Quality of Service Evaluation for Bucket Wheel Excavator

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Bucket wheel excavator can be considered as one of the most complex technical systems. Life-cycle of bucket wheel excavators is analyzed in this paper. Special attention is devoted to their quality of service characteristics and a model for quality of service evaluation based on fuzzy sets theory and evidential reasoning is developed. Dependability performance is used as a measure for quality of service. Dependability evaluation is done on the basis of information like expertise opinions and judgments. Finally, mechanical parts of the bucket wheel excavators are analyzed in detail and their dependability is determined.

Keywords: *Quality of service, Life-cycle, Dependability, Fuzzy sets, Evidential reasoning, Bucket wheel excavator*

1. INTRODUCTION

Rapid expansion of global demands for electricity power in the second half of the last century has caused much greater exploitations of lignite in the open step mines. At the same time, there has been a necessity for development of complex machinery, primary bucket wheel excavators (BWE). The first excavators in Serbia started their operation in the fifties of the 20-th century, and the wider usage of these machines started at the end of the sixties. Today, almost thirty bucket wheel excavators are in operation in the open step mines Kolubara and Kostolac. They are of German production, and they were purchased from the producers, such as TAKRAF, O&K, KRUPP, during the past several decades. This caused an unnecessary great variety of machine designs, and made their maintenance especially complicated. In this sense, on the basis of information from the position of maintenance in open step mine, activity of the reconstruction of these machines was permanently practiced.

The high percent of the bucket wheel excavators in the open step mines of Electric power industry of Serbia is older than 25 years, which is the optimal economic life time of these machines according to the some earlier recommendations of the manufacturers. It is evident that it is necessary to execute some serious actions of revitalization, redesigning and modernization, with the aim to prolong the excavators' lifetime. Significant development in usage techniques (especially control and electro equipment), materials and the like [1] makes opportunities for considerable improvements of BWEs' performances.

Hence, the strategic directions of mining industry's managements would be the determination when and how to start with the activity of BWE revitalization, redesigning and modernization. In that sense, it is very important to define and to evaluate the BWE quality of service, i.e. to find proper indicators and their boundary measure for the beginning of stated activities.

With the beginning of systems' sciences development, a series of concepts have been defined in appropriate engineering and scientific literature. The idea was to describe essential characteristics of technical systems from the point of their quality of service. Dependability concept was introduced through ISO-IEC standards [2] for simultaneous survey of technical system behaviors in operation and in periods of failure. Dependability includes availability performance, as its measure, and its influencing factors: reliability performance, maintainability performance, and maintenance support performance. Implementation of dependability concept was developed in detail in IEC-300 standards where dependability objectives were defined and principles of dependability management systems were introduced. Special attention was devoted to the degree of customers' satisfaction with the given product and consideration of entire product life-cycle phases concerning planning, design, production, operation and maintenance, and finally disuse. Dependability was introduced to be the most complete concept that describes availability of considered technical system, i.e. presents the most complete quality of service measure. Implementation of dependability concept in essence includes information about system behaviors during up and down-time with regards to design and logistic indicators (concrete information related to reliability, maintainability and maintenance support) as it were defined in ISO–IEC 300.

In the analysis of reliability and maintainability based on probability theory, these characteristics are expressed quantitatively, i.e. as the probability function for failure likelihood in the case of reliability or as the probability function for duration of selected maintenance operation in the case of maintainability. In these analyses, especially for complex mechanical systems (as the example of such system, bucket-wheel excavator will be analyzed later), problems related to systems' structure definition in reliability sense, characterizations of incomplete failures and similar problems can arise as serious obstacles in definition of probability functions. Also, problems in collecting and

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quality of collected data in the sense of uncertainty and generalization can make difficulty, i.e. demands very sophisticated IT infrastructure for monitoring of system work. Such infrastructure usually doesn't exist in mechanical systems in lignite open step mines in Serbia. Therefore, experts' judgments and estimations can be very important in reliability and maintainability evaluation. On the other hand, analyses of maintenance support can only be based on experts' evaluations.

Therefore, the problem is to make synergetic approach to all dependability indicators and their synthesis at dependability itself. Fuzzy sets theory has arisen as appropriate tool that will work simultaneously with insufficiently accurate terms and expressions that can hardly be represented by models with numerical inputs, as well as with to some extent strongly determined facts. Considering dependability indicators, fuzzy sets theory property to calculate with linguistic variables is especially applicable in integration of maintenance support performance in dependability evaluation. In the analysis of logistic parameters as the maintenance support is, at the level of dependability determination, practically there is no other way for its estimation without utilization of experts' judgments given as linguistic descriptions. However, even reliability and maintainability performances very often can only be expressed at the level of experts' opinions. Therefore, fuzzy model for dependability evaluation should enable synthesis of differently defined dependability indicators, but it also should enable possibility for quality and systematical analysis of relations and connections between individual indicators, i.e. stated performances of technical systems' behaviors.

