

**UNCERTAINTY PROBLEM IN DECISION SUPPORT  
SYSTEM FOR MEANS OF TRANSPORT MAINTENANCE  
PROCESSES PERFORMANCE DEVELOPMENT**

**PROBLEM NIEPEWNOŚCI W SYSTEMIE WSPARCIA  
DECYZYJNEGO PROCESÓW UTRZYMANIA W STANIE  
ZDATNOŚCI ŚRODKÓW TRANSPORTU**

**Tomasz Nowakowski, Sylwia Werbińska-Wojciechowska**

Wrocław University of Technology, Wrocław, Poland,  
e-mails: tomasz.nowakowski@pwr.wroc.pl; sylwia.werbinska@pwr.wroc.pl

***Abstract:** In this paper, the authors' research work is focused on uncertainty analysis implementation in the developed DSS for transportation means' maintenance processes performance. Thus, in the Introduction section, the transportation means' maintenance processes issues and the uncertainty problem are described. Later, there is briefly literature overview in the research area discussed. In the next Section, the expert system for means of transport maintenance processes performance is also investigated. Following this, the uncertainty analysis is developed and the examples of expert system implementation are given. The work ends up with summary and directions for further research.*

***Keywords:** passenger transportation, maintenance strategy, expert system, delay-time*

***Streszczenie:** W artykule autorzy skupili się na analizie niepewności danych w opracowanym systemie wsparcia decyzyjnego procesów utrzymania w stanie zdatności środków transportu. We wprowadzeniu problem niepewności oraz zagadnienia utrzymania w stanie zdatności środków transportu zostały omówione. Następnie, przedstawiono krótki przegląd literatury z badanego obszaru. W kolejnym kroku, przedstawiono system ekspertowy wspierający proces decyzyjny w badanym obszarze. Pozwoliło to na opracowanie analizy niepewności oraz jej implementację w systemie ekspertowym. Pracę kończy podsumowanie i wskazanie kierunków dalszych prac badawczych.*

***Słowa kluczowe:** transport pasażerski, strategia obsługiwanania, system ekspertowy, opóźnienie czasowe*

## **1. Introduction**

One of the main decision groups in the transportation systems performance regards to maintenance tasks which includes the definition of maintenance strategies of transportation infrastructure, system elements, or operation control systems [22]. According to [22, 35], a transportation system is very complex one with different functional characteristics depending on medium of movement, particular technology used and demand for movement in the particular medium. Aspects of these modes are e.g. vehicle, the way, control of the system, the technology of motion, intermodal transfer points, payload, drivers and pilots.

As a result, uncertainty connected with the maintenance decisions is an essential component of everyday life, and has become an important characteristic of modern decision support systems [70].

Following this, the focus of this study is to develop the method of information uncertainty definition in DSS for means of transport maintenance processes performance which is implemented into Exsys Corvid Shell system.

Thus, the article is organized as follows: First, literature overview in the research area is discussed. Later, the conception of decision support system for means of transport maintenance processes performance is also investigated. The research area encompass formulation of methods and algorithms of right maintenance strategy (traditional/Delay Time Approach) for system elements selection. The solution is based on decision rules implementation. As a result, the main decision criteria are also defined, and the main maintenance strategy and their parameters are investigated. Thus, the problem of DSS uncertainty is investigated providing the definition of data uncertainty notation in the chosen expert system. The work ends up with summary and directions for further research.

## **2. Decision support systems in transportation systems performance – state of art**

The concept of a decision support system (DSS) is extremely broad and its definitions may vary depending on the author's point of view and the way of its use [15]. According to DSSResorces.com, a DSS is defined as *an interactive computer-based system or subsystem intended to help decision makers use communications technologies, data, documents, knowledge, and/or models to identify and solve the problems, complete decision process tasks, and make decisions* [56]. Thus, the systemic framework should be used as an organizing concept when designing an effective and reliable DSS [1]. The application of systems theory needs following five aspects consideration: environment, role, components, arrangement of components and the resources required to support the system [1]. For more information, we recommend reading e.g. [1, 15, 23, 45, 56]. Later, in [36], authors propose a classification of the errors that can be found in DSSs and describe the various DSS testing methods that have been proposed. Authors also give advice for choosing DSS testing methods.

The literature review in the area of decision support systems designing and applications issues may be found e.g. in [2, 16, 17, 18, 61, 73].

One of the first research works dedicated to DSS issues review is [61], where authors focus on the DSS effectiveness. The paper reports on a simple laboratory experiment to assess the effectiveness of DSS in a task environment characterized by uncertainty in competitors' actions and economic conditions. In work [18], author examines the issues confronting DSS in the business area. Later, in work [16] authors focus on the identification of research directions for Expert Systems and knowledge-based DSS, from the end-user point of view. The DSS application possibilities and their classification problems are investigated also in [17]. Author, in his work points out the possible future directions of DSS development. The review in the area of DSS applications development is given in [73]. Authors in their work analyse the development of the model-driven DSS, data-driven DSS, Group Communications-driven DSS, Document-driven DSS, Knowledge-driven DSS and Web-based DSS. Later, Power in his work [55] focuses on data-driven DSS investigation.

In [2], authors carry out the analysis of more than thousands of DSS articles published in 14 major journals from 1990 to 2004. This analysis let authors to find the eight key issues that the DSS field should address for to continue to play an important part in information systems scholarship. These eight issues include e.g. the relevance of DSS research, DSS research methods and paradigms, or discipline coherence. Later, in [37], author surveyed ES development using a literature review and classification of articles from 1995 to 2004. The paper surveys and classifies ES methodologies using the eleven categories, including e.g. rule-based systems, knowledge-based systems, neural networks, fuzzy ESs, or intelligent agent systems.

Moreover, there can be found many classifications of support systems in the literature. In work [15], there are investigated passive, active and cooperative DSS. According to the authors [45], there is necessary to define a distinction between main types of systems: DSS and Management Information Systems (MIS). As a result, the authors propose the following classification:

- Transaction Processing System (TPS) – programs for gathering, updating and posting information according to pre-defined procedures,
- Management Information System (MIS) – a system with pre-defined aggregation and reporting capabilities,
- Decision Support System (DSS) – an extensible system with intrinsic capability to support ad hoc data analysis and reduction, as well as decision modelling activities.

The broad discussion of two kinds of information systems – MIS and DSS is presented in [3]. Authors provide the characteristics of those kinds of information systems, interrelationship and their relations with decision-making process in an organization.

