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INTEGRATED SYSTEM OF CONTROL AND MANAGEMENT OF EXPLOITATION OF WATER SUPPLY SYSTEM

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Summary

The paper presents a brief summary of the research and implementation works carried out by the authors in three research projects in years 2005-2011 within one of the companies managing water supply system. Exploitation and diagnostic specificity of the operation of water supply systems was discussed. Opportunities and needs of supporting the exploitation and diagnosis of the water supply system, and the capabilities and needs of a computer-aided maintenance in this task area are discussed. Based on our recognition and analysis, two computer subsystems were presented, which are main parts of an Integrated System for Control And Management of Exploitation of the Water Supply System. In this regard, there was presented a key model aspects that underpin the construction of subsystems, and it was discussed how the system works in the context of supporting selected tasks carried out by the technical staff of the analyzed company.

Keywords: water supply system, leakage monitoring, maintenance policy

ZINTEGROWANY SYSTEM STEROWANIA I ZARZĄDZANIA EKSPLOATACJĄ SIECI WODOCIĄGOWEJ

Streszczenie

W artykule przedstawiono podsumowanie prac badawczych i wdrożeniowych realizowanych przez autorów w ramach trzech projektów badawczych w latach 2005-2011 w obrębie jednego z przedsiębiorstw zarządzających systemem wodociągowym. Omówiono eksploatacyjną i diagnostyczną specyfikę funkcjonowania sieci wodociągowych. Dokonano także przeglądu możliwości i potrzeb komputerowego wspomagania w omawianym obszarze zadaniowym. W oparciu o przeprowadzone rozpoznanie i analizę zaprezentowano dwa podsystemy informatyczne tworzące Zintegrowany System Sterowania i Zarządzania Eksploatacją Sieci Wodociągowej. W tym zakresie przedstawiono kluczowe aspekty modelowe stojące u podstaw budowy poszczególnych podsystemów, a także omówiono sposób działania systemu w kontekście wspomagania wybranych zadań realizowanych przez służby techniczne badanego Przedsiębiorstwa.

Słowa kluczowe: system wodociągowy, monitorowanie wycieków, polityka eksploatacyjna

1. INTRODUCTION

Maintenance management decision-making process should be considered from many points of view [14]. In this perspective, effective implementation of the activities of the technical services in an industrial enterprise not only refers to the technical aspects and the "computer-based-tools", but also covers organizational, technical and information-related issues of the supervision of a company's machinery park, as well as preparation and execution maintenance work [16, 28].

Water supply networks are one of the most crucial components of the urban infrastructure [4], [11]. They are of significant importance for existing large population centers, contributing to improving the quality of life at that areas. The life cycle for this kind of technical objects is counted in decades. Such long time distance makes that proper activities, connected with the maintenance and diagnostics, are undervalued. Instead of that the maintenance strategy very often limits to the attitude "repairs and wait for the next failure." Meanwhile it is the fact that the rational maintenance policy can bring significant benefits to water supply companies.

The article presents a brief summary of the research and implementation works carried out by the authors in three research projects in years 2005-2011. The results of these projects were implemented one of the Polish water supply and sewerage companies.

The need for studies undertaken resulted from the common problems for most of the cities of the Silesian Agglomeration in Southern Poland.

They are related to long-time used water networks, thus exploitation problems, including increased number of failures and lack of full effective response to these.

The research described in the paper has been carried out in a comprehensive manner by two teams of the Silesian University of Technology (Institute of Production Engineering team and Institute of Fundamentals of Machinery Design team), aimed to evaluation and improvement of the effectiveness of exploitation of a water supply system and functioning of technical staff of companies in the studied company. The results of the work undertaken and completed are reflected in the form of model solutions, as well as developed and implemented computer tools.

