environmental protection for air quality management systems.

There were implemented two main dedicated modules based on analytical platform: a module for measurement data quality assessment and warning forecasts, whose implementation was subsequent to the following studies (Badyda et al. 2015, 2016):

- A study of methodology for measurement data quality assessment in automatic networks monitoring atmospheric conditions in an agglomeration as well as extension of previously used proposed methods. It is aimed at supporting the process of verification of historical data quality in time, spatial and frequency domains.
- Creating a system warning against high concentration of pollutants, which allows to use local data fully and to integrate them with data from mesoscale models

Analytical platform

System is based on the assumptions that may be summarized by the following:

1. Flexibility: realized by integrated IM modules and external EM modules (Fig. 5).
2. Stability: realized by assuming that only MS Windows operating system mechanisms will be used while programming.

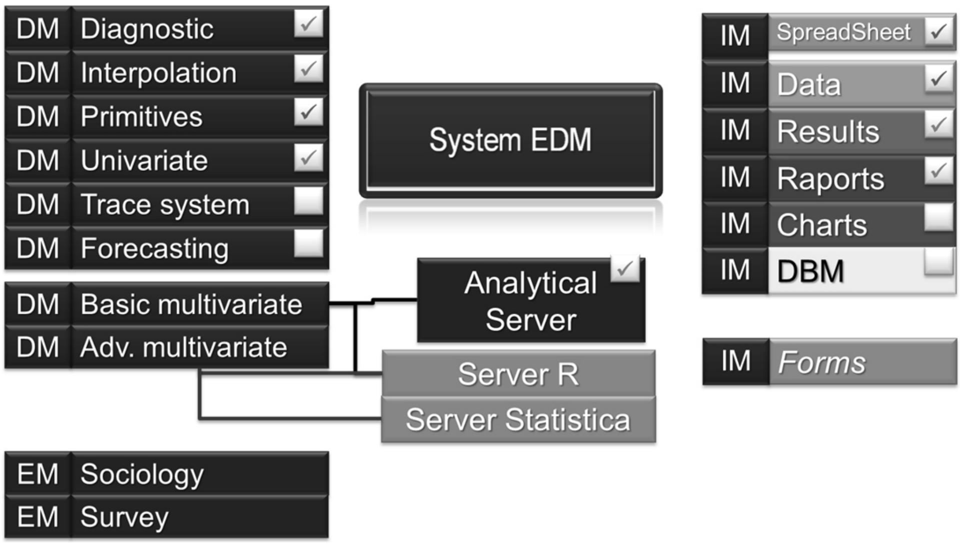

FIGURE 5. EDM system internal structure

3. Scalability: external EM modules, DM dedicated modules (Fig. 5).
4. Convenience for users: both advanced and those who need only a reporting tool – realized by user-friendly interface.
5. Easy serviceability: the application is programmed in the way that allows user's problems to be identified in the widest and the fastest way.

The analytical platform is the main element of the system. Its task is to integrate low-level modules (libraries and mathematical, statistical econometric and procedures both authors and open source) with dedicated modules (e.g. measurement data quality analysis).

Multilayer structure of the application (Fig. 6) enables relatively simple expansion both on the side of dedicated external modules, which can be created in any language as classes, using system in the function of namespace, which contain cohesive environment of object system of database management and which make analytical methods available, as well as on the side of internal modules such as e.g. a subsystem of conducting surveys in the future. Integrated modules: Spreadsheet, Data, Reports, Results – which can share both data streams and calculation results are, from the user's point of view, cores of the application.

Pollution forecast model (short-term, multivariate)

It is based on principal components analysis model by Hotteling (PCA). Based on the previous research (Badyda et al. 2016), the model allowed forecasting the atmospheric conditions leading to high concentrations of a pollutant from two to ten hours in advance.

The warning system

It is the key element of emission control in urban-industrial agglomerations. Combined with large-scale forecasts of meteorological conditions, it is going to allow decreasing real dangers to people's health, resulting from pollution. The

