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DEPENDABILITY ASSESMENT OF OPEN-PIT MINES EQUPMENT – STUDY ON THE BASES OF FUZZY ALGEBRA RULES

OCENA NIEZAWODNOŚCI SPRZĘTU WYKORZYSTYWANEGO W KOPALNIACH ODKRYWKOWYCH – BADANIA OPARTE NA REGUŁACH ROZMYTEJ ALGEBRY

This article aims to present a new approach for assessing of maintenance support and model for its introduction into dependability concept. Process of expertise judgment is used directly for assessing the organization of maintenance support and it is shown in the form of linguistic variables as appropriate fuzzy sets. For the introduction of maintenance support into dependability, fuzzy composition is used. Since reliability and maintainability are also influential indicators of dependability, it was necessary to develop a methodology for fuzzification of corresponding reliability and maintainability probability functions. This methodology is developed by using empirical scaling. The proposed approach has been applied to different types of bulldozers, as a usual technical system that operates at open pit mine.

Keywords: *dependability, maintenance support, fuzzy sets, bulldozer.*

Niniejszy artykuł ma na celu przedstawienie nowej metody oceny wspomagania obsługi oraz modelu opisującego jej zastosowanie w odniesieniu do pojęcia niezawodności. Proces wydawania opinii eksperckiej wykorzystano bezpośrednio do oceny organizacji wspomagania obsługi i przedstawiono go w postaci zmiennych lingwistycznych jako odpowiednie zbiory rozmyte. W celu odniesienia wspomagania obsługi do niezawodności, posłużono się kompozycją zbiorów rozmytych. Ponieważ nieuszkadzalność i obsługiwalność są również ważnymi wskaźnikami niezawodności, konieczne było opracowanie metodologii rozmywania odpowiednich funkcji prawdopodobieństwa działania i obsługi. Niniejsza metodologia została opracowana przy użyciu skalowania empirycznego. Proponowane podejście zastosowano w odniesieniu do różnych typów spychaczy, składających się na przeciętny układ techniczny funkcjonujący w obrębie kopalni odkrywkowej.

Słowa kluczowe: *stal duplex, obróbka skrawaniem, toczenie, okres trwałości ostrza, metoda powierzchni odpowiedzi.*

1. Introduction

Life cycle management of technical systems that are characterized by high investment value on the one hand, and by high specific work value, namely the high costs of unplanned shut downs on the other, is an especially complex and responsible task. Open pit mines and their equipment represent the genuine example of these technical systems. According to Study [16], an hour of unplanned break down at lignite open pit mines within Electric Power Industry of Serbia causes the expenses of around 10.000 € for coal and of around 3.000 € for overburden. Machines engaged on continual exploitation systems (bucket wheel excavator, stacker) today cost 10–12 € per kilo at average, and themselves can even weight several thousand tons. Machines belonging to auxiliary machinery can cost several thousand euros. Management of maintenance is very responsible duty, also as model for its determination and evaluation. In that sense, the science articles in the area of maintainability and reliability engineering, are very topical [2–4, 6–9, 11–18].

In order to simplify this management's task, it is needed to define indicators of quality of service for technical systems. Some authors Kuo[12] and Seo[14] assert that the life cycle of a technical systems must be seen from the point of costs, namely, the reduction of total life cycle costs for a certain product is considered as an essential part of technical system and serving. There are also the indicators that analyze technical system based to the ratio of the uptime and downtime. Among them, the best known are indicators of availability performance, namely dependability. Dependability concept was introduced through ISO-IEC standards [14]. Dependability includes availability performance, as its measure, with influencing factors – performances of reliability, maintainability and maintenance support. 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. The special attention was devoted to degree of customers' satisfaction with appropriate product and consideration of entire product life-cycle phases concerning planning, design, production, operation and maintenance, and finally disuse. Some authors Avizienis [1] and Ebramhimipour [3] have defined dependability as an integrative concept which also includes safety. In any case, contemporary approaches to estimation of the quality of service level for technical systems are engineering that support system reliability and maintenance and consider them in the synthesis form. Dependability engineering [14], through various techniques and concepts of systems' sciences, considers the performance of technical system through its life cycle and estimates to what degree and for how long it can be relied on at any time. RAMS Engineering (Reliability Availability Maintainability Supportability) has the goal to reduce number of failures and minimize their consequences [13].

Analysis of these synthesized indicators can be carried out most easily through the mean time to restore equipment to its original working status or through the use of model for prediction on the basis of operational research [13] as well as through the use of fuzzy algebra rules [2], [6] and [10]. Secondly mentioned models are more complex for use, but they give mutual relation of influential parameters and enable finding the weak points of the technical system

Special place in grasping the availability and dependability of technical system, plays the choice of suitable conception of maintenance organization [4] and [11], and consequently of the level of maintenance support. In practice, various conceptions [9] are used - from the simplest ones such as breakdown maintenance, to the advanced ones such as predictive. Maintenance support hereby has the task to support the uninterrupted performance of suitable maintenance conception, namely to enable the required level of availability and dependability of technical system.