2. WATER SUPPLY SYSTEM AS AN EXPLOITATION AND DIAGNOSIS OBJECT

Water supply system, which functions as a collective water supply consisting of the exploration, treatment and water supply to its customers [3, 5]. Water supply operating should meet the needs of the population in terms of organization and continuity, with the required level of pressure and of appropriate quality (i.e. smell, taste, chemical composition). Exploitation specificity of a technical network system requires ensuring continuity and quality of supplies within an extensive technical infrastructure geographically dispersed over a large area [3]. This simply means the need to ensure an adequate level of reliability [9]. Therefore, such systems are characterized by a number of specific features, which include [12, 6, 2, 15]:

- territorial dispersion of the system components,
- specific location of system components, often difficult to access - underground, at a height,
- high structural complexity, large number and variety of types of objects within the system, powerful links and relationships between system components,
- high dynamics of the system, which requires continuous control and monitoring of the processes performed,
- uninterrupted operation for most installations, equipment and buildings belonging to the system.

These features determine specific capabilities and limitations of maintenance tasks that differ from the works in typical industrial enterprises focused on the production line exploitation.

The need to diagnosing and monitoring water supply systems is mainly caused by leaks. This is not a trivial issue, because a significant number of leakages does not manifest its presence on the ground.

There are tools for building numerical models and simulating operation of water supply systems, for example EpaNET [25], however, the need for a detailed determination of the model features, limits their practical effectiveness. In particular, problems with modeling work of water supply network include:

- more difficult access to most objects thus the limited possibility to evaluate their condition (eg. the degree of encrustation of pipes),
- difficult to identify the features of the individual pipes (eg. hydraulic resistance),
- difficult flow measurements in different sections of the network (installation of measuring equipment needs to unveil the pipe),
- almost impossible to accurately determine the current consumption of water by consumers.

In addition, the territorial extension and dispersion of the network makes difficult to construct the measuring system, and a variety of topologies causes, that each network is somewhat unique. To draw general conclusions regarding the modeling and diagnosing is practically impossible.

There is a large group of methods used for diagnosing leaks and monitoring condition of a network, including [1, 9]: balancing the amount of water supplied and sold within the district metering area (DMA), observing night flows (minimum night flow) and a review of a water supply system. These methods have their undoubted advantages, but they don't solve all key problems, founded in analyzed company. These problems were the basis of research conducted by the authors.

3. REVIEW OF OPPORTUNITIES AND NEEDS OF SUPPORTING OF EXPLOITATING AND DIAGNOSING OF THE WATER SUPPLY SYSTEM

There were three different IT tools supporting operations management of water supply systems. Basing on the analysis of operational tasks performed by a maintenance staff in water supply companies, the needs and opportunities for IT supporting within the area of maintenance have been identified. They can be divided into three main groups [6, 11, 7, 8]:

a. tools for registration components of the networks and technical facilities (materials, tools) used for maintenance and repair works - Egeria ERP System (fig. 1).

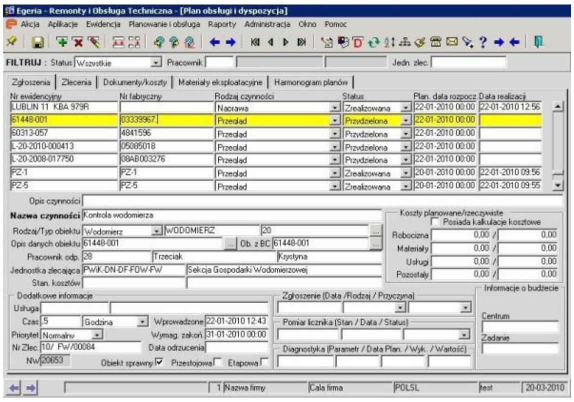

Fig. 1. Sample screen of ERP Egeria system

b. tools for monitoring the condition of water supply system - SCADA System (fig. 2)

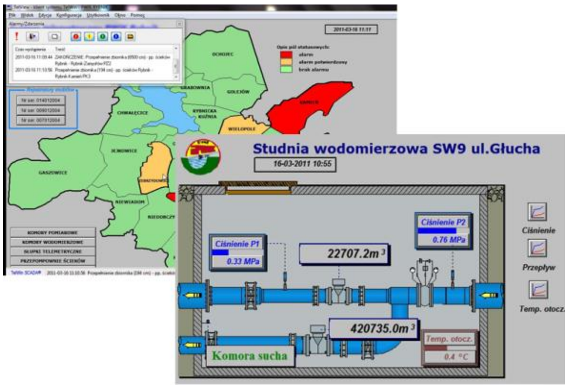

Fig. 2. Sample screens of SCADA system

c. tools for identification and spatial location of the water supply components - Sonet GIS System (fig. 3)