To overcome some of the mentioned problems, in this paper model for determination bucket wheel excavator quality of service, based on analysis of information given as the experts' judgments and estimations, was formed. As the measure and the most complete evaluation for quality of service, dependability was used. Dependability at the lowest constructive and functional level of bucket wheel excavator was obtained by integration of reliability, maintainability and maintenance support performances. Fuzzy sets theory was used for that integration.

In the next step of dependability evaluation it was necessary to make gradual synthesis of components' estimations to the level of whole technical system. For that purpose, i.e. for integration of partial dependability evaluation to the level of subsystems, systems and bucket wheel excavator itself, Evidential Reasoning theory was used.

2. MATHEMATICAL AND CONCEPTUAL MODEL OF BUCKET WHEEL EXCAVATOR DEPENDABILITY EVALUATION

Mathematical and conceptual model that properly includes experts' opinions and estimations, i.e. evaluates bucket wheel excavator quality of service by dependability performance, is given in the following text and includes three phases: definition of bucket wheel excavator hierarchical structure, dependability performance analysis at the excavator's lowest constructive and functional level, synthesis to the level of whole bucket wheel excavator.

2.1. Hierarchical structure

The first phase in evaluation model formation is definition of hierarchical structure for technical system, i.e. system decomposition. Bucket wheel excavator will be considered through 4 levels of hierarchical structure: component level, sub-system level, system level and whole technical system – bucket wheel excavator.

Based on different constructive and functional parts, decomposition is done. On the level of the systems there can be identified: system for excavation, system for materials' transport, system for excavator' transport, system for boom lifting, system for upper construction rotation, main structure and accessory structure [3]. Control and electro supply systems are also generally significant for excavator functionality but here they are, excluded from analysis because of limited space. Quality of technical system evaluation depends to a great extent of decomposition itself. Decomposition must be implemented to the as low constructive levels as it is possible, but part and elements at considered levels must have a clearly defined function.

2.2. Analysis of dependability performance based on fuzzy sets theory

The second phase of mathematical and conceptual model is practically summarized at two steps: fuzzy proposition of dependability performance and its indicators; and definition of fuzzy composition, i.e. structure of indicators' influences on the dependability performance.

Fuzzy proposition, i.e. procedure for representing the statement that includes linguistic variables based on available information about considered technical system, is the most sensitive step in creating the model for technical system evaluation. In the case of dependability indicators (reliability, maintainability and maintenance support) analysis it is necessary to define names for fuzzy sets i.e. linguistic variables and their structure as well as measuring units that will represent quality level for analyzed phenomena.

Reliability is usually expressed as interval 0…1 or 0…100%. The same situations are for maintainability. Maintenance support is inherently a linguistic variable, i.e. without any measuring units. Therefore, in the case of analysis based on experts' estimations, as the measuring unit can be introduced class, as usually used concept for representing performances' quality [4,5], for all three indicators.

Regarding of the number of linguistic variables, it can be found that seven is the maximal number of rationally recognizable expressions that human can simultaneously identify. However, for identification of considered characteristics even a lesser number of variables can be useful because flexibility of fuzzy sets to include transition phenomena as experts' judgments is common. According to the above, five linguistic variables for representing reliability performances are included: highly reliable, very reliable, averagely reliable, acceptably reliable and unreliable. Model of these linguistic variables is given as appropriate reliability fuzzy sets and they are presented in Table 1. Reliability is theoretically expressed as probability of operation without any failure during the period t. The seven classes adopted for measuring units in representation of reliability quality level could be easily split to cover time intervals between 0 and t. However, in that case it would be necessary to complete examination and to find reliability functions for considered technical system. This is a very difficult and often impossible task (Section 1). In reliability examinations a lot of significant information can be obtained from experts' estimations and judgments. In proposed model those experts' opinions can be used for determination of membership degrees (μ) to classes. For example, if opinion of selected authority is that reliability performance of some system can be estimated as "averagely reliable", it means that reliability fuzzy set for that system will be (according to Table 1):

$$R = \{1/0,\ 2/0,\ 3/0.5,\ 4/1.0,\ 5/0.5,\ 6/0,\ 7/0\}. \qquad (1)$$

Table 1: Reliability fuzzy sets defined by linguistic variable and membership function to the classes

	1.	2.	3.	4.	5.	6.	7.
Unreliable	0	0	0	0	0	0.25	1.0
Acceptable	0	0	0	0	0.5	1.0	0
Averagely	0	0	0.5	1.0	0.5	0	0
Very	0	1.0	0.5	0	0	0	0
Highly	1.0	0.25	0	0	0	0	0

Maintainability is primarily concerned with system design accommodation to maintenance actions. As in the reliability case, maintainability performance evaluation can be performed as probability function of maintenance operation with duration t_0 or according to experts' judgments. Again, both approaches lead to membership degrees determination.