Taking into account another approaches, there can be distinguished [15, 56]:

- at a conceptual level: Communication-Driven DSS, Data-Driven DSS, Document-Driven DSS, Knowledge-Driven DSS, and Model-Driven DSS,
- at a technical level: enterprise-wide DSS and desktop DSS.

In the article [23] authors define the main types of DSS being used in practical applications and investigate the problem of their reliability. The authors focus on two types of DSS: Executive Information Systems (EIS) and Expert Systems (ES). Moreover, they analyse the DSS being offered by different producers according to their possibility of implementations and main functions (e.g. systems INSERT Analytik or Matrix). Later, Arnott and Pervan in their work [2] defines DSS according to the number of system's users or their application field. The major DSS sub-fields are defined as: Personal DSS, Group DSS, Negotiation Support Systems, Intelligent DSS, Knowledge Management-Based DSS, Data Warehousing, and Enterprise Reporting and Analysis Systems.

The exemplary implementation areas for DSS are [23]:

- financial issues (e.g. risk-cost analysis, effectiveness analysis, financial management),
- marketing issues (e.g. market analysis, sales analysis),
- production and logistics issues (e.g. production processes optimization, transportation planning optimization),
- human resource management issues (e.g. work time planning, turnover of staff analysis).

The target of this study needs the investigation of DSS which were developed in the area of transportation problems performance, especially connected with maintenance issues and DSS uncertainty. The complexity of maintenance planning decisions regards an online decision support systems to assist the maintenance decision maker [39]. Thus, the main role of a DSS is to enhance the decision making by an individual through easier access to problem recognition, problem structure, information management, statistical tools, and the application of knowledge [60]. Usually, DSS for maintenance is defined as a systematic way of selecting a set of diagnostic and/or prognostic tools to monitor the condition of a single component or machine [39].

The DSS for maintenance problems are developed since 1960s [39]. The DSS for industry-based maintenance of a single machine can be found e.g. in [57], where authors develop an intelligent maintenance support system for air traffic control, or in [64], where authors describe an integrated maintenance support system for a textile company designed by a GRAI method and based on causal probabilistic networks implementation. Another application area is given in [12], where author develops a model of selection of diagnostic techniques and instrumentation in a predictive maintenance program based on AHP and FA (factor analysis) implementation, and tests it in screw compressor. The continuation of maintenance decisions support for equipment operating under condition-based maintenance strategy is given e.g. in [20, 69, 74] and in [40], where authors analysed Intelligent Maintenance Systems based on CBM implementation.

The computerized information systems used to support exploitation processes performance can be also found e.g. in [29]. In this work, authors focused on Belt Conveyor Editor performance. There are described the system structure and operation, including operational information and its availability analysis. The similar problem is investigated in [31], where authors focused on the problem of operation planning processes for machinery room. The main assumptions and structure of the system for supporting operating, repair and modernisation decisions for the steam turbines is given in [34]. The example of decision support system implementation in the area of aviation maintenance can be found in [72]. The model is based on Fuzzy Petri Nets use. A knowledge based expert system developed to guide the rail scheduling problem is described in [42]. The model is developed in conjunction with Burlington Northern Railroad in order to define rational criteria for rail replacement. The backgrounds for projected software system dedicated for supporting the management of railcar operation is given in [6]. A decision support system prototype for maintenance management is given also in [38]. The prototype is developed using an agent-based approach for integrating distribution networked systems. Moreover, in work [48], the expert system for technical objects' reliability prediction is developed. The solution is based on EXSYS Professional system implementation. The similar problem for production system performance planning is investigated in [32].

In the area of passenger transportation processes performance, one of the problems being analysed in the literature regarded to timetable adjustments [44]. In this paper, authors propose a DSS, which allows for timetable planning assessing the impact of different scenarios taking into account the expected passengers' waiting time at the bus stop and the operational costs of the operator. The problem of DSS development for facilitating critical decisions related to transportation infrastructure planning in the public sector and supply chain planning in the private sector is given in [30].

Another problem is investigated in [24]. Author in his work, develop a GIS-based (Geographic Information System) DSS designed to facilitate transportation system planning process for the provincial transportation department. The role of DSS in transportation planning is also discussed in [11]. In this work, there is presented the information system which is designed to support transportation planning tasks in the Lombardy Region according to the defined Plan of Mobility and Transports.

In [63], there is a SMILE (Strategic Model for Integrated Logistic Evaluations) developed. The model is constructed as a joint effort of the Transport Research Centre of the Ministry of Transport and research organizations NEI and TNO Inro for effective freight flows organization. The transportation mode selection problem is investigated in [54]. Author, in his work, develop a decision support system based on AHP method implementation.

Moreover, in [52], there is presented a multi-agent architecture of DSS which was implemented in two transportation management domains in Spain: traffic control within part of the high-capacity road network in the Bilbao area, and bus fleet management of parts of the public bus network in downtown Malaga. This problem is also investigated in [53], where authors investigate the agent-based DSS for

transportation management, or in [9], where authors present a multi-agent approach for the regulation of traffic within a disrupted transportation system. In [33] author proposes a decision-aid tool within a DSS using Fuzzy-AHP for the systemic analysis. The tool can assist countries in developing strategic policy decision making for the facilitation of international intermodal transport routes linking different countries. A Transportation DSS model which allows formulation of aggregate and long-term scenarios to support policy makers in their analysis on passenger and freight demand in the future is given in [65]. Moreover, the problem of transportation system safety during emergencies is analysed in [71]. Authors in their work develop a DSS for emergency response to assess the state of preparation of a transportation agency to respond to emergencies, enable the development of new standard operating procedures, and to better train and empower employees in the decision making process.

Following this briefly literature review, the conception of DSS in the area of means of transportation maintenance processes performance is developed.

### **3. Decision support system in means of transport maintenance processes performance - conception**

The authors' research focus is connected with the definition of DSS conception for transportation means' maintenance process performance. The research area encompasses a formulation of methods and algorithms of right maintenance strategy (traditional/DTA based) for system elements selection. The solution is based on decision rules implementation. These decision rules are the base for computer procedure of decision support definition. The main decision criteria encompass economical effectiveness, dependability and security. More information can be found e.g. in [7, 49, 50].

The expert system is prepared as a computer program which enables easier and faster conclusion acquirement. The solution is based on EXSYS Professional system implementation. The general decision support program's structure is given e.g. in [7]. Moreover, the example of decision rules edition process is given in [48] and the introduction to the presented problem is given in e.g. in [50].

The purpose of the DSS performance is connected with possible maintenance strategy for technical object definition based on chosen maintenance and dependability indicators' values.