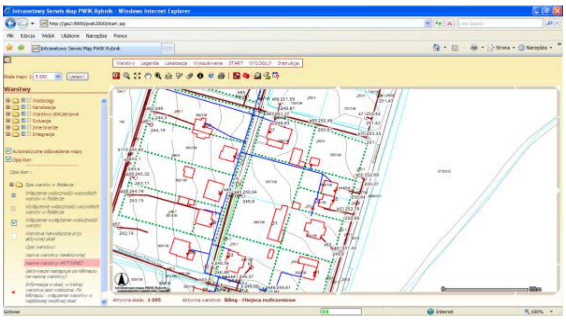

Fig. 3. Sample screen of Sonet GIS

A review of methods and tools used to support the exploitation and diagnosing of the selected technical network systems showed [15]:

- high diversity and dispersal of information and information technology, manifested in a lack of continuity and a low compatibility tools to "produce" exploitation information, which does not constitute analytical grounds for the exploitation decision making process,
- incomplete information and utilities connections between different decision-making areas of exploitation process (e.g. separate systems supporting the identification, diagnostics, maintenance or documentation tasks),
- insufficient considering the exploitation and diagnostics specificities of particular technical systems,
- insufficient use of model solutions and analytical tools, especially in supporting long-term exploitation analysis and long-term exploitation decision-making process.

It should be noted, that methods and tools used in this area do not allow for full utilization of collected information about the exploited objects, exploitation events and exploitation processes, for the needs of exploitation decision-making process. In particular, there is a clear need to supplement the information path of the exploitation processes for:

- tools of both pre-detection and location of failures, that would be easy for automation to promptly detect and locate individual events, and, thereby, reduce the time required for the reaction and removing the of failures
- typical analytic and decision-making tools allowing efficient enrichment of existing management solutions,

The concept of the support system, outlined by the conclusions from the analysis carried out in the studied company, relied on adding supplement organizational and technical solutions that operating in the company with tools to support the detection and location of a network failure, as well as a comprehensive assessment of the operational activities. In this way, it was developed the Integrated System of Control and Management of Exploitation of the Water Supply System, which idea is schematically shown in fig. 4.

The Integrated System of Control and Management of Exploitation of the Water Supply System in addition to the formerly described modules, includes two new subsystems:

1. Intelligent System of Failure Detection and Localization - SysDetLok,
2. Intelligent System for Supporting Operational Events - ISSOE.

The main screen of the system developed is shown in fig. 5.

4. INTELLIGENT SYSTEM OF FAILURE DETECTION AND LOCALIZATION - SysDetLok

The concept of supporting the monitoring the water supply network was the assumption that the measurement results of water supply network parameters in several selected points can form a certain pattern – an image of the network corresponding to the current condition.

This assumption allowed applying methods that have previously been used in the process diagnosis. They are based on object models.

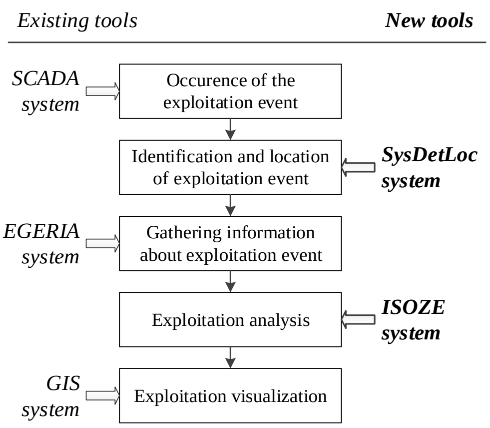

Fig. 4. Concept of Integrated System of Control and Management of Exploitation of Water Supply System

Fig. 5. Main screen of the Integrated System of Control and Management of the Exploitation of Water Supply System [21]

They are based on approximate models of the object and on condition classifiers. The assumed advantage of this approach was to move away from balancing flows as the basis for detection and location of failure, so that the expected number of required sensors would be smaller. As part of the planned works, it was extended previously developed method for failure detection based on approximate models [29], so as to allow the detection of smaller leaks.