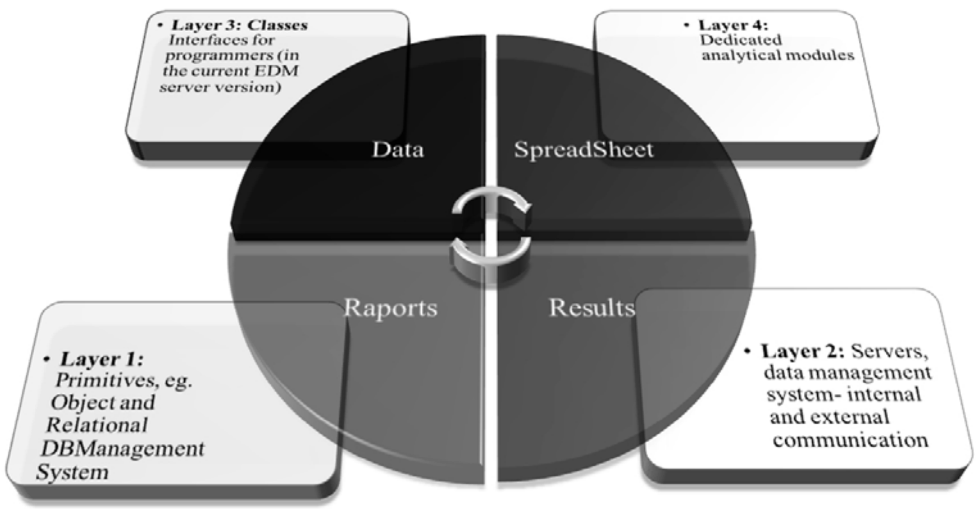

FIGURE 6. Layers of EDM system application

analysis of measurement data quality is carried out in accordance with own methodology proposal (Czechowski 2013, Czechowski et al. 2013) using robust estimators and being a complex solution for this issue. Attention to measurement data quality is an important issue, if not a key one, in a system of continuous atmosphere monitoring. Therefore this element was emphasized, proposing the numerical implementation of both methods used in the European Union, the United States (Badyda et al. 2016) and own methodology was used.

The idea of proposed data quality methodology is the identify the measurement result, deviating from the reference level, like a wrong is not enough. Required a detailed reason analysis, in order to take a decision to eliminate erroneous measurement or leaving an unusual measure, but correct.

The question is: How to distinguish erroneous measurements of observations caused by natural factors, such as e.g. sudden changes in weather or incidental traffic? Influence analysis of the removal measurement/group faulty measurements for the other, in various aspects of the phenomenon, allows identifying the causes of potential error and the decision to eliminate it. The proposed methodology, at present, include a select set of measures and six stages endearing four key aspects of the phenomenon:

1. Raw data in time and frequency domains aspect detects deterministic errors, thresholds problems and other rough errors (UA_Data).
2. Statistical distributions identified variable distribution (–log MLE) and through linearized distribution function identified outliers groups – UB_Distr. (Czechowski and Kraszewski 2009).
3. Non-linear Fourier regression model with periodicity (all assumptions of stochastic processes checked) detects outliers in time domain – UC_QAAH1.
4. Statistical tests, EPA and EEA procedures (EPA 2007), stage based on author's iterative enlargement of Rosner and Grubbs tests and robust estimators – MA_Pairs.
5. Multivariate pairs stage through models identified relationship between two variables (LS and MLE) detects impacts of direct pollutions and outliers in this interdependence – MB_All (Kalnay 2003).
6. Last stage – the assessment multidimensional impact of exogenous factors (Calori et al. 1994).

The main mechanism in the process is to assess the influence of remove faulty measurements on the others. Selected measures on the basis of cause and effect determined by the models aim to identify the identification causes of errors in a relationship (exogenous factors, endogenous or in combination). Stages of process diagnostics recognize sources of errors that were previously classified. The dependent variable – being assessed quality – is chosen series of measurements in a strong measurement scale.

The aim of the proposed methods is assistance while detecting potential outliers. The final decision of eliminating observation results from data set is taken by a human. The idea of the method was based on analysis of untypical observations (influential observations, distance observations or outliers).

The key issue of the solution is estimation of three main measures, which enable to classify the causes of identifying an observation as incorrect or untypical:

- DFITS measure – indicates highly untypical nature of an observation, without listing its causes.
- Mahalanobis distance – allows estimating the distance between the result listed by DFITS and distribution of dependent variables (e.g. concentration). Therefore it is possible to answer the question whether the cause of identification is connected to the dependent variable.
- Cook's distance – allows estimating the distance between a measurement and centroid, which is a point of reference in a multidimensional space of independent variables (e.g. meteorological measurements, data from balance models or predicators identifying periodicity).

It is assumed that outliers (in relation to univariate distribution and those not caused by changes in the atmosphere) will allow to identify abnormalities in measurements not resulting from natural causes. To achieve its aim, the method requires to realize certain stages in univariate part and in multivariate (Fig. 7): in pairs, where a particular dependent variable is analyzed with each independent variable separately and in the approach of combined influence of all given independent variables on a particular dependent variable.

The final step is to calculate the proposed measure IdOR (Identification odds ratio). IdOR measures the chances of each measurement it is an error. It also indicates in an understandable way the cause of error identification: UA_Data – source of error from measurement data analysis stage, UB_Distr – source of error in statistical distributions stage, UC_QAAH1 – source of error from time series models analysis stage, MA_Pairs and MB_All – source of error from multivariate statistical models respectively pairs and cause effect type models (the table).