The main *assumptions* taken during the DSS development encompass [7]:

- performance of a multi-component (or complex), repairable transportation system investigation,
- investigation of maintenance strategies for systems with and without components dependence,
- corrective maintenance strategy omission,
- condition-based maintenance models omission – because of the different approach to maintenance performance than PM models,
- maintenance information management models omission – because of focusing on proper organization of maintenance information management processes necessary to effective performance of a system,

- cannibalization maintenance models omission – because of focusing on such issues as inventory planning problem, spares allocation problem, or supply cannibalization issues.

Following these considerations, in the DSS development process we examine various types of maintenance policies for multiunit or complex systems, which are the most commonly used (for review see e.g. [51]).

One step further, the main *input data* which are necessary to be used in a DSS performance can be classified into three groups [7]:

- general data, which describe transportation system performance,
- data which describe the actual state of transportation system,
- data which describe the maintenance costs of transportation system performance.

More information can be found in [7].

Based on the gathered information in the system, the main *conclusions* in a DSS may be defined [Bojd'12]. The exemplary ones are given below:

- MAINTENANCE ACCORDING TO SERVICE MANUAL ( $t_0$ ) – indicate, that mean of transport maintenance should be made according to the given service directions included in object's documentation. Such a conclusion is stated when there is no operational information available in a system,
- MAINTENANCE ACCORDING TO CHOSEN STRATEGY – indicate, that there should be implemented maintenance strategy in a system,
- MAINTENANCE ACCORDING TO DTA IMPLEMENTATION – suggests implementation of maintenance strategy based on Delay Time approach (DTA).

The final conclusions which end the chosen branch of a decision tree are indexed according to  $t_i$ , where  $i$  – defines  $i$ -th final conclusion in the DSS,  $i = 0, 1, 2, \dots$

Taking into account the analysed DDS, the decisions are made based on the information about the state of a system, maintenance costs and data accessibility. These input data being defined more precisely and quantified are used to develop *decision rules*, which are the simple logical sentences [34]. Moreover, the presented below decision rules can be used only in the situation when all the prerequisites connected with input data availability are defined. Decision rules are of both types, indirect and direct ones [7, 49].

The presented below decision rules can be used only in the situation when all the prerequisites connected with input data availability are defined. Decision rules are of both types, indirect and direct ones.

In the first step of decision making process, there is a necessity to define the type of maintenance performance in order to the level of maintenance costs and failure consequences:

If {CM small and R low} then CORRECTIVE MAINTENANCE  
else PLANNED MAINTENANCE

and

If { $c_{in}$  non-negligible and R high} then PREVENTIVE MAINTENANCE  
else C-B MAINTENANCE

The First decision tree for the initial verification of the type of maintenance strategy is shown in Figure 1.

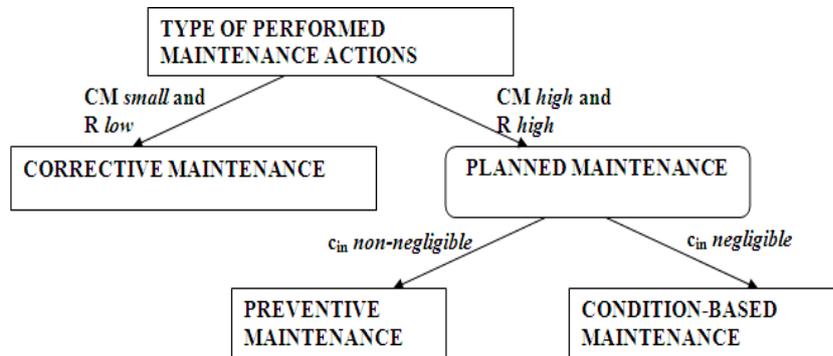


Fig. 1. Initial decision tree of the analysed DSS

The rest of the DSS can only apply in the selection of preventive maintenance strategy for means of transportation performance.

First decision rule defines if there is a possibility to use one of the maintenance strategies. The condition regards to data accessibility (I):

If {I - inaccessible} then MAINTENANCE ACCORDING TO SERVICE MANUAL  
 else MAINTENANCE ACCORDING TO CHOSEN STRATEGY

When data are available, second problem is connected with the system components which are to be maintained. The first condition regards to components' dependency (L):

If {L - independent} then MAINTENANCE STRATEGY FOR INDEPENDENT SYSTEM COMPONENTS  
 else MAINTENANCE STRATEGY FOR DEPENDENT SYSTEM COMPONENTS

When there is known expected delay time  $E[h]$ , and its relation to the length of time between maintenance actions performance is greater than a specified value  $x$  (subjectively estimated by experts), then we can choose one of the inspection strategies based on Delay Time approach (DTA) implementation:

If { $E[h]$  known and  $E[h]/T_{cw} \geq x$ } then MAINTENANCE ACCORDING TO DTA IMPLEMENTATION  
 else MAINTENANCE ACCORDING TO PM STRATEGY

Another decision problem concerns the number of system elements:

If { $N_p$  - complex system} then MAINTENANCE ACCORDING TO PM STRATEGY FOR COMPLEX SYSTEMS  
 else MAINTENANCE ACCORDING TO PM STRATEGY FOR MULTI-UNIT SYSTEMS

There is also a possibility, that there is known maximal level of cost of corrective action performance  $C_{mn}^{max}$  in a system. When the decision which maintenance strategy is effective for a system depends on this costs level we should choose one of the known Repair Limit Policies:

If  $\{ C_{mn}^{max} \text{ known and } c_{nm} \leq C_{mn}^{max} \}$  then MAINTENANCE ACCORDING TO REPAIR LIMIT POLICY  
 else MAINTENANCE ACCORDING TO TIME-BASED MAINTENANCE POLICY

The examples of decision tree part, which illustrates the presented decision rules, is given in Fig. 2. Table 1 shows a list of basic maintenance strategies included in the DSS. The described DSS was implemented into Exsys Corvid „Shell” computer system – for more information we recommend reading e.g. [49, 50]. The main information, which are necessary to be gathered to implement the DSS are investigated e.g. in [7, 8]. In the next Sections, there is investigated the uncertainty problem in DSS development and performance.