This paper presents procedure – model for estimation of maintenance support and dependability determination according to maintenance support and other influential indicators (reliability and maintainability). Furthermore, maintenance support is estimated on the basis of expert judgment, while reliability and maintainability monitoring period of up-time and down-time. In order to comprehend the impact of these various values to dependability, the rules of fuzzy algebra are used. In the article was also specifically developed procedure for reliability and maintainability probability functions fuzzification on the base of empirical scaling. Model is tested and implemented to dependability determination of different types of bulldozers operated at open pit mine Drmno.

It can be said that this article constitutes an improvement of the [6], when the dependability indicators were analyzed only on the base of expertise judgment, without of fuzzification of statistical data. Also, this paper presents a maintenance support evaluation model. Unlike performances of reliability and maintainability, maintenance support did not have a conventional system for evaluation,

2. Maintenance support analysis and dependability integration based to fuzzy sets theory

Maintenance support represents the ability of an organization in charge of maintenance to secure required maintenance of technical system under given condition, in accordance with maintenance policy. In other words, certain technical system has the appropriate maintenance support if the required maintenance activity is carried out at required place in the given time during a certain time period. Maintenance support is not directly influenced by construction characteristics of technical system which is the object of maintenance.

In analysis of logistic parameters as the maintenance support is, practically there is no other way for its estimation without utilization of experts' judgments given as linguistic descriptions. Fuzzy sets theory has arisen as appropriate tool that will work with linguistic form, apropos simultaneously with insufficiently accurate terms and expressions that hardly can be represented by models with numerical inputs, as well as with to some extent strongly determined facts. In this sense, fuzzy set theory will in this paper be used for the analysis of maintenance support through the procedure of identification of the fuzzy sets as well as for the integration on the dependability level using the procedure of composition of the fuzzy sets.

2.1. Identification of the fuzzy sets, maintenance support evaluation

By analysis of maintenance conditions that usually exist at complex industrial systems, for maintenance support systems [6] can be identified: maintenance through services by producers or licensed organizations, maintenance developed by consumer, maintenance by consumers' request and without organized maintenance.

Efficiencies of the first two cases are hard to be distinguished. 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. These types of maintenance support are provided by almost all producers of equipment which is produced in large series, such as auxiliary machinery of the open pit mines. 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 at open pit mines are good examples of such systems. Without consideration 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 by 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: excellently developed maintenance support, well developed maintenance support, limited maintenance support and inexistence of maintenance support. It is necessary to put these linguistic variables into appropriate coordinate system of membership function and measuring units. Maintenance support as well as the dependability is without conventional measuring units. In other words, maintenance support is inherently 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 [19] and [20]. Hence, the structure of maintenance support indicator with seven classes (i =1 to 7) as measures of appropriate fuzzy sets will be as follows:

$$\boldsymbol{L} = \{1/\mu^1_L, 2/\mu^2_L, 3/\mu^3_L, 4/\mu^4_L, 5/\mu^5_L, 6/\mu^6_L, 7/\mu^7_L\};\ \mu^i_L \in [0,1] \quad (1)$$

Where is $\boldsymbol{L}$ mark for maintenance support (practically logistics) and μ^i_L membership function.

For two more efficiency 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 producer to carry out maintenance actions doesn't necessary mean that the maintenance support is excellently developed. For remaining two less efficiently maintenance support options linguistic variables limited and inexistence are introduced. These two maintenance policies are quite 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. These settings are shown in Fig. 1.

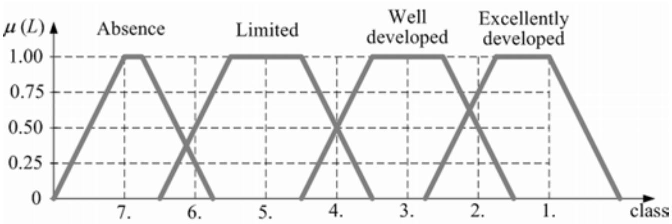

Fig. 1. Maintenance support fuzzy sets

2.2. Composition of the fuzzy sets, maintenance support and dependability

Composition of the fuzzy sets is a process of defining the relationship between fuzzy relations in order to obtain the score of synthesis of these relations. In our case, the score would represent dependability (*D*), while fuzzy relations are: reliability (*R*), maintainability (*M*) and maintenance support (*L*), namely all partial indicators of dependability. Synthesis was done based on appropriate max-min composition [10]:

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

Conjunction "and", that is product with operator (°) is used in cases when fuzzy sets and/or relations simultaneously or there is no functional relationship between them. This product is here used 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 [10] of maintenance related indicators, maintainability and maintenance support, i.e. appropriate membership function is defined as follows:

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

with:

$$\mu^{ij}_{M \times L} = \min(\mu^{i}_{M},\ \mu^{j}_{L}) \tag{4}$$

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

$$\mu_{M} = (\mu^{1}_{M},\ \mu^{2}_{M},\ \ldots,\ \mu^{n}_{M}) \tag{5}$$

$$\mu_{L} = (\mu^{1}_{L},\ \mu^{2}_{L},\ \ldots,\ \mu^{n}_{L}) \tag{6}$$

Composition of dependability membership function, for reliability membership functions:

$$\mu_{R} = (\mu^{1}_{R},\ \mu^{2}_{R},\ \ldots,\ \mu^{n}_{R}) \tag{7}$$

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

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

here is:

$$\mu^{j}_{D} = \max(\min(\mu^{1}_{R},\ \mu^{1j}_{M \times L}),\ \ldots,\min(\mu^{n}_{R},\ \mu^{nj}_{M \times L})),\ j = 1, 2, \ldots, n. \tag{9}$$

Max-min composition defined in equation (9) set up maintenance support fuzzy sets as "critical" or more precise as fuzzy sets with the dominant influence to 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 is the essence of the integration of maintenance support in dependability. This feature characterized max-min composition as a "pessimistic" but it is often used in an analysis of technical systems.

Proposed fuzzy composition as an output has dependability performance in relation (by appropriate membership function) with classes (1 to 7):

$$\boldsymbol{D} = \{1/\mu^{1}_{D},\ 2/\mu^{2}_{D},\ 3/\mu^{3}_{D},\ 4/\mu^{4}_{D},\ 5/\mu^{5}_{D},\ 6/\mu^{6}_{D},\ 7/\mu^{7}_{D}\};\ \mu^{i}_{D} \in [0,1] \tag{10}$$

Thereby, *L* is given in the form (1), while *R* and *M* are also given in relation to classes in the form:

$$\boldsymbol{R} = \{1/\mu^{1}_{R},\ 2/\mu^{2}_{R},\ 3/\mu^{3}_{R},\ 4/\mu^{4}_{R},\ 5/\mu^{5}_{R},\ 6/\mu^{6}_{R},\ 7/\mu^{7}_{R}\};\ \mu^{i}_{R} \in [0,1] \tag{11}$$

$$\boldsymbol{M} = \{1/\mu^{1}_{M},\ 2/\mu^{2}_{M},\ 3/\mu^{3}_{M},\ 4/\mu^{4}_{M},\ 5/\mu^{5}_{M},\ 6/\mu^{6}_{M},\ 7/\mu^{7}_{M}\};\ \mu^{i}_{M} \in [0,1] \tag{12}$$

Dependability, as the parameter of quality of service level, is a value without conventional evaluation system and measurement unit. Therefore, in this article it is given in the form of fuzzy sets depending from membership function $\mu_{(D)}$ and class (1 to 7). These settings are shown in Fig. 2.

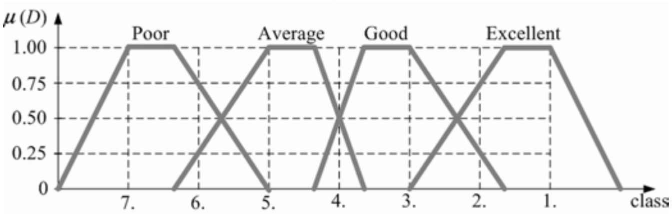

Fig. 2. Dependability fuzzy sets

The expression (10) of dependability performance is necessary to map back to the defined dependability fuzzy sets (Fig. 2). Best-fit method [19] is used for transformation of dependability description (10) to form that which defines grade of membership to fuzzy sets: poor, average, good, excellent (Fig. 2). 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 (Fig. 2).

$$d_i(D,H_i) = \sqrt{\sum_{j=1}^{7}\left(\mu^{j}_{D} - \mu^{j}_{H_i}\right)^2},\ i = 1,\ldots,4;\ \ H_i\ =\ \{\text{excellent, good, average, poor}\} \tag{13}$$

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

Suppose $d_{i\,\min}$ (i = 1, 2, 3, 4) is the smallest among the obtained distances for *D* and let α_1, α_2, α_3 and α_4 represent the reciprocals of the relative distances between the identified fuzzy dependability description *D* and the each of the defined dependability expressions with reference to d_i . Then, α_i can be defined as follows:

$$\alpha_i = \frac{1}{d_i / di_{\min}}, \quad i = 1,2,3,4. \tag{14}$$

If $d_i = 0$ it follows that $\alpha_i = 1$ and the others are equal to zero. Then, α_i can be normalized by:

$$\beta_i = \frac{\alpha_i}{\sum_{i=1}^{4} \alpha_i}, \quad i = 1,2,3,4. \qquad \sum_{i=1}^{4} \beta_i = 1 \tag{15}$$

Each β_i (i = 1, 2, 3, 4) represents the extent to which *D* belongs to the i-th defined dependability expressions. It can be noted that if *D* completely belongs to the *i*-th expression then β_i is equal to 1 and the others are equal to 0. Thus β_i could be viewed as a degree of confidence that *D* belongs to the *j*-th reliability expressions. Final expression for dependability performance is obtained in form (according to Fig.2):

$$D = \{(\beta_1, \text{"poor"}), (\beta_2, \text{"average"}), (\beta_3, \text{"good"}), (\beta_4, \text{"excellent"})\} \tag{16}$$

3. Reliability and maintainability integration

Maintenance support (*L*) is defined by expertise judgments and it is given directly in fuzzy form (1), as opposed to reliability and maintainability which are usually given in the form of function of time, *R*(*t*) and *M(t)*. To calculate dependability (2), it is necessary to do the fuzzification of reliability function *R*(*t*) and maintainability function *M(t)* into the fuzzy numbers (11) and (12).