The basis for leak detection consists in measuring the flow rate in the supply point of diagnosing network and then building predictive model of this flow. In the built system, there were applied two predictive modules – the first one based on the model with one input and one output (single input single output SISO) [26, 30], and the second, based on the model with multiple inputs and one output (multi input single output MISO). In second variant, additional inputs are the flow rates in selected similar networks (those for which it was found that the consumption of water has a similar pattern as the network diagnosed). Residuum signal is assessed and on this basis a diagnostic signal is calculated, It indicates emergence of a leak [23]. Application of MISO model allowed reducing the number of false alarms. The Scheme of the applied detection method is shown in fig. 6 [30].

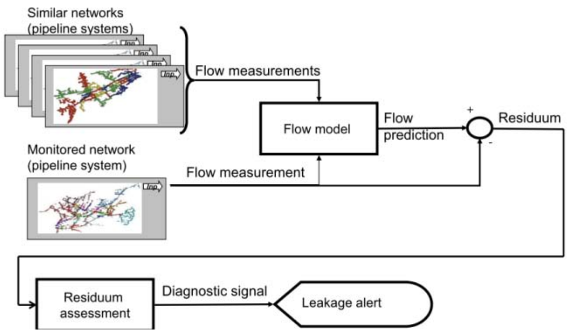

Fig. 6. A scheme of an leakage detection method [30]

Failure location is based on the similar principle. In this regard, there are used flow measurements at the input to the network and selected points "inside" of the network. Methods of location of measurement points is described in [24].

For each measuring point, there are built forecasting models with a single input and output (SISO). Vector of detected flow changes is the basis for the classification of network condition [26]. As distinguishable conditions, there are assumed leaks in a specific, pre-defined area of the network. Details of the method and constructed models were described in [19, 20, 18]. The scheme of the method is shown in fig. 7 [30].

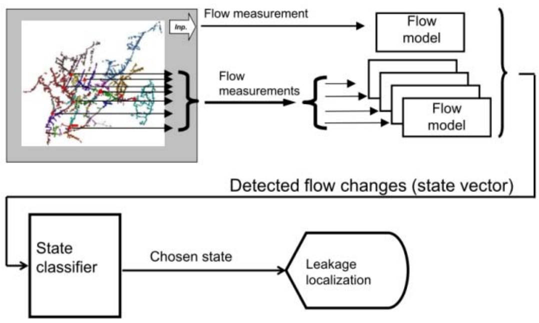

Fig. 7. A scheme of an leakage location method [30]

The Intelligent System of Failure Detection and Localization was implemented as a service running "in the background" on a dedicated server. The system does not have its own separate user interface. For the needs of communication with the operator there are used SCADA system (alarm signalling), GIS system (localization and visualization within selected failure area). The only point of direct operator interaction with the system is resetting alarms. To reset the alarm it was prepared an additional interface, which is accessible through a Web browser. It allows you to store information about the operator's decision in the event database of SCADA system.

The functional diagram of the system and its components is shown in fig. 8.

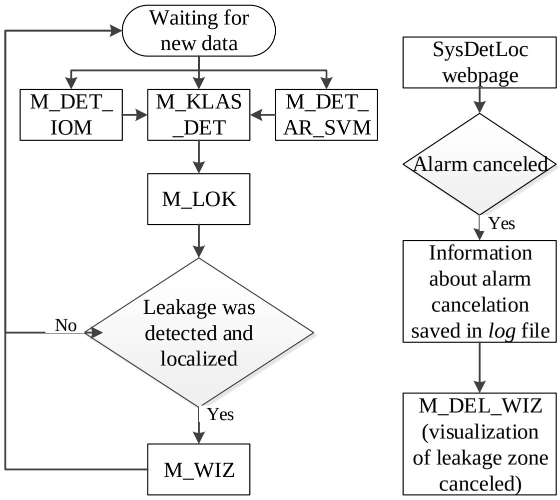

Fig. 8. Schemat działania systemu SysDetLog [21]