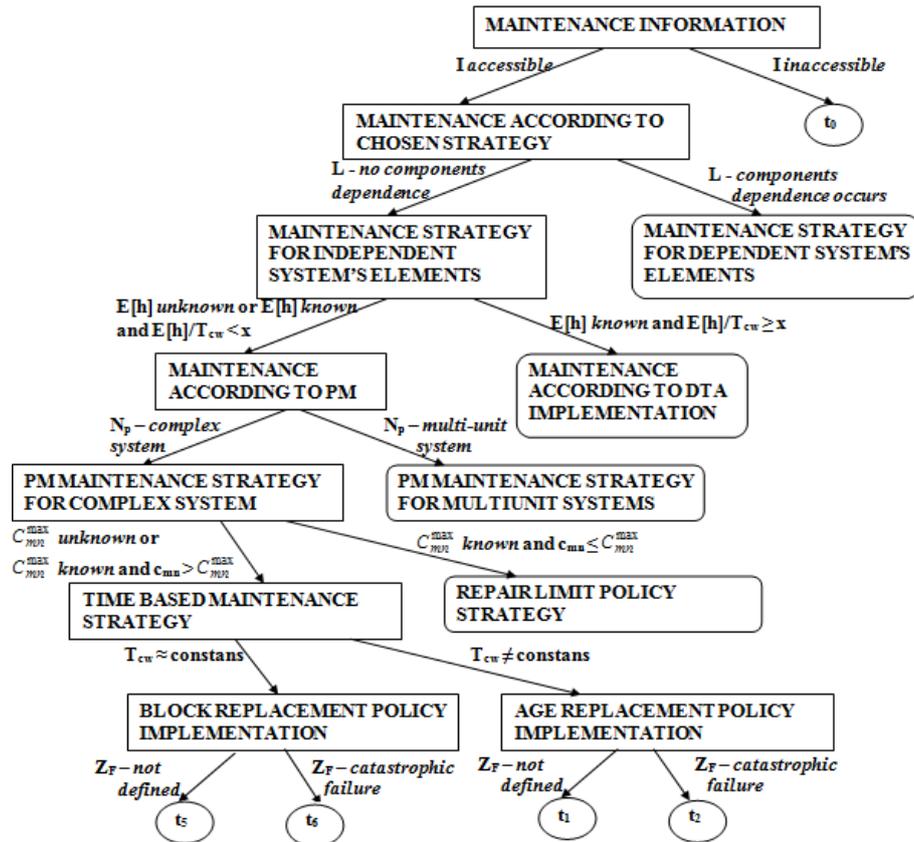


Fig. 2. The exemplary part of a DSS decision tree

*Table 1. List of maintenance strategies included in the DSS (with index) [7]*

PM strategy index	PM strategy definition
t <sub>1</sub>	Age Replacement Policy (ARP) with minimal repair
t <sub>2</sub>	Age Replacement Policy with CF
t <sub>3</sub>	Age Replacement Policy for multi-unit system with cost constrains
t <sub>4</sub>	Age Replacement Policy for multi-unit system with availability constrains
t <sub>5</sub>	Block Replacement Policy (BRP) with minimal repair
t <sub>6</sub>	Block Replacement Policy with CF
t <sub>7</sub>	Block Replacement Policy for multi-unit system with availability constrains
t <sub>8</sub>	Block Replacement Policy for multi-unit system with 3 types of maintenance
t <sub>9</sub>	Block Replacement Policy for multi-unit system with common cause shock failure
t <sub>10</sub>	Repair Limit Policy (RLP) with imperfect repair
t <sub>11</sub>	Repair Limit Policy with minimal repair
t <sub>12</sub>	Repair Limit Policy with CF
t <sub>13</sub>	(L-u,L) policy
t <sub>14</sub>	Opportunistic maintenance policy (OMP) with CF
t <sub>15</sub>	(τ,T) policy with costs
t <sub>16</sub>	(τ,T) policy with availability
t <sub>17</sub>	Simple group maintenance policy (GMP)
t <sub>18</sub>	Simple group maintenance policy (GMP) with minimal repair
t <sub>19</sub>	Simple T-policy
T <sub>20</sub>	Simple T-policy with minimal repair
t <sub>21</sub>	m – failure policy
t <sub>22</sub>	(m,T) policy
t <sub>23</sub>	Delay Time Model (DTM) for multi-unit systems
t <sub>24</sub>	Delay Time Model for multi-unit systems with imperfect inspections
t <sub>25</sub>	Delay Time Model for complex systems and non-negligible RT
t <sub>26</sub>	Delay Time Model for complex systems
t <sub>27</sub>	Delay Time Model for complex systems with imperfect inspections
t <sub>f</sub> – time moments of failure occurrence t <sub>RT</sub> – time moments of repair action finishing	

#### 4. The uncertainty problem in decision support systems development

Uncertainty may be defined as “...any departure of the unachievable ideal of complete determinism and perceived to be of either an epistemic or a stochastic nature, i.e. either due to a lack of knowledge or due to natural variability in the system” [66].

In typical expert systems the uncertainties may be connected e.g. with inputs and outputs. Inputs are knowledge (e.g. rules) and information (facts, observations etc.). Both can be available in numerical, quantitative, qualitative, or linguistic form [75]. Thus, this types of information may be connected with various kinds of uncertainty (probability, truth, possibility, etc.) which can be expressed either numerically or linguistically [75].

In the area of maintenance, typical uncertainties connected with the maintenance performance and not included in the models are associated with the cost of inspection, repair and failure [58]. Moreover, the uncertainties may be connected with parameters of distributions involved, such as mean repair time, mean time of planned maintenance, or system failure rate [58].

In [46], authors define the four main sources of uncertainty: unreliable information, imprecise descriptive languages, inference with incomplete information, and poor combination of knowledge from different experts.

Moreover, the uncertainty issue can be addressed from fuzzy set theoretic backgrounds [26]. From this perspective, uncertainty is the result of some information deficiency. Information may be incomplete, imprecise, contradictory, not fully reliable or vague. In [47] uncertainty is understood as:

- the degree of conformity with the reality,
- the absence of relevant information for undertaking the considered decision.

Moreover, in [66] three dimensions of uncertainty are investigated:

- nature (‘epistemic’),
- level (‘statistical’),
- location (‘output’).

In [26], authors define the following uncertainties:

- context uncertainty – which results from the step of natural system to conceptual model,
- model structure uncertainty – “...arising from a lack of sufficient understanding of the system that is the subject of the policy analysis, including the behaviour of the system and the interrelationships among its elements”
- model technical uncertainty – which concerns aspects related to the computer implementation of the model,
- input uncertainty – of stochastic nature, connected with external forces that produce changes in the system, and uncertainty of system data,
- parameter uncertainty – related to the a priori chosen parameters, that may be difficult to identify by calibration,
- aggregated uncertainty – results from all uncertainties above.