As linguistic variables in maintainability performance fuzzy sets the following five expressions can be defined (Table 2):

- Optimal for maintenance; this linguistic variable is concerned with practically automated maintenance systems, without any additional tools utilization and accessibility of locations are without influence on maintenance operation.

- Easy maintenance; this linguistic variable includes practically the most favorable cases for the complex mechanical systems, because previous linguistic variable can mostly be applicable for electrical systems.

- Average maintainability; this is the most often case in complex mechanical systems. Compared with previous variable it implicated somewhat more complicated maintenance operation and/or more inaccessible location.

- Complicated for maintenance; technologically more complicated but predictable maintenance operations (for example, tendency to rust).

- Hard for maintenance; beside high technological complexity, unpredictable situations during the maintenance operation can almost always be expected.

According to concerning system, even more precise descriptions for maintenance operations can be used as linguistic variables in fuzzy sets.

Table 2: Maintainability fuzzy sets defined by linguistic variable and membership function to the classes

	1.	2.	3.	4.	5.	6.	7.
Hard for m...	0	0	0	0	0	0.25	1.0
Complicate...	0	0	0	0	0.5	1.0	0
Average ...	0	0	0.5	1.0	0.5	0	0
Easy m …	0	1.0	0.5	0	0	0	0
Optimal …	1.0	0.25	0	0	0	0	0

By analysis of maintenance conditions that usually exist in complex industrial systems, four maintenance support systems can be identified:

- Maintenance through services by producers or licensed organizations
- Maintenance developed by the consumer
- Maintenance by consumers' request
- Without organized maintenance

Efficiencies of the first two cases are hard to distinguish. Maintenance with services performed by producers or licensed organizations is characteristic for recent maintenance concepts. Here, producers of equipments give guarantee for their correct operation. Maintenance developed by consumers is somewhat obsolete maintenance concept but it is still present for complex and valuable systems which have been produced in small amounts and which can have significant modification in design during their lifetime. Huge bucket wheel excavators in open pit mines are good examples of such systems. Without considerations of economic aspects of such maintenance policy, it can be estimated as quite successful, primary because close relationship of maintenance service with design development and modernization of such machines during their lifetime.

Maintenance at consumers' request can be characterized as very inertial concept, but it can satisfy demands with limited number of activities necessary for keeping system as available. However, the consequences of inertia, i.e. lacking of forehand and organized maintenance actions, can be very serious especially for systems implemented for expensive technological process. As the uncertainty and vagueness are inherent to this concept, its fuzzy set will have significantly wide range.

Inexistence of organized maintenance is connected to component and parts of systems which are rare, unique or reliable in the degree that any failure is unexpected (for example support construction, hollow shafts and planetary gears of large dimensions, etc.). Storage of such components would have high expenses but the failures of these components are frequently fatal for whole system.

According to four identified maintenance policy concepts, four linguistic variables for maintenance support can be introduced (Table 3): excellently developed maintenance support, well developed maintenance support, limited maintenance support and inexistence of maintenance support. Again, classes are used as measuring units for representation of maintenance support quality (in interval 1 ... 7). For two more efficient concepts, linguistic variables excellently developed and well developed are set up but without strict identification. In other words, maintenance through services by producers or licensed organizations can principally be identified as excellently developed maintenance support but without absolute certainty. The same is with maintenance developed by consumer and linguistic variable well developed. With strict identification of proposed linguistic variables and maintenance policies advantages of fuzzy sets utilization would also be neutralized. For example, obligation of the producer to carry out maintenance actions doesn't necessary mean that the maintenance support is excellently developed. For remaining two less efficient maintenance support options linguistic variables limited and inexistence are introduced. These two maintenance policies are easier for differentiation, and strict identification with linguistic variables is evident. Also, according to previous considerations outer linguistic variables excellently developed and inexistence are not mutually symmetrical.

Table 3: Maintenance support fuzzy sets defined by linguistic variable and membership function to the classes

	1.	2.	3.	4.	5.	6.	7.
Inexistence	0	0	0	0	0	0.25	1.0
Limited	0	0	0	0.5	1.0	0.5	0
Well	0	0.5	1.0	0.5	0	0	0
Excellently	1.0	0.75	0	0	0	0	0

The second step of the dependability determination is definition of relations and compositions between partially considered indicators: reliability, maintainability and maintenance support. In other words, it is necessary to complete synthesis of estimations for reliability (*R*), maintainability (*M*) and maintenance support (*L*) to dependability (*D*) level. Synthesis was done based on appropriate fuzzy composition. Here, max-min composition is used as follows:

$$D = R\circ(M\times L) \tag{2}$$

Conjunction "and", that is product with operator (°) is used in cases when fuzzy sets and/or relations simultaneously exist [4] or there is no functional relationship between them. This product is used here for integration of performance that describes times in operation and failure time, i.e. reliability indicator with maintenance indicators. Functional relationship between maintainability and maintenance support certainly exists. These indicators can be even technologically dependent and the Cartesian product is used for their integration.