SysDetLok works together with the database, in which there are recorded an ongoing basis the results of measurements. The appearance of new measurements starts the process of leak detection. This process is performed by various methods within the two modules, M_DET_IOM and M_DET_AR_SVM. The result of these activities is agreed upon within the M_KLAS_DET module, which allows you to generate binary diagnostic signal characteristics. Information about leak detection is sent to the SCADA and begins operation of the location M_LOK module. Successful leak location launches M_WIZ module, which prepares information about potential leakage for GIS system. This information is transmitted to that system via the proxy DEIT module.

The system operator makes the final decision on activities related to the leak detection. The operator communicates with the system via M_DEL_WIZ module. Operation of the modules synchronizes the master SYS_DET_LOK module, and the communication between them is done through a blackboard.

SysDetLok was tested with regard to simulation data derived from active experiments, and then, as a passive experiment, based on actual measurements. The tests confirmed the assumptions and the correct operation of the system.

In fig. 9 and fig. 10 there are showed two examples of failure detection. The charts are based on the provisions of the internal "blackboard".

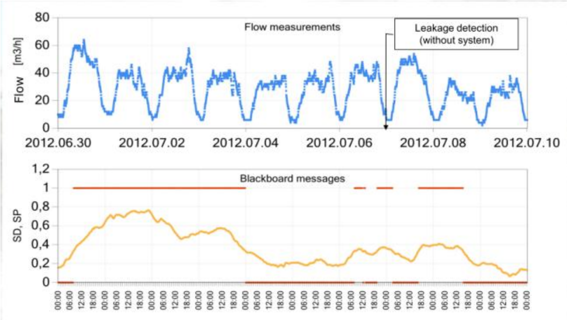

Fig. 9. Example of failure detection within SysDetLok system [21]

Fig. 8 shows the signal of the flow rate, with the point of failure detection (requisition).

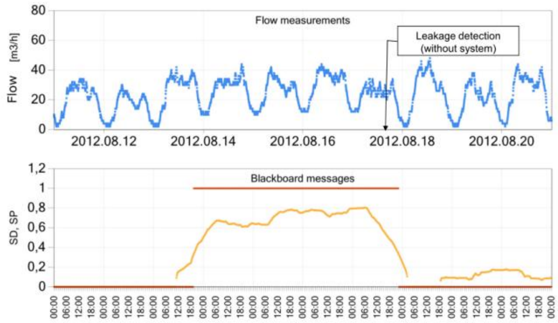

Fig. 10. Example of failure detection within SysDetLok system [21]

Fig. 9 shows the course of the beliefs level about existence of failure and binary decision signal.

Visual results of the SysDetLok operation are:

a. highlighted zones with abnormalities into SCADA system (fig. 11),
b. blackboard with failures marked (fig. 12).

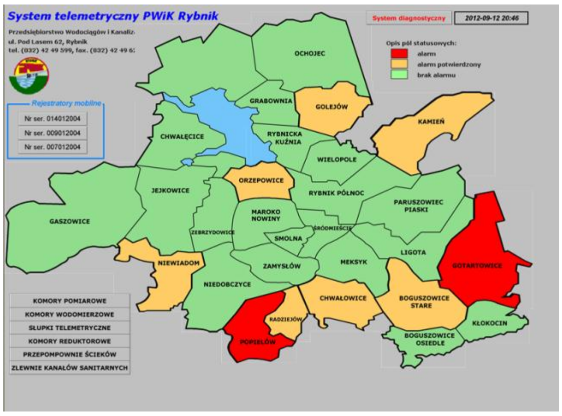

Fig. 11. Visual results of the SysDetLoc operation - highlighted zones [21]