Thus, for a decision maker it is important to know how uncertain the results are and how uncertainty is propagated in the decision model [58]. The commonly used DSS tools in this area are Analytic Hierarchy Process (AHP) (e.g. [5, 10, 12, 68, 70]), neural networks (e.g. [28, 59, 69]), fuzzy logic, fuzzy networks (e.g. [4, 13, 43, 62]), Bayesian theory (e.g. [14]), and Petri nets (e.g. [27]). The review of most commonly used tools to model uncertainty may be found e.g. in [41, 47, 75].

### **Measures of uncertainty**

To measure uncertainty or information, there is necessity to strictly define what we are trying to measure [25]. The problem of uncertainty measures in expert system is investigated e.g. in [21, 25, 67].

In [67], author compares four measures that have been advocated as models for uncertainty in expert systems. He is focused on mathematical measures of uncertainty, which include Bayesian probabilities, coherent lower previsions, belief functions and possibility measures. The measures of uncertainty are compared according to the six criteria, like interpretation, imprecision, calculus, consistency, assessment, and computation.

Later, in [25], author provide an overview of the approaches, results and history of attempts at measuring uncertainty and information in the various theories of imprecise probabilities. He is focused on two approaches the theory of belief functions and the possibility theory.

In [21], authors define an imprecision importance measure to evaluate the effect of removing imprecision to the extent that a probabilistic representation of uncertainty remains, as well as to the extent that no epistemic uncertainty remains.

### **Uncertainty analysis of developed expert system – case study**

Uncertainty in expert system is expressed by confidence variables. Confidence variables are a special type of Corvid variable [19] that has a value which, indicates how likely it is that the variable applies in a particular situation. A Confidence variable can be assigned multiple values during a session and Corvid will automatically combine the various values into a single overall confidence value. Corvid provides various ways to mathematically combine the values, ranging from simple to complex. The overall value of the variable can be used in sorting (displaying the ones with the highest confidence) or used in any mathematical expressions allowing the confidence of one part to propagate through to other parts of the system.

The calculation parameters control how the values assigned to the variable will be combined to a single overall confidence value. There are 8 options for how to combine values [19]:

- Sum - The values are added together. Positive values increase the confidence, negative values decrease the confidence. This is a simple system, but works very well for many systems. Unless there is valid statistical data on a process, this may be a good way to combine competing factors in a decision.

$$[CONF\_SUM] = \sum_{I=1}^{I=N} [CONF\_I]$$

for

$$[CONF\_I] \in [-\infty, +\infty]$$

- Average - The values are added together as with “Sum”, and then divided by the number of values. This provides another simple way to combine competing factors, with individual factors having less influence when there are many values added.

$$[CONF\_AVERAGE] = \frac{1}{N} \sum_{I=1}^{I=N} [CONF\_I]$$

for

$$[CONF\_I] \in [-\infty, +\infty]$$

- Independent probability - The values are combined as if they were independent probabilities. This is a statistically more rigorous approach, but requires that there be valid statistical data that can be applied.

$$[CONF\_INDEP\_PROB] = 1 - ((1 - [CONF\_X])(1 - [CONF\_Y]))$$

for

$$[CONF\_X] \in [0,1], [CONF\_Y] \in [0,1]$$

- Dependent probability - The values are combined as if they were dependent probabilities. As with the Independent mode it requires valid statistical data.

$$[CONF\_DEP\_PROB] = [CONF\_X] \cdot [CONF\_Y]$$

for

$$[CONF\_X] \in [0,1], [CONF\_Y] \in [0,1]$$

- Multiply - The values are multiplied. This is basically the same as the dependent probability mode, but here there is no assumption that the values actually represent probabilities, and the values can be any positive value in any range.

$$[CONF\_MULT] = \prod_{I=1}^N [CONF\_I]$$

for

$$[CONF\_I] \in [0, +\infty]$$

- MAX - returns the largest value assigned. This is useful for cases where individual rules can indicate a variable is “good”, regardless of lower values from other rules.

$$[CONF\_MAX] = \max\{[CONF\_I]\}$$

for

$$[CONF\_I] \in [-\infty, +\infty]$$

- MIN - returns the smallest value assigned. This is the opposite of MAX. It is good when a rule can eliminate a variable by giving it a low value, regardless of high values given by other rules.

$$[CONF\_MIN] = \min\{[CONF\_I]\}$$

for

$$[CONF\_I] \in [-\infty, +\infty]$$

- Mycin - This is one of the traditional approaches for combining confidence, often called the Mycin method. This confidence mode has a long history and it allows combination of factors that indicate a goal is valid along with factors that indicate that the goal is not valid.

$$[CONF\_MYCIN] = \begin{cases} 0, & \text{for } [CONF\_OLD] = 1 \text{ and } [CONF\_NEW] = -1 \\ [CONF\_NEW] + ([CONF\_OLD] \cdot (1 - [CONF\_NEW])), & \\ & \text{for } [CONF\_OLD] \geq 0 \text{ and } [CONF\_NEW] \geq 0 \\ [CONF\_NEW] + ([CONF\_OLD] \cdot (1 + [CONF\_NEW])), & \\ & \text{for } [CONF\_OLD] < 0 \text{ and } [CONF\_NEW] < 0 \\ \frac{[CONF\_OLD] + [CONF\_NEW]}{1 - \min\{|[CONF\_OLD]|, |[CONF\_NEW]|\}}, & \text{otherwise} \end{cases}$$

for

$$[CONF\_OLD / NEW] \in [-1, +1]$$

Thus, the numeric value assigned (confidence values) indicates if the choice is "good" or "bad" based on the logic of the rule and the end user's input. A specific variable may be assigned values by many rules. These values are combined from all the rules to determine the overall confidence value for the variable - which determines if that variable is the best recommendation.

Following the first step of decision making process (a necessity to define the type of maintenance performance in order to the level of maintenance costs and failure consequences) with confidence variable we've obtained:

If {CM small and R low} then CORRECTIVE MAINTENANCE = [CONF\_CM]  
 and PLANNED MAINTENANCE = [CONF\_PM]

Depending on the chosen confidence combining system and [CONF\_CM] and [CONF\_PM] values we can, for example:

- close the decision process by assigning in the independent probability system [CONF\_PM] = 0 and [CONF\_CM] = 1; it means: "only corrective maintenance, not the preventive one",
- leave the decision process open by assigning [CONF\_PM] = 0,1 and [CONF\_CM] = 0,9; it means: "rather corrective than preventive maintenance".

If there were other rules that fired, which assigned a value to [CONF\_CM] and [CONF\_PM], their values would be combined according to the chosen confidence system.

## **5. Conclusions**

The presented issue is a continuation of research work connected with developing a decision support system for transportation means' maintenance processes performance. The system gives decision makers a hint which one from the defined maintenance strategies is the most advisable to implement in a defined circumstances. Thus, the main decision support process' backgrounds include present technical state of an object, maintenance standards, and input data availability. Another problem regards to maintenance data and decision uncertainty.