The Cartesian product of maintenance related indicators, maintainability and maintenance support, i.e. appropriate membership function (μ) is defined as follows:

$$\mu_{M\times L} = (\mu_{M\times L}^{ij})_{n\times n}, \tag{3}$$

with

$$\mu_{M\times L}^{ij} = \min(\mu_M^i, \mu_L^j), \tag{4}$$

where the membership functions for maintainability and maintenance support are given as:

$$\mu_M^i = (\mu_M^1,\ \mu_M^2,\ \dots\ \mu_M^n), \tag{5}$$

$$\mu_L^i = (\mu_L^1,\ \mu_L^2,\ \dots\ \mu_L^n). \tag{6}$$

For reliability membership functions:

$$\mu_R^i = (\mu_R^1,\ \mu_R^2,\ \dots\ \mu_R^n) \tag{7}$$

and Cartesian product of maintainability and maintenance support membership function given in (3), composition of dependability membership function can be determined as:

$$\mu_D = \mu_{R\circ M\times L} = (\mu_D^j)_{1\times n}. \tag{8}$$

Here is:

$$\mu_D^j = \max(\min(\mu_R^1, \mu_{M\times L}^{1j})\ \dots$$
$$\dots\min(\mu_R^n, \mu_{M\times L}^{nj})), \quad j = 1, 2,\ \dots\ n. \tag{9}$$

Max-min composition defined in (9) set up maintenance support fuzzy sets as "critical", or more precise, as fuzzy sets with the dominant influence on over all dependability. For example, if considered system is with excellent performances of reliability and maintainability but with relatively poor characteristic for maintenance support, overall performance of dependability will be also at low level and significantly lower than in some other combinations of these indicators. This feature characterized max-min composition as a "pessimistic" but it is often used in the analysis of technical systems.

Proposed fuzzy composition as an output has dependability performance in relation (by appropriate membership function) with classes:

$$D = \{1/(0...1.0),\ 2/(0...1.0),\ 3/(0...1.0),\ 4/(0...1.0),$$
$$5/(0...1.0),\ 6/(0...1.0),\ 7/(0...1.0)\}. \tag{10}$$

This expression of dependability performance is necessary to map back to the defined dependability fuzzy sets (Table 4).

Table 4: Dependability fuzzy sets defined by linguistic variable and membership function to the classes

	1.	2.	3.	4.	5.	6.	7.
Poor	0	0	0	0	0	0.75	1.0
Average	0	0	0	0.5	1.0	0.25	0
Good	0	0.25	1.0	0.5	0	0	0
Excellent	1.0	0.75	0	0	0	0	0

Best-fit method is used for transformation of dependability description (10) to form that which defines grade of membership to fuzzy sets: poor, average, good, excellent. This procedure is recognized as dependability identification. Best-fit method uses the distance (*d*) between dependability attained by "max-min" composition (10) and each of the dependability expressions to represent the degree to which D is confirmed to each of them (Table. 4).

$$d_{ij}(D_i, H_j) = \sqrt{\sum_{j=1}^{7}\left(\mu_D^j - \mu_{Hj}^j\right)^2}\ ,$$

$$j = 1, \dots, 4\ , \tag{11}$$

$$Hj\ =\ \{\text{excellent, good, average, poor}\}\ .$$

The closer D_i is to the *j*-th linguistic variable, the smaller d_{ij} is. Distance d_{ij} is equal to zero, if D_i is just the same as the *j*-th expression in terms of the membership functions. In such a case, D_i should not be evaluated to other expressions at all due to the exclusiveness of these expressions.

Suppose $d_{ij,\min}(j = 1,\ 2,\ 3,\ 4)$ is the smallest among the obtained distances for D_i and let α_{i1}, α_{i2}, α_{i3} and α_{i4} represent the reciprocals of the relative distances between the identified fuzzy dependability description D_i and the each of the defined dependability expressions with reference to d_{ij}. Then, α_{ij} can be defined as follows:

$$\alpha_{ij} = \frac{1}{d_{ij} / d_{i\min}}\ ,\ \ j = 1,2,3,4. \tag{12}$$

If $d_{ij} = 0$ it follows that $\alpha_{ij} = 1$ and the others are equal to zero. Then, α_{ij} can be normalized by:

$$\beta_{ij} = \frac{\alpha_{ij}}{\sum_{m=1}^{4}\alpha_{im}},\quad j = 1,2,3,4.$$

$$\sum_{j=1}^{4}\beta_{ij} = 1\ \ . \tag{13}$$

Each β_{ij} (j = 1, 2, 3, 4) represents the extent to which D_i belongs to the *i*-th defined dependability expressions. It can be noted that if D_i completely belongs to the *i*-th expression then β_{ij} is equal to 1 and the others are equal to 0. Thus β_{ij} could be viewed as a degree of confidence that D_i belongs to the *j*-th reliability expressions. Final expression for dependability performance at the level of component *i,* considered as the lowest level in hierarchical structure of BWE, is obtained in form:

$$D_i = \{(\beta_{i1}, \text{"poor"}), (\beta_{i2}, \text{"average"}), (\beta_{i3}, \text{"good"}), (\beta_{i4}, \text{"excellent"})\}\ . \tag{14}$$