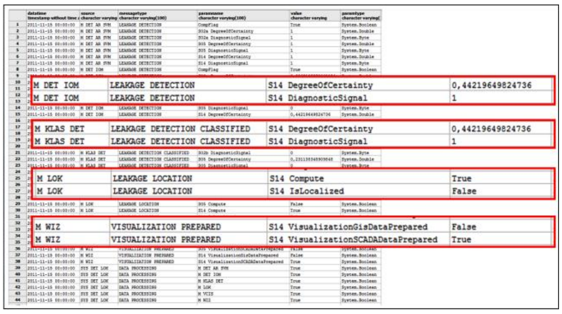

Fig. 12. Visual results of the SysDetLoc operation - blackboard [21]

5. INTELLIGENT SYSTEM FOR SUPPORTING ASSESSMENT OF OPERATIONAL EVENTS

The main purpose of building a subsystem of maintenance management of the water supply system supporting the decision making process on the basis of continuous assessment of changes of exploitation potential value, with using the information acquired during use and maintenance work for water supply system.

The basis of the subsystem construction was to develop a model for assessing exploitation policy, based on the information about events and ongoing maintenance work [13]. The concept of an intelligent support system based on the assumption that the source data for calculating operating ratios should be contained in the ERP system (Enterprise Resource Planning) [27] or CMMS/EAM (Computerized Maintenance Management System/Enterprise Asset Management) [16] representing the effect of workflow in the organization of water supply companies.

Fig. 13 presents a scheme that shows the linkage of IT tools supporting the proposed system.

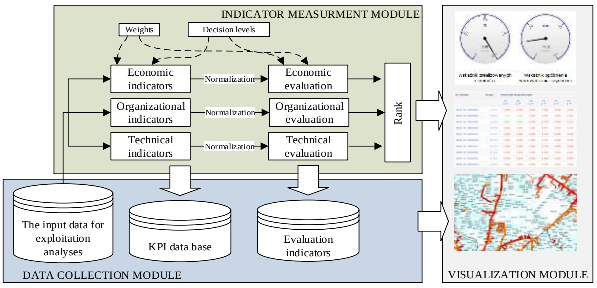

Fig. 13. Information flow into ISSOE system

ISSOE consists of three modules differing the scope of the data collected and the role into the system concept. In particular, there can be distinguished:

1. ISSOE database, whose role is to collect data and input information with the use of models of objects, events, and processes of exploitation of the water supply system and operation of the maintenance staff. These data is imported in a cyclic manner from ERP Egeria system. This database also includes controls of Egeria, to allow proper organization of procedures for exploitation data acquisition. The results of this research are given in [8].
2. Analytical module, the aim of which is to determine the potential of exploitation value of each object within the water supply system. It was assumed that the basis for assessing the exploitation potential value is a set of exploitation measures, large and adequate to the analyzed system. These measures are technical, organizational and economic. Applying normalization and aggregation of the measures (according to the principles of numerical taxonomy [17, 22]) allows determining the rank of the resultant objects. Their geometric interpretation defines the exploitation potential value. Constructed in this way taxonomic method of assessing the potential exploitation was discussed in detail in [13]. In fig. 14 the key mathematical components of the method are shown in a synthetic way.

$$R = \left(\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \cdot \begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix} \right) \cdot \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix}^T$$

$$\sum_{i=1}^{N} g_i = 1 \qquad a_{ij} = \sum_{i=1}^{N} OC_{ij} \cdot g_i$$

$$OC_{is} = \frac{10 \cdot M_i}{M_{i_{max}} - M_{i_{min}}} \qquad OC_{id} = 10 - \frac{10 \cdot M_i}{M_{i_{max}} - M_{i_{min}}}$$

Fig. 14. A set of mathematical components of taxonomic model for assessing exploitation potential value [13]

A means of organizing measures for the needs of taxonomic model for assessing exploitation potential value, is presented in tab. 1.