The confidence variables approach allows the decision support system to give an overall best recommendation, even when a particular variable may not be perfect in all respects. But it still requires selection of mathematical approaches to combining the individual values assigned to confidence variables and assumptions on confidence variables values estimation.

As a result, the main problems which are necessary to be solved regard to decision support system implementation.

## **6. References**

- [1] Ariav G., Ginzberg M. J.: DS design: a systemic view of decision support. *Communications of the ACM*, Vol. 28, No. 10, pp. 1045-1052, 1985.
- [2] Arnott D., Pervan G.: Eight key issues for the decision support systems discipline. *Decision Support Systems*, 44, pp. 657-672, 2008.
- [3] Asemi A., Safari A., Asemi Zavareh A.: The Role of Management Information System (MIS) and Decision Support System (DSS) for Manager's Decision Making Process. *International Journal of Business and Management*, Vol. 6, No. 7, pp. 164-173, 2011.
- [4] Baraldi P., Librizzi M., Zio E., Podolfini L., Dang V. N.: Two techniques of sensitivity and uncertainty analysis of fuzzy expert systems, *Expert Systems with Applications*, 36, pp. 12461-12471, 2009.
- [5] Bevilacqua M., Braglia M.: The analytic hierarchy process applied to maintenance strategy selection, *Reliability Engineering and System Safety*, 70, pp. 71-83, 2000.
- [6] Bojda K., Młyńczak M., Restel F. J.: The concept of software support system for the management of railcar operation (in Polish), *Proceedings of TRANSCOMP – XIV International Conference Computer Systems Aided Science, Industry and Transport*, Zakopane, Poland, 2010.
- [7] Bojda K., Werbińska-Wojciechowska S.: Data accessibility problem in transportation means' maintenance performance, [in]: *Transport - strategical and operational issues : monograph*, Agnieszka Stachowiak (ed.). Poznań: Publishing House of Poznan University of Technology, pp. 69-87, (Logistics & Production), 2012.
- [8] Bojda K., Werbińska-Wojciechowska S.: Bojda Krzysztof, Werbińska-Wojciechowska Sylwia: Wspomaganie decyzji w procesach utrzymania środków transportu a dostępność danych, *Gospodarka Materialowa a Logistyka*, nr. 12, pp. 34-38, 2012.
- [9] Borne P., Fayeche B., Hammadi S., Maouche S.: Decision Support System for Urban Transportation Networks. *IEEE Transactions on Systems, Man, and Cybernetics – Part C: Applications and Reviews*, Vol. 33, No. 1, pp. 67-77, 2003.

- [10] Burhanuddin M. A., Halawani S. M., Ahmad A. R., Tahir Z.: Failure-based Maintenance Decision Support System using Analytical Hierarchical Process, *International Journal of Advanced Computer Science*, Vol. 1, No. 1, pp. 1-9, 2011.
- [11] Burla M., Laniado E., Romani F., Tagliavini P.: The Role of Decision Support systems (DSS) in Transportation Planning: the Experience of the Lombardy Region. *Proceedings of Seventh International Conference on Competition and Ownership in Land Passenger Transport*, Molde, Norway, 25-28 June 2001.
- [12] Carnero M. C.: Selection of diagnostic techniques and instrumentation in a predictive maintenance program. A case study, *Decision Support Systems*, 38, pp. 539-555, 2006.
- [13] Chang Y-H., Yeh C-H., Cheng J-H.: Decision support for bus operations under uncertainty: a fuzzy expert system approach, *Omega*, vol. 26, no. 3, pp. 367-380, 1998.
- [14] Charniak E.: Bayesian Networks without Tears, *AI Magazine*, 12 (4), pp. 50-64, 1991.
- [15] Decision Support Systems, www: <http://diuf.unifr.ch/ds/courses/dss2002/pdf/DSS.pdf> (22.03.2012).
- [16] Despres S., Rosenthal-Sabroux C.: Designing Decision Support Systems and Expert Systems with a better end-use involvement: A promising approach. *European Journal of Operational Research*, 61, pp. 145-153, 1992.
- [17] Eom S. B.: Decision Support Systems. [in]: *International Encyclopedia of Business and Management*, 2<sup>nd</sup> Edition, Warner M. (ed.), International Thomson Business Publishing Co., London, 2001.
- [18] Er M. C.: Decision Support Systems: A Summary, Problems, and Future Trends, *Decision Support Systems*, 4, pp. 355-363, 1988.
- [19] Exsys Corvid Knowledge Automation Expert System Development Manual. Exsys Inc. 6301 Indian School Rd. NE, Suite 700, Albuquerque, NM 87110, U.S.A.
- [20] Fernandez O., Labib A. W., Walmsley R., Petty D. J.: A decision support maintenance management system: development and implementation, *International Journal of Quality and Reliability Management*, Vo. 20, Issue 8, pp. 965-979, 2003.
- [21] Flage R., Aven T., Baraldi P, Zio E.: An imprecision importance measure for uncertainty representations interpreted as lower and upper probabilities, with special emphasis on possibility theory, *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, vol. 226, no. 6, pp. 656-665, 2012.
- [22] Fricker J D. & Whitford R K.: *Fundamentals of Transportation Engineering. A Multimodal Systems Approach*, Pearson Education, Inc. Upper Saddle River, New Jersey, USA, 2004.
- [23] Grobarek I., Grzywański Ł., Mączka I., Tomalik D., Twórz K.: *Niezawodność Systemów Wspomagania Decyzji*. Wrocław 2007, -opracowanie.pdf (22.03.2012). <http://www.ioz.pwr.wroc.pl/Pracownicy/mercik/zbiory/Prezentacje%202007/z3>
- [24] Han K.: Developing a GIS-based Decision Support System for Transportation System Planning, AASHTO GIS-T 2006, www: <http://www.gis-t.org/files/gnYKJ.pdf> (23.03.2012).
- [25] Harmanec D.: Measures of uncertainty and information, *Imprecise Probabilities Project*, %3c<http://ensmain.rug.ac.be/ipp%3e>, 1999.
- [26] Janssen J. A. E. B., Krol M. S., Schielen R. M. J., Hoekstra A. Y., de Kok J-L.: Assessment of uncertainties in expert knowledge, illustrated in fuzzy rule-based models, *Ecological Modelling*, 221, pp. 1245-1251, 2010.