2.3. Hierarchical evaluation, ER-algorithm

Synthesis of obtained dependability assessments in dependability evaluation at the levels of subsystems systems or whole system (BWE) is done by utilization of hierarchical evidential reasoning algorithm

Every technical system consists of a series of components, constructively and/or functionally integrated in subsystems and systems. Partial evaluations of components' dependability performances are necessary to synthesize to upper levels of subsystems and finally to overall technical system dependability performance.

For synthesis of information procedure based on evidence theory will be used. The evidence theory was first developed by Dempster (1967) and was later extended and refined by Shafer (1976). Therefore, this theory is also called the Dempster–Shafer theory of evidence, or the D–S theory for short. It was not until 1994 that the D–S theory was first combined with a distributed modeling framework to develop the Evidential Reasoning (ER) approach [6] for dealing with Multi Attribute Decision Analyses (MADA) problems with probabilistic uncertainty. ER approach offers a rational, reliable way to aggregate uncertain, incomplete and vague data. In recent years, this approach has been applied to different fields such as engineering design selection, organizational self-assessment, safety and risk assessment and supplier assessment. Nowadays, ER approach is considered as one of the best approaches to deal with MADA problem with uncertainty. The kernel of the ER approach is an evidential reasoning algorithm developed on the basis of MADA framework and the evidence combination rule of the D–S theory. It is different from most conventional (12 MADA modeling methods in the following three aspects: (1) it employs a belief structure to represent an assessment as a distribution instead of as a single numerical score, which can capture various types of uncertainties such as vagueness in subjective judgments; (2) when decision-maker is not able to provide a precise judgment because of inadequacy of information available, the ER approach allows decision analyzers to define a degree of belief of less than 1. No other MADA approaches can deal with this level of uncertainty; (3) it (13) employs the evidential combination rule to aggregate degrees of belief rather than scores. In this way, the evidential reasoning approach can preserve the qualitative feature of subjective attribute in aggregation process.

ER algorithm will be implemented to the evaluation of bucket wheel excavator as follows: obtained dependability evaluation at particular hierarchical level will be considered as a hypothesis, i.e. as a partial piece of evidence for the evaluation at the next higher hierarchical level. Hierarchical evaluation process assures systematical approach to aggregation of such uncertain components' dependability assessments with the aim of creation of evaluations for subsystems, systems and whole considered excavator.

To apply D-S theory, the mutual exclusiveness and exhaustiveness of all hypotheses have to be satisfied. The linguistic variables defined for dependability, satisfy the requirements of exclusiveness and exhaustiveness. This enables us to employ the ER – algorithm developed to synthesize the uncertain safety evaluations generated for appropriate components' dependability evaluations obtained as fuzzy sets.

Suppose H represents a set of linguistic variables for dependability expressions and H_j the *j*-th linguistic variable such as 'good'. Then, H is defined by:

$$H = \{H_1, \ldots, H_j, \ldots, H_n\}, \tag{15}$$

where n is the number of the linguistic variables defined. In Section 2.2, for example, H is defined by:

$$H = \{poor, average, good, excellent\}, \quad n = 4. \tag{16}$$

Suppose there are L_k components (the lowest level in hierarchical structure with obtained dependability performance, Section 2.2) associated with the k-th subsystem (the first upper level of hierarchical structure). Let f_{ki} denote component i associated with subsystem k, denoted by s_k. The set of the components for the subsystem can then be defined by:

$$F_k = \left\{ f_{k1}, \ldots, f_{ki}, \ldots, f_{kL_k} \right\}. \tag{17}$$

Let λ_{ki} be the normalized relative weight of component i in evaluation of the dependability of subsystem k where:

$$0 < \lambda_{ki} < 1. \tag{18}$$

Suppose $m_{ki}^j = m(H_j / f_{ki})$, $(m_{ki}^j \le 1)$, is a real number, referred to as a basic probability assignment, which represents a degree to which the obtained dependability evaluation of the i-th component supports a hypothesis that the dependability of the k-th subsystem is confirmed to H_j. Then, m_{ki}^j may be obtained as follows:

$$m_{ki}^j = \lambda_{ki}\ \beta_{ij}, \tag{19}$$

where β_{ij} is given with respect to the k-th subsystem, as discussed in Section 2.2 (14).

As $0 \le \lambda_{ki} \le 1$ and $\sum_{j=1}^{N} \beta_{ij} = 1$, then $\sum_{j=1}^{N} m_{ki}^j \le 1$.