Tab. 1. A means of organizing exploitation measures of taxonomic model for assessing exploitation potential value [13]

	Economic measures weight k_1	Technical measures weight k_2	Organizational measures weight k_3
Level 1 weight p_1	a_{11} $OC_{E1},\ldots,OC_{Em}$ (sum of the weights is 1)	a_{12} $OC_{T1},\ldots,OC_{Tm}$ (sum of the weights is 1)	a_{13} $OC_{O1},\ldots,OC_{Om}$ (sum of the weights is 1)
Level 2 weight p_2	a_{21} $OC_{Em+1},\ldots,OC_{En}$ (sum of the weights is 1)	a_{22} $OC_{Tm+1},\ldots,OC_{Tn}$ (sum of the weights is 1)	a_{23} $OC_{Om+1},\ldots,OC_{On}$ (sum of the weights is 1)
Level 3 weight p_3	a_{31} $OC_{En+1},\ldots,OC_{Ep}$ (sum of the weights is 1)	a_{32} $OC_{Tn+1},\ldots,OC_{Tp}$ (sum of the weights is 1)	a_{33} $OC_{On+1},\ldots,OC_{Op}$ (sum of the weights is 1)

The set of measures included in the model is shown in tab. 2.

Tab. 2. The set of measures included in the model for assessing exploitation potential value [21]

Indicator description	
$E1 = \frac{\text{maintenance cost}}{\text{water production}}$	economic (cost) indicators
$E2 = \frac{\text{water unavailability cost}}{\text{water production}}$	
$E3 = \frac{\text{water availability time}}{\text{total maintenance cost}}$	
$E4 = \frac{\text{internal personnel cost}}{\text{total maintenance cost}}$	
$E5 = \frac{\text{external personnel cost}}{\text{total maintenance cost}}$	
$E6 = \frac{\text{maintenance materials cost}}{\text{total maintenance cost}}$	
$E7 = \frac{\text{maintenance supplementary cost}}{\text{total maintenance cost}}$	
$E8 = \frac{\text{materials cost for object}}{\text{total materials cost}}$	
$E9 = \frac{\text{corrective maintenance cost}}{\text{total maintenance cost}}$	
$E10 = \frac{\text{preventive maintenance cost}}{\text{total maintenance cost}}$	
$E11 = \frac{\text{condition based maintenance cost}}{\text{total maintenance cost}}$	
$E12 = \frac{\text{removal of failure maintenance cost}}{\text{total maintenance cost}}$	
$E11 = \frac{\text{improvements maintenance cost}}{\text{total maintenance cost}}$	
$E14 = \frac{\text{maintenance training cost}}{\text{total count of maintenance staff}}$	
$T1 = \frac{\text{breakdown time}}{\text{total downtime}}$	technical (time) indicators
$T2 = \frac{\text{correcive time}}{\text{total downtime}}$	
$T3 = \frac{\text{no. of failures causing injury to people}}{\text{total number of failures}}$	
$T4 = \frac{\text{no. of fail. causing damages to environment}}{\text{total number of failures}}$	
$T5 = \frac{\text{total operating time}}{\text{number of failures} + 1}$	
$T6 = \frac{\text{total repair time}}{\text{number of failures} + 1}$	
$T7 = \frac{T5}{T5 + T6}$	
$T8 = \frac{\text{total manhours}}{\text{total maintenance time}}$	
$O1 = \frac{\text{number of direct maintenance personnel}}{\text{total employees}}$	organizational indicators
$O2 = \frac{\text{number of indirect maintenance personnel}}{\text{total employees}}$	
$O3 = \frac{\text{planned maintenance manhours}}{\text{total maintenance manhours}}$	
$O4 = \frac{\text{preventive maintenance manhours}}{\text{total maintenance manhours}}$	
$O5 = \frac{\text{correcive maintenance manhours}}{\text{total maintenance manhours}}$	
$O3 = \frac{\text{failire maintenance manhours}}{\text{total maintenance manhours}}$	

3. Visualization module, the aim of which is to set the results of the analyzes both in quantitative-tabular form, as well as in terms of graphic-spatial (fig. 15, fig. 16 and fig. 17).