For determination of fuzzy numbers (11) and (12), it is necessary to:

– define relationship between classes (1 to 7) and registered periods of operation and periods of maintenance,
– define fuzzy numbers *R* and *M* to be the best approximations of functions *R*(*t*) and *M*(*t*), i.e. to define location and shape of fuzzy numbers according to classes as the measure of reliability and maintainability.

3.1. Relationship between classes and times

Recorded minimal and maximal periods in operation should be used as representatives of the seventh (the poorest) and the first (the best) classes of reliability, respectively. Theoretically it would be correct if the shortest and the longest expected time would be taken into consideration, i.e. times *t* for $R(t) \to 0$, $R(t) \to 1$, $M(t) \to 0$ and $M(t) \to 1$. However, these times are usually excluded from consideration as unrealistic.

3.2. Location and shape of fuzzy numbers

The Weibull distribution is one of the most commonly used distributions in reliability engineering because of the many shapes it attains for various values of shape parameter. It can therefore model a great variety of data and life characteristics [7]. Periods until the unexpected failures - up times could be recorded and used for determination of reliability function as two parameters Weibull distribution:

$$R(t) = e^{-(\frac{t}{\eta})^{\beta}} \tag{17}$$

where β is shape and η is scale parameter.

Similarly, for maintainability function, periods necessary for repair of damages (i.e. for return in operation readiness) – down times could be measured. According to Ivkovic [7] if there is no unplanned delay in maintenance two parameters Weibull distribution could also be used for approximation of maintainability function, as:

$$M(t) = 1 - e^{-(\frac{t}{\eta})^{\beta}} \tag{18}$$

In both cases, the mean time and standard deviation could be calculated as

Mean time

$$\bar{T} = \eta \cdot \Gamma\left(1 + \frac{1}{\beta}\right) \tag{19}$$

Standard deviation $$\sigma = \sqrt{\eta^2 \cdot \left\{\Gamma\left(1+\frac{2}{\beta}\right) - \left[\Gamma\left(1+\frac{1}{\beta}\right)\right]^2\right\}} \tag{20}$$

where Γ is gamma function.

Approximation of reliability and maintainability function could be done by triangular or trapezoidal fuzzy number. In [2] triangular fuzzy numbers were used for probability density function approximation, as a practical model for approximation of Normal distribution, for example. In this paper, gives a different approach to approximation. Dependence between parameter *β* in *R*(*t*) and *M*(*t*), and shape of fuzzy number is quite evident (Fig. 3). For the cases when Weibull distribution is inclined to Exponential distribution *(0,5 ≤ β ≤ 1,5)* [7] triangular fuzzy number is optimal, while when Weibull distribution is inclined to Normal distribution (2,5 ≤ *β* ≤ 4) [7] trapezoidal fuzzy number can be used for approximation. As the boundary value for shape parameter, *β* = 2 is adopted.

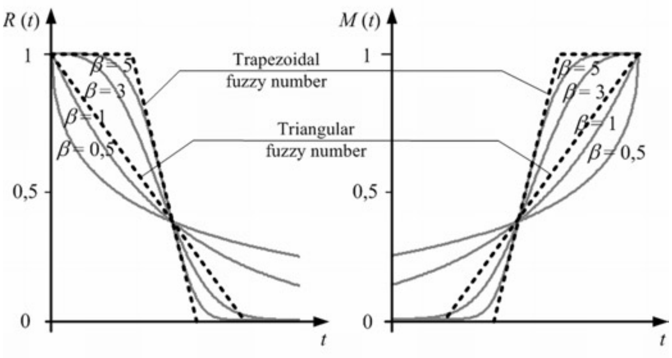

Fig. 3. Selection of fuzzy number shape according to shape parameter β

For approximation in the form of triangular fuzzy number, 3 break points have to be defined:

$$FN1 = (bp_1, bp_2, bp_3) \tag{21}$$

While the choice of mean time $\bar{T}$ for bp_2 break point is quite reasonable, selection of bp_1 and bp_3 is not so clear. The most logical choice is to connect these break points with standard deviation *σ*, as a dissipation measure, of recorded times around the mean time. For example, for Normal distribution, recorded time in the interval from [$\bar{T}$ -σ, $\bar{T}$, $\bar{T}$ +σ] covering 68,26 per cent of all recorded time, while in the case of Exponential distributions rule covering rate is almost 100 per cent [7]. For Weibull distribution does not exist in principle, such rules, but depending on the parameter *β*, it can be determined individually. Hence, triangular fuzzy number can be defined as:

$$FN1 = (\bar{T} - x_1 \cdot \sigma,\ \bar{T},\ \bar{T} + x_2 \cdot \sigma) \tag{22}$$