Suppose $m_{ki}^H = m(H / f_{ki})$ is the basic probability assignment to H, which is the remaining belief unassigned after commitment of belief to all H_j $(j = 1, \ldots, N)$, that is, $\sum_{j=1}^{N} m_{ki}^H = 1 - m_{ki}^j$. A basic probability assignment matrix $m(s_k / F_k)$ for evaluation of the dependability of the subsystem s_k through the associated components F_k may then be formulated by:

$$M(s_k / F_k) = \\ = \begin{bmatrix} m_{k1}^1 & \ldots & m_{k1}^j & \ldots & m_{k1}^N & m_{k1}^H \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ m_{k\,i}^1 & \ldots & m_{k\,i}^j & \ldots & m_{k\,i}^N & m_{k\,i}^H \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ m_{k\,Lk}^1 & \ldots & m_{k\,Lk}^j & \ldots & m_{k\,Lk}^N & m_{k\,Lk}^H \end{bmatrix} \begin{matrix} \{f_{k1}\} \\ \ldots \\ \{f_{k\,i}\} \\ \ldots \\ \{f_{k\,Lk}\} \end{matrix} \tag{20}$$

Suppose $m_{s_k}^j$ is a degree of confidence to which the dependability of the k-th subsystem is evaluated to H_j. Then, $m_{s_k}^j$, can be obtained by synthesizing the basic probability assignments as listed in $M(s_k / F_k)$ using the evidential reasoning algorithm as described below.

Suppose Z is a subset of H. Define a subset $f_{l_k(i)}$ of F_k and a combined probability assignment $m_{l_k(i)}^Z$ as follows:

$$f_{l_k(i)} = \left\{ f_k^1 \ \ldots \ f_k^i \right\}, \qquad 1 \le i \le L_k, \\ m_{l_k(i)}^Z = m(Z_{l_k(i)}), \tag{21}$$

where $m(Z / f_{l_k(i)})$ is a combined probability assignment to Z confirmed by $f_{l_k(i)}$.

Then, the recursive algorithm can be stated as follows:

$$\left\{H_j\right\}: m_{lk(i+1)}^j = K_{lk(i+1)}(m_{lk(i)}^j m_{k,i+1}^j + \\ + m_{lk(i)}^j m_{k,i+1}^H + m_{lk(i)}^H m_{k,i+1}^j), \ j = 1, \ldots, N \\ \left\{H\right\}: m_{lk(i+1)}^H = K_{lk(i+1)} m_{lk(i)}^H m_{k,i+1}^H \\ K_{lk(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{j=1 \\ j \ne t}}^{N} m_{lk(i)}^t m_{k,i+1}^j \right]^{-1} \quad i = 1, \ldots, L_k - 1. \tag{22}$$

It can be proven from the algorithm that $m_{lk(L_k)}^Z$ is the overall probability assignment to $Z(\subseteq H)$ confirmed by F_k and $m_{lk(L_k)}^Z = 0$ for any $Z \subseteq H$ other than $Z = H_j\,(j = 1, \ldots, N)$ and H, or

$$m_{sk}^j = m(H_j / F_k) = m_{lk(L_k)}^j, \ j = 1, \ldots, N \text{ and} \\ m_{sk}^H = m(H / F_k) = m_{l_k(L_k)}^H, \\ m(Z / F_k) = m_{l_k(L_k)}^Z = 0 \ \text{ for any } Z \subseteq H \tag{23}$$

but $Z \ne H_j\,(j = 1, \ldots, N)$ and H.

Consequently, the dependability of the k-th subsystem can be evaluated in terms of the dependability expressions defined in H by the following expectation:

$$D(s_k) = \{(m_{s_k}^j, H_j), j = 1, \ldots, N\}, \tag{24}$$

that is, the k-th subsystem is evaluated to H_j with a degree of confidence of $m_{s_k}^j$, $j = 1, \ldots, N$.

Such an evaluation is generated by synthesizing the given dependability evaluations of the relevant components.

In a similar way, the dependability evaluation of upper level in the hierarchical structure of the BWE can be determined based on dependability evaluation of the first, previous lower level ($D_1, D_2, D_3, \ldots$, Table 4.). In the other words, ER algorithm will be implemented to the subsystems' levels for evaluation of systems' dependability and it will be implemented to the systems' levels for evaluation of dependability performance of bucket wheel excavator (whole system).

3. AN ILLUSTRATIVE EXAMPLE - DEPENDABILITY OF MECHANICAL PARTS ON THE BUCKET WHELL EXCAVATOR

Bucket wheel excavator SchRS 630 employed in open pit mine Kolubara–Tamnava West Field is considered. Excavator has been in operation since 1994; it was in operation 34,469 hours and produced 37,484,246 t of lignite and 4,594,498 m^3 of waste. Theoretical capacity of this excavator is 4,100 m^3/h, while realized capacity was 1,258.8 m^3/h.