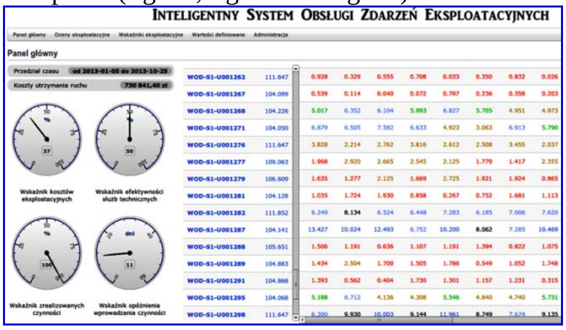

Fig. 15. The ISSOE screen with quantitative-tabular visualization of the analysis results [21]

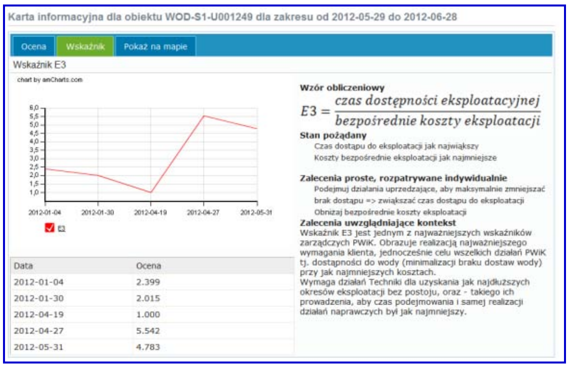

Fig. 16. The ISSOE screen with example single measure visualization of the analysis results [21]

The second way to visualize uses GIS techniques for the needs of spatial location of the events and the corresponding values of exploitation measures (fig. 17).

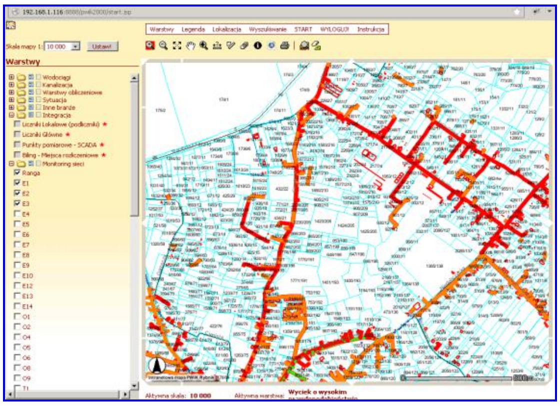
Fig. 16. The ISSOE screen with the method of spatial interpretation of measurement values [21]

Within the ISSOE system the main role of GIS is primarily visualization on the digital map the set of KPI and operational parameters of the water supply network. In order to achieve this goal firstly it was necessary to determine how to integrate GIS databases with data sources from other systems, such as Egeria and the ISSOE. Thanks to this on the map you can view any data collected in the Egeria

system, by which they gain a reference to geographic location, which is important from the standpoint of conducting spatial analysis within maintenance area. Presentation of the operational indicators (KPI) in the GIS can be carried out with the use of thematic layers and charts. Entered data in conjunction with information available on the other layers can be a source of interesting studies that provide valuable information for decision making.
The result of ISSOE is:

- possibility of assessment of the exploitation activity of maintenance staff respect to the defined parts of the water supply system,
- response possibility to adverse changes in the functioning of selected sections of the network appearing in time and in space,
- the possibility of shaping of exploitation policy based on the analysis and synthesis of selected exploitation measures.

6. SUMMARY

The Integrated System of Control and Management of Exploitation of Water Supply presented in the article is the result of several years of cooperative work conducted in the Institute of Fundamentals of Machinery Design and the Institute of Production Engineering at the Silesian University of Technology. The system was built by the authors and implemented into practice. It is utility complement, therefore, considerably enriches and improves management processes in the water and sewage company.
According to the authors, implementation of the system in the industrial environment is not the final step in the development of prepared methods and tools. At the current stage industrial research is being conducted. They depend on:

- SysDetLok: Improving the method of leakage detection, to make it more sensitive. Improving the method of leakage localization, to make it more robust and precision. Joining a method of automatic tuning of the hydraulic model,
- ISSOE: verifying the correctness and effectiveness of the rank method based on data from the real working environment - the activities of maintenance department. Verification will allow to make parameterization and positioning of the rank method, which relates to certain ambiguities of the method and its weak points, which concern: measures selection, ways of determining the weights, full use of the objects rank in company strategic planning [10].

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