For the selection of scale factors x_1 and x_2 scaling method is used in this paper. This method is a sort of empirical scaling [5], it reaches scaling on the expected value level, which is itself obtained on the basis of empirical study [21] and expertise judgment [17]. Unit fuzzy number will be adopted to stand for the expected value and reliability and maintainability fuzzy set definitions [6], will be used as empirical data. On the basis of these definitions, which were used in a similar example [6], it can be asserted that symmetry is the common characteristic of majority reliability and maintainability fuzzy sets, and that the minimal width, regarding the center of fuzzy set, is $1.25 \cdot c$ (c is difference between two successive classes). Now, for the unit triangular fuzzy number (Fig. 4), scale parameters could be calculated as:

$$x_1 = x_2 = \frac{1.25 \cdot c}{\min_i \sigma_i} \qquad (23)$$

where is $\min_i \sigma_i$ the smallest registered value of standard deviation in the range of observed phenomena (different reliability/maintainability functions).

Trapezoidal fuzzy number *FN2*, as approximation of reliability/maintainability function is defined by 4 break points:

$$FN2 = (bp_1, bp_2, bp_3, bp_4) \qquad (24)$$

As in the case of triangular fuzzy set, mean time $\overline{T}$ and standard deviation σ are used for definition of break points in trapezoidal fuzzy number:

$$FN2 = (\overline{T} - y_1 \cdot \sigma,\ \overline{T} - y_2 \cdot \sigma,\ \overline{T} + y_3 \cdot \sigma.\ \overline{T} + y_4 \cdot \sigma) \qquad (25)$$

Trapezoidal fuzzy numbers in reliability/maintainability fuzzy sets in Ivezic [6], are mostly symmetrical and minimal width of trapezoid fuzzy set was ($2{,}5 \cdot c$), so the unit trapezoidal fuzzy set can be defined in the form plotted in Fig. 5.

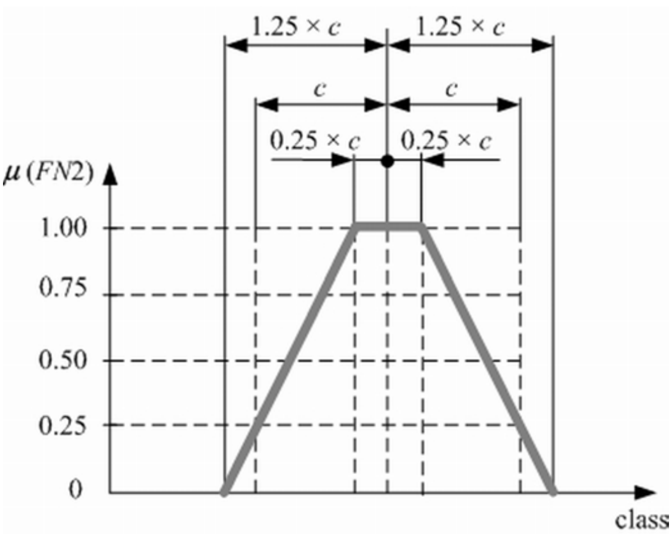

Fig. 4. Unit triangular fuzzy set

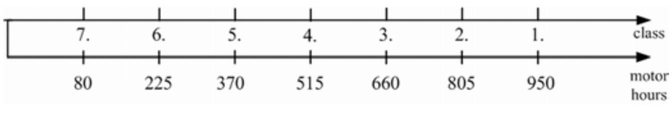

Fig. 5. Unit trapezoid fuzzy set

According to minimal standard deviation and adopted geometry of unit trapezoidal fuzzy number, scale parameters in expression (25) are calculated as:

$$y_1 = y_4 = \frac{1.25 \cdot c}{\min_i \sigma_i}, \quad y_2 = y_3 = \frac{1.25 \cdot c}{\min_i \sigma_i} \qquad (26)$$

For transformation of triangular/trapezoidal fuzzy numbers in the desirable form proposed by (11-12) intersections of obtained fuzzy numbers and ordinates of each class have to be calculated.

Proposed empirical scaling algorithm for determination of fuzzy membership function wideness can be considered as acceptable because in operations with fuzzy relations (fuzzy composition) the influence of fuzzy number with the highest degree of membership ($\mu(bp_2) = 1$ for triangular and $\mu(bp_2) = \mu(bp_2) = 1$ for trapezoidal) is the most significant [10].

3. Case study: Dependability determination of bulldozers

At the lignite open pit mine Drmno (Serbia) [8] there are more than 120 machines within the auxiliary machinery. They are very important for the smooth realization of core operation, and any unplanned absence of machines can cause enormous costs. In the auxiliary machinery, bulldozers are certainly the most important and it is therefore necessary to observe the dependability of these machines. Three types of bulldozers (B1, B2, B3[1]) operated at open pit mine Drmno and they are considered in this article.