System materials' transport / Sub-system – drive unit, with next components: electric engine, clutch, mechanical brake, gear box and locking assemblies is considered [7]. According with Table 1, 2 and 3, it can estimate dependability indicators (*R, M, L*) of these components. For estimation of dependability indicators experts' judgments were used and their dominant orientation to some of proposed fuzzy sets was adopted for introduction to model. In other words, fuzzy set that was accepted "to the greatest extent" was a little bit modified according to degree of acceptance. On the basis of max-min composition (2) – (9) dependability evaluations of analyzed components are obtained, as (10). Furthermore, using best-fit method (11) – (13), dependability (*D*) is determined as (14) with membership degree to fuzzy variables i.e. fuzzy sets of dependability (Table. 4).:

Electric engine
R =*averagely r*= {1/0,2/0.1,3/0.5,4/1.0,5/0.3,6/0,7/0}
M =*optimal for m.*= {1/1.0,2/0.3,3/0,4/0,5/0,6/0,7/0}
L =*excellently d.m.s.*= {1/1.0,2/0.75,3/0,4/0,5/0,6/0,7/0}
D={(0.23075,"poor"),(0.25146,"average"), (0.25632,"good"), (0.26147,"excellent")}

Clutch
R =*very r.*= {1/0.1,2/1.0,3/0.4,4/0,5/0,6/0,7/0}
M =*easy m.*= {1/0.1,2/1.0,3/0.4,4/0,5/0,6/0,7/0}
L =*excellently d.m.s.*={1/1.0,2/0.6,3/0.2,4/0,5/0,6/0,7/0}
D ={(0.09859, "poor"), (0.10303, "average"), (0.11962, "good"), (0.67876, "excellent")}

Mechanical brake
R =*very r.* = {1/0.2,2/1.0,3/0.3,4/0,5/0,6/0,7/0}
M =*optimal for m.*= {1/1.0,2/0.3,3/0.1,4/0,5/0,6/0,7/0}
L =*excellently d.m.s.*= {1/1.0,2/0.75,3/0,4/0,5/0,6/0,7/0}
D ={(0.20807, "poor"), (0.22482, "average"), (0.23705, "good"), (0.33006, "excellent")}

Gear-box
R =*very r.*= {1/0.1,2/1.0,3/0.4,4/0,5/0,6/0,7/0}
M =*optimal for m.*= {1/1.0,2/0.2,3/0.1,4/0,5/0,6/0,7/0}
L =*excellently d.m.s.*={1/1.0,2/0.5,3/0.2,4/0,5/0,6/0,7/0}
D ={(0.21117, "poor"), (0.22885, "average"), (0.28365, "good"), (0.27633, "excellent")}

Locking assembly
R =*very r.*= {1/0.1,2/1.0,3/0.5,4/0,5/0,6/0,7/0}
M =*easy m.*= {1/0,2/1.0,3/0.5,4/0,5/0,6/0,7/0}
L =*excellently d.m.s.*={1/1.0,2/0.4,3/0.1,4/0,5/0,6/0,7/0}
D ={(0.12927, "poor"), (0.13562, "average"), (0.14807, "good"), (0.58704, "excellent")}

Following described model for dependability synthesis based to ER algorithm (15)-(24), dependability performance at the level of sub-system – drive unit:

D ={(0.1662, "poor"), (0.1799, "average"), (0.2063, "good"), (0.4475, "excellent")}

For considered components, values for λ (18) are adopted as: 0.30, 0.30, 0.08, 0.40, 0.25, respectively.

Besides drive unit subsystem for materials' transport includes also: rotating elements, main structure, rubber belt with steel core, lubrications system. Their dependability performances and λ (18) values are given in next part of the text:

Drive unit:
D ={(0.1662, "poor"), (0.1799, "average"), (0.2063, "good"), (0.4475, "excellent")} λ= 0.30

Rotating elements:
D ={(0.17152, "poor"), (0.18291, "average"), (0.21077, "good"), (0.43481, "excellent")} λ= 0.60

Main structure:
D ={(0.17152, "poor"), (0.18291, "average"), (0.21077, "good"), (0.43481, "excellent")} λ = 0.80

Rubber belt:
D ={(0.04782, "poor"), (0.04985, "average"), (0.05570, "good"), (0.84663, "excellent")} λ = 0.40

Lubrications system:
D ={(0.10288, "poor"), (0.12853, "average"), (0.65319, "good"), (0.11541, "excellent")} λ = 0.25

Using ER algorithm, final dependability evaluation at the level of system for materials' transport is obtained:

D ={(0.1334, "poor"), (0.1447, "average"), (0.2162, "good"), (0.5056, "excellent")}

Beside system for materials' transport, bucket wheel excavator includes six mechanical systems. In same sense, in further text are given only finale estimations, as well as λ values for others systems.