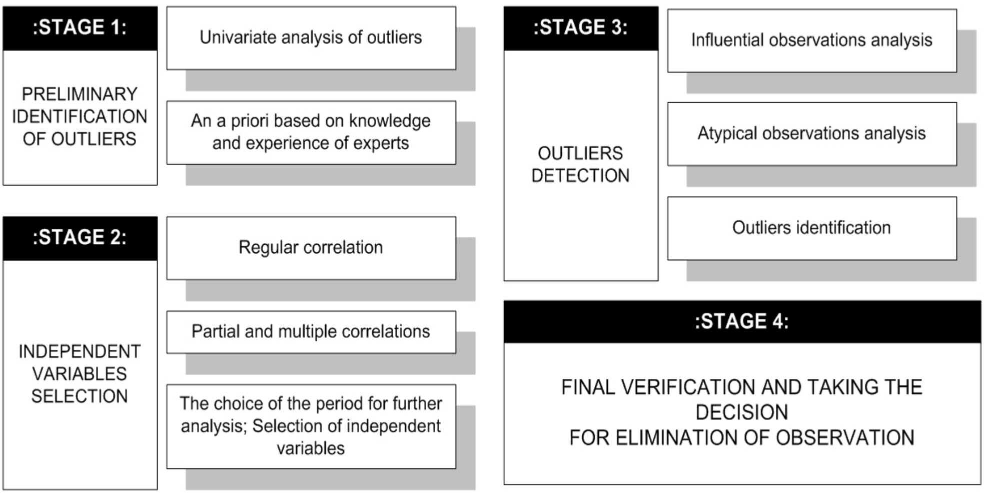

FIGURE 7. Multivariate data quality analysis stages in system – base scenario

TABLE. Identification odds ratio results in final diagnostic report

Observations	NO_2	UA_Data (%)	UB_Distr. (%)	UC_ QAAH1 (%)	MA_Pairs (%)	MB_All (%)	IdOR (%)
189	87.77	–	–	16.1	–	–	14.1
608	89.69	–	–	16.1	–	–	14.1
550	5.57	–	–	–	–	19.4	11.8
1	162.21	–	–	–	13.5	–	7.6
1 415	420.19	1.6	–	–	–	–	1.4

CONCLUSIONS

The aim of the article is to present important elements of smart city system: air pollution monitoring system based on implementations made by the team in Poland and selected new smart systems. Focused on the stochastic modeling part of data quality subsystems. Second topic is modelling the impacts of air pollutions on health.

Global forecasts indicate that the number of population in urban areas is increasing rapidly worldwide. Just as the level of air pollutions. This synergy will develop. Air pollution monitoring information systems will gain in importance mainly because of the need to inform the society about the risks. Ensuring a high level of data quality is essential in the construction of effects on health models.

Currently realized projects show the possibilities available to smart cities in this area. New ideas and measures, now designed and tested, will increase the accuracy and detail of such applications among others by the idea of measurement fields.

Currently, the developed methodology for assessing the quality of data is designed to be flexible and useful in the situation of the vast expansion the system database infrastructure and measurement. Developed solutions are scalable and easy to use practically. It is not possible to perform comparative analysis of data quality assessment systems because there are no similar comprehensive solutions. In practice, selected procedures in existing air monitoring systems in Paris, London, Barcelona and others.

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Streszczenie: *Dostarczanie wysokiej jakości danych pomiarowych w analitycznym systemie monitorowania zanieczyszczenia powietrza i kluczowe znaczenie tych danych w koncepcji inteligentnego miasta.* W artykule przedstawiono wybrane, główne elementy koncepcji podsystemu analitycznego automatycznych sieci monitoringu powietrza w koncepcji inteligentnego miasta na podstawie przykładów z Polski: zaimplementowanego systemu AirPomerania, idei nowego systemu w Warszawie AirVarsovia oraz pilotażowych badań w Nowym Sączu. Każdy z systemów jest wynikiem prac zespołu – począwszy od etapu projektu informatycznego podsystemu, poprzez opracowanie nowych metodologii badawczych i budowę aplikacji, aż po etap wdrożenia w działające systemy monitorujące inteligentnego miasta. W artykule położono nacisk na najbardziej newralgiczne elementy: podsystem diagnostyki danych pomiarowych oraz nową koncepcję nowych przenośnych mierników zanieczyszczeń powietrza i możliwości ich zastosowania w badaniach oraz modelowaniu. Szczególną uwagę poświęcono modelom stochastycznym i metodologii statystycznej, którą przyjęto za rozwiązanie w systemie analitycznym.

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