- [27] Jeng M. D.: Petri Nets for Modeling Automated Manufacturing Systems with Error Recovery, *IEEE Transactions on Robotics and Automation*, vol. 13, No. 5, pp. 752-760, 1997.
- [28] Jin B., Hurson A. R., Miller L. L.: Neural network-based decision support for incomplete database systems: knowledge acquisition and performance analysis, *Proceedings of the conference on Analysis of neural network applications ANNA'1991*, ACM, New York, pp. 62-75, 1991.
- [29] Kacprzak M., Kulinowski P., Wędrychowicz D.: Informatyczny system zarządzania procesem eksploatacji górniczych przenośników taśmowych. *Eksploatacja i Niezawodność – Maintenance and Reliability*, nr 2, pp. 81-93, 2011.
- [30] Kamath M., Srivathsan S., Ingalls R. G., Shen G., Pulat P. S.: TISCSOft: A Decision Support System for Transportation Infrastructure and Supply Chain System Planning. *Proceedings of the 44<sup>th</sup> Hawaii International Conference on System Sciences*, 2011.
- [31] Kamiński P., Tarełko W.: Prototyp komputerowo wspomaganego systemu przydziału zadań eksploatacyjnych realizowanych w siłowni okrętowej. *Przegląd Mechaniczny*, R 67, nr 3, pp. 30-34, 2008.
- [32] Kantor J.: Komputerowy system wspomaganie decyzji w planowaniu przeglądów i remontów w przedsiębiorstwie produkcyjnym. *Rozprawa doktorska PWr.*, Wrocław 2009.
- [33] Ko H. J.: A DSS approach with Fuzzy AHP to facilitate international multimodal transportation Network. *KMI International Journal of Maritime Affairs and Fisheries*, vol.1 issue 1, pp. 51-70, 2009.
- [34] Kosman G., Rusin A.: Conception of the system for supporting operating and repair decisions for the turbine durability (in Polish), *Zeszyty Naukowe Politechniki Śląskiej, Seria: Energetyka*, Z.131, nr kol. 1427, 1999. Kosman G., Rusin A., *Zeszyty Naukowe Politechniki Śląskiej, Seria: Energetyka*, 1999, Z.131, nr kol. 1427, pp. 87-105.
- [35] Kutz M. (ed.): *Handbook of transportation engineering*, M. McGraw-Hill Companies, Inc. 2004.
- [36] Lamy J-B., Ellini A., Nobecourt J., Venot A., Zucker J-D.: *Testing Methods for Decision Support Systems*. [in]: *Decision Support Systems*, Jao Ch. S. (ed.), InTech, 2010.
- [37] Liao S-H.: Expert system methodologies and applications – a decade review from 1995 to 2004, *Expert Systems with Applications*, 28, pp. 93-103, 2005.
- [38] Lihovd E., Steinebach Ch., Rassmussen M.: A Decision Support System Prototype for Maintenance Management, *The 13<sup>th</sup> European Maintenance Conference*, Copenhagen, Denmark, 1996.
- [39] Lin L., Ambani S., Ni J.: Plant-level maintenance decision support system for throughput improvement, *International Journal of Production Research*, vol. 47, no. 24, pp. 7047-7061, 2009.
- [40] Liyanage J. P., Lee J., Emmanouilidis Ch., Ni J.: Integrated E-maintenance and Intelligent Maintenance Systems, [in] Ben-Daya M., Duffuaa S. O., Raouf A., Knezevic J., Ait-Kadi D.: *Handbook of Maintenance Management and Engineering*, Springer-Verlag, London, 2009.

- [41] Lopez I., Sarigul-Klijn N.: A review of uncertainty in flight vehicle structural damage monitoring, diagnosis and control: challenges and opportunities, *Progress in Aerospace Sciences*, 46, pp. 247-273, 2010.
- [42] Martland C. D., McNeil S., Acharya D, Mishalani R.: Applications of expert systems in railroad maintenance: scheduling rail relays. *Transportation Research Part A: Policy and Practice*, vol. 24A, No. 1, pp. 39-52, 1990.
- [43] Mechefske C. K., Wang Z.: Using fuzzy linguistics to select optimum maintenance and condition monitoring strategies, *Mechanical Systems and Signal Processing*, 15 (6), pp. 1129-1140, 2003.
- [44] Mendes-Moreira J., Duarte E., Belo O.: A decision support system for timetable adjustments. *Proceedings of the XIII Euro Working Group on Transportation Meeting (EWGT 2009) - September 2009*.
- [45] Moore J., H., Chang M. G.: *Design of Decision Support Systems*. ACM SIGMIS Database - Selected papers on decision support systems from the 13th Hawaii International Conference on System Sciences, Vol. 12, Issue 1-2, ACM New York, NY, USA Fall 1980.
- [46] Ng K-Ch., Abramson B.: *Uncertainty Management in Expert Systems*, *IEEE Expert: Intelligent Systems and Their Applications*, vol. 5, issue 2, pp. 29-48, 1990.
- [47] Nowakowski T.: Problems with analyzing operational data uncertainty, *Archives of Civil and Mechanical Engineering*, vol. X, no. 3, pp. 95-109, 2010.
- [48] Nowakowski T.: *Metodyka prognozowania niezawodności obiektów mechanicznych*. Praca naukowa Instytutu Konstrukcji i Eksploatacji Maszyn Politechniki Wrocławskiej, Wrocław 1999.
- [49] Nowakowski T., Werbińska-Wojciechowska S.: *System komputerowego wspomaganie decyzji w procesach utrzymania środków transportu*, W: *Niezawodność infrastruktury krytycznych: materiały XLI Jubileuszowej Zimowej Szkoły Niezawodności*, Szczyrk, [6-12 stycznia] 2013. Radom: Wydawnictwo Naukowe Instytutu Technologii Eksploatacji, 2013.
- [50] Nowakowski T., Werbińska-Wojciechowska S.: Means of transport maintenance processes performance. *Decision support system, Carpathian Logistics Congress, CLC' 2012: congress proceedings*, Jeseník, Czech Republic, November 7th-9th 2012. Ostrava: Tanger, 2012.
- [51] Nowakowski T., Werbińska S.: On problems of multicomponent system maintenance modeling, *International Journal of Automation and Computing*, vol. 6, no. 4, pp. 364-378, 2009.
- [52] Ossowski S., Fernandez A., Serrano J. M., Perez-de-la-Cruz J. L., Belmonte M. V., Hernandez J. Z., Garcia-Serrano A. M., Maseda J. M.: *Designing Multiagent Decision Support System The Case of Transportation Management*. *Proceedings of AAMAS'04*, July 19-23 2004, New York, USA.
- [53] Ossowski S., Hernandez J. Z., Belmonte M-V., Fernandez A. Garcia-Serrano A., Perez-de-la-Cruz J-L., Serrano J-M., Triguero F.: *Decision support for traffic management based on organisational and communicative multiagent abstractions*. *Transportation Research Part C*, vol. 13, pp. 272-298, 2005.
- [54] Ozceylan E.: *A Decision Support System to Compare the Transportation Modes in Logistics*. *International Journal of Lean Thinking*, Vol. 1, Issue 1, pp. 58-83, (June) 2010.