System for excavation:
D= {(0.0867, "poor"), (0.7420, "average"), (0.0938, "good"), (0.0774, "excellent")} λ = 0.76

System for materials' transport:
D= {(0.1334, "poor"), (0.1447, "average"), (0.2162, "good"), (0.5056, "excellent")} λ = 0.67

System for excavator's transport:
D= {(0.1727 "poor"), (0.2497, "average"), (0.3815, "good"), (0.1960, "excellent")} λ = 0.60

System for boom lifting:
D= {(0.1428, "poor"), (0.1550, "average"), (0.5221, "good"), (0.1799, "excellent")} λ = 0.80

System for upper construction rotation:
D= {(0.0864, "poor"), (0.1029, "average"), (0.7134, "good"), (0.0971, "excellent")} λ = 0.70

Main structure:
D = {(0.0530, "poor"), (0.0553, "average"), (0.0616, "good "), (0.8299,"excellent")} λ = 0.80

Accessory structure:
D = {(0.0530, "poor"), (0.0553, "average"), (0.0616, "good"), (0.8299,"excellent")} λ = 0.20

Finally, dependability performance for whole analyzed bucket wheel excavator is determined as:

$D_{b.w.e}$ = {(0.1000, "poor"), (0.2286, "average"), (0.3199, "good"), (0.3514,"excellent")}

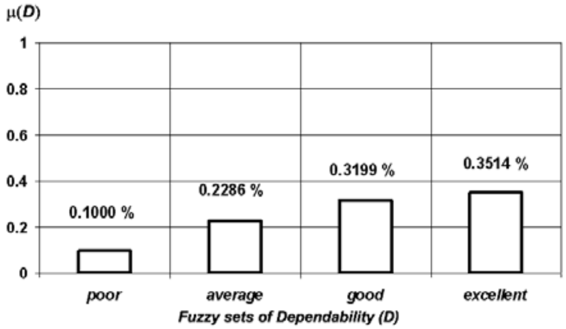

Figure 1 Evaluated dependability of mechanical parts on the bucket wheel excavator SchRs 630, open pit Tamnava West, Serbia

Graphical presentation of obtained result is shown in Figure 1. Evaluated dependability of considered SchRs 630 bucket wheel excavator is to the greatest extent (35.14%) excellent, that is, matched to 1. and 2. classes. Somewhat less is evaluated as good, i.e. matched to class 3. Dependability of this excavator can be considered as average and poor in relatively small percentages. Evaluation in such form can also be considered as expected availability of selected excavator. In the case of simultaneous analysis of more excavators, information about quality of different design solutions and maintenance organization could be obtained. If dependability at different hierarchical levels is analyzed, it can be used for identification of weak points on the machine. For example, on the level of the system, it is evident that system for excavation is amechanical system in this excavator with the worst dependability performance, i.e. system with maximal influence on excavator availability reduction.

4. CONCLUSION

This paper presents mathematical model for dependability performance evaluation based on theoretical interpretation of dependability concept which was introduced in standard IEC-300. The established model for evaluation of dependability of the bucket wheel excavators, based on fuzzy sets theory and evidential reasoning, tries to completely absorb expertise opinions and judgments given in linguistic forms. This form arose as the most proper for introduction of knowledge and experiences accumulated during the BWE design, operation and maintenance, namely, related to bucket wheel excavator's construction and logistic characteristics. The model output is in the linguistic, continual form and thus gives a multidimensional character to evaluation of bucket wheel excavators, which differs from usually applied models for evaluation of bucket wheels excavators quality of service that use quotient of time or capacity utilization.

Proposed model was used for analysis of mechanical systems in bucket wheel excavator SchRs 630, employed in open pit Tamnava West. Mechanical systems are selected for consideration as a dominant in significance to overall machine operation. Dependability performance of overall mechanical systems in this excavator is obtained as a proper fuzzy set and their dependability is estimated as "excellent" in the greatest extent. This information could be interesting in comparison with dependability of other excavators in open pit, i.e. for decision-making about order in revitalization, reconstruction, etc. On the other hand, presented results about BWE dependability at the different hierarchical levels (systems, subsystems or components) are significant for BWE reconstruction or redesigning, because week points are clearly indicated at each level as well as critical dependability indicators (reliability, maintainability or maintenance support). For example, it is clear that the system for excavation is a weak point in SchRs 630, main structure is critical in the system for materials' transport and electric engine and gear box are indicated as weak points in drive unit with demands for their reliability improvement.

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ПРОЦЕНА УПОТРЕБНОГ КВАЛИТЕТА РОТОРНОГ БАГЕРА

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Роторни багер може да се опише као један од најкомплекснијих техничких система у индустрији. У овом раду је управо анализиран животни век ових машина. При томе, посебна пажња је посвећена развоју модела процене употребног квалитета на бази теорије фази скупова и чињеничног закључивања. Перформанса сигурности функционисања је коришћена као мера употребног квалитета. Процена сигурности функционисања је вршена на бази експертских процена. На крају рада, дат је конкретан пример анализе сигурности функционисања механичких компоненти роторног багера.