Technical and operational characteristics of considered machines are presented below:

B1: ***Engine:*** Liebherr D 9406 TI-E – 13000 ccm, Power 242 kW – 1800 r/min; Torque 1284 Nm;
Transmission: Power shift – Hydrostatic; ***Speed**:* 11/11 km/h; ***Mass**:* 34800 kg;

B2: ***Engine**:* Cummins N14C – 15000 ccm, Power 238 kW – 1400 r/min; Torque 1647 Nm;
***Transmission**:* Power shift – Hydrodynamic; ***Speed**:* 10,6 /12,7 km/h; ***Mass**:* 36210 kg;

B3: ***Engine:*** CAT 3406E – 14600 ccm, Power 252 kW – 2386 r/min; Torque 1009 Nm;
Transmission: Power shift – Hydrodynamic; ***Speed**:* 10,6 / 13,8 km/h; ***Mass**:* 37771 kg.

3.1. Maintenance support analyses

Maintenance support (L) is defined based to expertise judgment and is given directly in fuzzy form. For the selected bulldozers maintenance support is designed as maintenance through services by licensed organizations. Generally this type of maintenance support can be considered as excellent developed maintenance support. However, the quality of its implementation is not the same for all selected bulldozers and the evaluation of maintenance support was done through the questionnaires filled up by ten maintenance engineers. For machine B1, all of the 10 engineers responded that the maintenance support is "well developed"; for machine B2 all of the ten engineers responded that the maintenance support is "excellently developed", while for machine B3 seven engineers responded with "excellently" and three responded as "well developed."

Obtained fuzzy numbers for maintenance support are:

$\boldsymbol{L}_{B1} = \boldsymbol{L}_{(well...)} = \{1/0, 2/0.5, 3/1.0, 4/0.5, 5/0, 6/0, 7/0\}$

$\boldsymbol{L}_{B2} = \boldsymbol{L}_{(exc...)} = \{1/1.0, 2/0.75, 3/0, 4/0, 5/0, 6/0, 7/0\}$

$\boldsymbol{L}_{B3} = \boldsymbol{L}_{(70\%\, exc.. \,+\, 30\%\, wel..)} = \{1/0.7, 2/0.675, 3/0.3, 4/0.15, 5/0, 6/0, 7/0\}$

1 Bulldozers: Liebher PR752 lit, DresstaTD25H, Caterpillar D8R, respectively

Calculation procedure for L_{B3} is shown in Table I

Table I. Calculating fuzzy number procedure for the case when expert estimation differs among the evaluated, as in the case of machine L_{B3}.

L_{B3}	1. class	2. class	3. class	4. class	5. class	6. class	7. class
Excellently developed 70 %	1.0 × 70 %	0.75 × 70 %	0 × 70 %	0 × 70 %	0 × 70 %	0 × 70 %	0 × 70 %
Well developed 30 %	0 × 30 %	0.5 × 30 %	1.0 × 30 %	0.5 × 30 %	0 × 30 %	0 × 30 %	0 × 30 %
Σ	**0.7**	**0.675**	**0.3**	**0.15**	**0**	**0**	**0**

3.2. Reliability and maintainability analysis

Failures in undercarriage running wheels are characteristic for bulldozer B1, while gear-boxes and torque mechanisms failures are characteristic for B2 and B3, respectively. Algorithm for dependability function determination is well known, and in Table II only final reliability functions for different bulldozer types are presented. According to small number of available data median ranking and Bernard's approximation was used.

Table II. Reliability functions for different bulldozers

Mach.	UP TIME [motor hours]	Reliability function	$\bar{T}$ [motor hours]	σ [motor hours]
B1	187, 710, 822, 921	$R(t)=e^{-(\frac{t}{828,43})^{1,24}}$	773,43	647,27
B2	80, 100, 214, 386, 421, 622, 831	$R(t)=e^{-(\frac{t}{434,83})^{1,18}}$	410, 97	363, 13
B3	118, 480, 622, 710, 950	$R(t)=e^{-(\frac{t}{712,54})^{1,20}}$	670,23	580,96

For maintainability function, periods necessary for return in operation readiness are measured for all three types of bulldozers. Maintainability function is determined in Table III.

Table III. Maintainability functions for different bulldozers

Mach.	DOWN TIME [hours]	Maintainability function	$\bar{T}$ [hours]	σ [hours]
B1	6.8 ; 10; 10.5; 11;	$M(t)=1-e^{-(\frac{t}{10,54})^{4,23}}$	9,58	2,55
B2	8,0; 10,2; 10,9; 11,4; 12,0; 13,7; 15,0;	$M(t)=1-e^{-(\frac{t}{12,57})^{5,20}}$	11,57	2,55
B3	2,5; 3,5; 4,2; 5,1; 6,2;	$M(t)=1-e^{-(\frac{t}{4,84})^{2,97}}$	4,32	1,59

3.2.1. Relationship between classes and times

For the analyzed bulldozers, 950 hours and 80 hours are the longest (machine B3) and the shortest (machine B2) recorded periods in operation. Relationship between classes and periods in operation is presented in Fig. 6.

Theoretical cases ($R(t) \to 0$ and $R(t) \to 1$) are excluded and justification for this approximation lies in the fact that, for example $R(t) = 0{,}0036$ means that some machine works about 3000 hours, i.e. about triple more than the largest recorded period in operation, or $R(t) = 1$ means that some machine is completely out of use.