- [55] Power D. J.: Understanding Data-Driven Decision Support Systems. *Information Systems Management*, Vol. 25, Issue 2, pp. 149-154, 2008.
- [56] Power, D. J.: A Brief History of Decision Support Systems. *DSSResources.COM*, [www: http://DSSResources.COM/history/dsshistory.html](http://DSSResources.COM/history/dsshistory.html), version 4.0, March 10, 2007.
- [57] Rao M., Theisen Ch., Luxhoj J. T.: Intelligent system for air-traffic control, *Proceedings of the 5<sup>th</sup> IEEE international symposium on intelligent control*, vol. 2, Philadelphia, PA, pp. 859-863, 1990.
- [58] Rocco C. M., Miller A. J., Moreno J. A., Carrasquero N., Medina M.: Sensitivity and uncertainty analysis in optimization programs using an evolutionary approach: a maintenance application, *Reliability Engineering and System Safety*, 67, pp. 249-256, 2000.
- [59] Samhoury M., Al-Ghandoor A., Alhaj Ali S., Hinti I., Massad W.: An Intelligent Machine Condition Monitoring System Using Time-Based Analysis: Neuro-Fuzzy versus Neural Network, *Jordan Journal of Mechanical and Industrial Engineering*, Vol. 3, No. 4, pp. 294-305, 2009.
- [60] Santana M.: Managerial Learning: A Neglected Dimension in Decision Support Systems, *Proceedings of the 28<sup>th</sup> annual Hawaii international conference on system sciences*, vol. 4, Kihei, Maui, Hawaii, pp. 82-91, 1995.
- [61] Sharda R., Barr S. H., McDonnell J. C.: Decision support system effectiveness: a review and an empirical test. *Management Science*, Vol. 34, No. 2, pp. 139-159, 1988.
- [62] Simoes-Marques M., Ribeiro R. A., Gameiro-Marques A.: A fuzzy decision support system for equipment repair under battle conditions, *Fuzzy sets and Systems*, vol. 115, no. 1, pp. 141-157, 2000.
- [63] Tavasszy L.A., Van Der Rest H.: Scenario-Wise Analysis of Transport and Logistics Systems with a SMILE. *Selected Proceedings of the 8th World Conference on Transportation Research*, 1999.
- [64] Tu Y., Yeung E. H. H.: Integrated maintenance management system in a textile company, *International Journal of Advanced Manufacturing Technology*, 13 (6), pp. 453-462, 1997.
- [65] Ulengin F., Onsel S., Topcu Y. I., Aktas E., Kabak O.: An integrated transportation decision support system for transportation policy decisions: The case of Turkey. *Transportation Research Part A*, vol. 41, pp. 80-97, 2007.
- [66] Walker W. E., Herremoes P., Rotmans P., Van der Sluis J. P., Van Asselt M. B. A., Janssen P., Krayner von Krauss M. P.: Defining uncertainty – a conceptual basis for uncertainty management in model-based decision support, *Integrated Assessment*, Vol. 4, No. 1., pp. 5-17, 2003.
- [67] Walley P.: Measures of uncertainty in expert systems, *Artificial Intelligence*, 83, pp. 1-58, 1996.
- [68] Wang L., Chu J., Wu J.: Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process, *International Journal of Production Economics*, 107 (1), pp. 151-163, 2007.
- [69] Yam R. C. M., Tse P. W., Li L., Tu P.: Intelligent predictive decision support system for condition-based maintenance, *International Journal of Advanced Manufacturing Technology*, 17 (5), pp. 383-391, 2001.
- [70] Yang W. Z., Ge Y. H., He J. J., Liu B.: Designing a group decision support system under uncertainty using group Fuzzy analytic network process (ANP), *African Journal of Business Management*, 4(12), pp. 2571-2585, 2010.

- [71] Yoon S. W., Velasquez J. D., Partridge B. K., Nof S. Y.: Transportation security decision support system for emergency response: A training prototype. *Decision Support Systems*, 46, pp. 139-148, 2008.
- [72] Zhang P., Zhao S-W., Tan B., Yu L-M., Hua K-Q.: Applications of Decision Support System in Aviation Maintenance, *Efficient Decision Support Systems - Practice and Challenges in Multidisciplinary Domains*. Prof. Chiang Jao (Ed.), InTech, 2011, www: <http://www.intechopen.com/books/efficient-decision-support-systems-practice-and-challenges-in-multidisciplinary-domains/applications-of-decision-support-system-in-aviation-maintenance>.
- [73] Zhengmeng Ch., Haoxiang J.: A Brief Review on Decision Support Systems and It's Applications. *Proceedings of International Symposium on IT in Medicine and Education (ITME) 2011*, 9-11. December 2011, vol. 2, pp. 401-405.
- [74] Zhu K. X.: Sensor-based condition monitoring and predictive maintenance – an integrated intelligent management support system, *Intelligent Systems in Accounting, Finance and Management*, 5 (4), pp. 241-258, 1996.
- [75] Zimmermann H. J.: Problems and tools to model uncertainty in expert and decision support systems, *An International Journal of Mathematical and Computer Modelling*, Vol. 14, pp. 8-12, 1990.



*Professor **Tomasz Nowakowski**, Wrocław University of Technology, Division of Logistics and Transportation Systems, director of Institute of Machines Design and Operation at WUT. President of Polish Logistic Association, member of Transport Committee of Polish Academy of Science, vice-president of Polish Maintenance Society, chief editor of scientific journal "Logistics and Transport" and editor of Terotechnology section of quarterly "Scientific Problems of Machines Operation and Maintenance". Major fields of interest concern: reliability, maintainability, safety of technical (generally transportation and logistic) systems, computer aided operation, knowledge based (expert) systems, uncertainty of operation & maintenance data.*



*PhD. **Sylwia Werbińska-Wojciechowska**, Wrocław University of Technology, Division of Logistics and Transportation Systems; PhD. work concerns the problems of logistic support systems for technical objects exploitation process performance modelling; now she is interested in delay-time modelling, especially concerned with application issues for transportation systems maintenance performance.*