The same logic is used for determination of relationship between periods in maintenance and classes of maintainability. For the first class i.e. the most quality is used period of 2.5 hours, while the seventh class corresponds to 15 hours in maintenance.

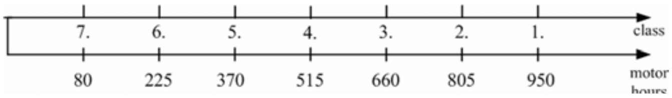

Fig. 6. Dependence of periods in operation (motor hours) and classes of reliability

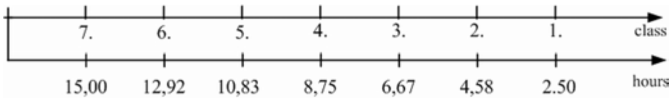

Fig. 7. Dependence of periods in maintenance (hours) and classes of maintainability

3.2.2. Location and shape of fuzzy numbers

According to obtained reliability functions (Table II) shape parameters are: 1.18, 1.20 and 1.24, while in the case of maintainability functions (Table III), this parameter has the next values: 5.20, 2.97 and 4.23. Hence, triangular fuzzy numbers will be used for reliability functions, while maintainability functions will be approximated by trapezoidal fuzzy numbers.

Scale parameters are calculated as:

$$x_1 = x_2 = \frac{1.25 \cdot c}{\min\limits_i \sigma_{Bi}} = \frac{(1.25 \cdot 145)\ \text{motor hours}}{363.13\ \text{motor hours}} = 0.499$$

$$y_2 = y_3 = \frac{0.25 \cdot c}{\min\limits_i \sigma_{Bi}} = \frac{(0.25 \cdot 2.08)\ \text{hours}}{1.59\ \text{hours}} = 0.328$$

$$y_1 = y_4 = \frac{1.25 \cdot c}{\min\limits_i \sigma_{Bi}} = \frac{(1.25 \cdot 2.08)\ \text{hours}}{1.59\,\text{hours}} = 1.638$$

According to (21-23) and (24-26) scale parameter and fuzzy numbers, as the represents of reliability and maintainability of for selected machines, are calculated and plotted at Fig. 8–10.

R_{B1} = (450.4, 773.4, 1096.5); R_{B2} = (229.7, 411.0, 592.2); R_{B3} = (380.2, 670.2, 960.2);

M_{B1} = (5.4, 8.7, 10.4, 13.8); M_{B2} = (7.4, 10.7, 12.4, 15,7); M_{B3} = (1.7, 3.8, 4.8, 6.9);

From Figures 8-9 the values of intersection of fuzzy numbers B1, B2, B3, and ordinate for each class (from 1 to 7) could be taken, as it is explained at Fig. 10. These values determine reliability and maintainability fuzzy numbers in desirable form (11-12):

$\boldsymbol{R}_{B1}$ = {1/0.45, 2/0.90, 3/0.65, 4/0.20, 5/0, 6/0, 7/0};
$\boldsymbol{R}_{B2}$ = {1/0, 2/0, 3/0, 4/0.43, 5/0.77, 6/0, 7/0};
$\boldsymbol{R}_{B3}$ = {1/0.04, 2/0.54, 3/0.96, 4/0.46, 5/0, 6/0, 7/0};

$\boldsymbol{M}_{B1}$ = {1/0, 2/0, 3/0.38, 4/1.00, 5/0.88, 6/0.25, 7/0};
$\boldsymbol{M}_{B2}$ = {1/0, 2/0, 3/0, 4/0.41, 5/1.00, 6/0.85, 7/0.22};
$\boldsymbol{M}_{B3}$ = {1/0.38, 2/1.00, 3/0.12, 4/0, 5/0, 6/0, 7/0};

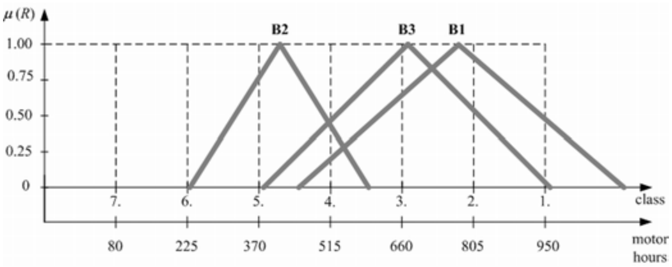

Fig. 8. Reliability fuzzy numbers for selected bulldozers

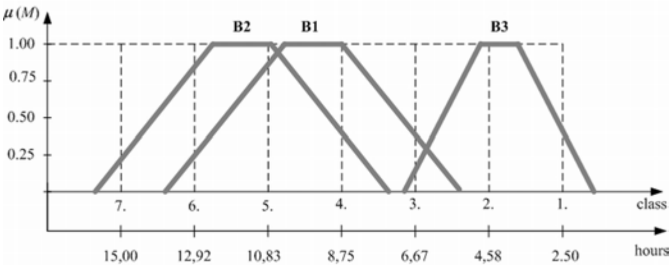

Fig. 9. Maintainability fuzzy numbers for selected bulldozers

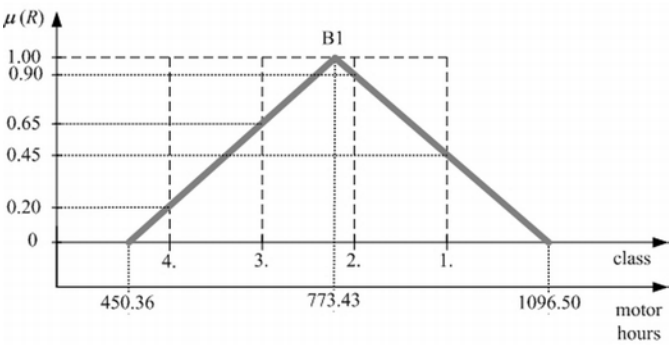

Fig. 10. Reading the coordinates for reliability of bulldozer B1

3.3. Bulldozers dependability determined by fuzzy model

For dependability determination, equation (2) is used. Calculation in detail is presented only for machine B1.

$$\mu_{L(B1)} = (0, 0.5, 1, 0.5, 0, 0, 0);$$

$$\mu_{R(B1)} = (0.45, 0.9, 0.65, 0.2, 0, 0, 0);$$

$$\mu_{M(B1)} = (0, 0, 0.38, 1, 0.88, 0.25, 0);$$

The first step of max-min composition (3-9) is used, as follows:

$$\mu_{M \times L} = (\mu^{ij}_{M \times L})_{7 \times 7},$$

$$\mu^{ij}_{M \times L} = \min(\mu^{j}_{M}, \mu^{j}_{L}) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.38 & 0.38 & 0.38 & 0 & 0 & 0 \\ 0 & 0.5 & 1 & 0.5 & 0 & 0 & 0 \\ 0 & 0.5 & 0.88 & 0.5 & 0 & 0 & 0 \\ 0 & 0.25 & 0.25 & 0.25 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

For

$$\mu^{j}_{D} = \max(\min(\mu^{1}_{R}, \mu^{1j}_{M \times L}), \ldots, \min(\mu^{7}_{R}, \mu^{7j}_{M \times L})), \; j = 1, \ldots, 7.$$

Dependability of machine B1 is estimated as:

$$\mu_{D(B1)} = \mu_{R \circ M \times L} = (\mu^{j}_{D})_{1 \times 7} = (0, 0.38, 0.38, 0.38, 0, 0, 0)$$

Otherwise stated, in form (10): D_{B1} = {1/0, 2/0.38, 3/0.38, 4/0,38, 5/0, 6/0, 7/0}

Dependability estimation (10) for other two types of bulldozers is obtained as:

D_{B2} = {1/0.77, 2/0.75 3/0, 4/0, 5/0, 6/0, 7/0}
D_{B3} = {1/0.54, 2/0.54, 3/0.3, 4/0.15, 5/0, 6/0, 7/0}

Transformation of obtained "classes related" fuzzy sets to linguistic dependability fuzzy sets by using best-fit method is straightforward and explained in detail in (13-16). Best-fit method and proposed dependability fuzzy set (Fig. 2) give the final dependability evaluation for the Machine B1 in the form (13):

$$d_1(D, excellent) = \sqrt{\sum_{j=1}^{7} \left(\mu^{j}_{D} - \mu^{j}_{iexcellent}\right)^2} = 1.19403$$

$$d_2(D, good) = \sqrt{\sum_{j=1}^{7} \left(\mu^{j}_{D} - \mu^{j}_{good}\right)^2} = 0.64475$$

$$d_3(D, average) = \sqrt{\sum_{j=1}^{7} \left(\mu^{j}_{D} - \mu^{j}_{average}\right)^2} = 1.16863$$

$$d_4(D, poor) = \sqrt{\sum_{j=1}^{7} \left(\mu^{j}_{D} - \mu^{j}_{poor}\right)^2} = 1.41269$$

Where is according to Fig.2.:

$\mu^{j=1to7}_{excellent} = (1, 0.75, 0, \ldots, 0)$; $\mu^{j=1to7}_{good} = (0, 0.25, 1, 0.5, 0, 0, 0)$;
$\mu^{j=1to7}_{average} = (0, 0, 0, 0.5, 1, 0,25, 0)$; $\mu^{j=1to7}_{poor} = (0, \ldots, 0, 0.75, 1)$;

For $d_{i\,min} = d_2$:

$$\alpha_1 = \frac{1}{d_4 / d_2} = 0.53998, \qquad \beta_1 = \frac{\alpha_4}{\sum_{i=1}^{4} \alpha_i} = 0.21192$$

$$\alpha_2 = \frac{1}{d_3 / d_2} = 1.00000, \qquad \beta_2 = \frac{\alpha_3}{\sum_{i=1}^{4} \alpha_i} = 0.39245$$

$$\alpha_3 = \frac{1}{d_2 / d_2} = 0.55171, \qquad \beta_3 = \frac{\alpha_2}{\sum_{i=1}^{4} \alpha_i} = 0.21652$$

$$\alpha_4 = \frac{1}{d_1 / d_2} = 0.45640, \qquad \beta_4 = \frac{\alpha_1}{\sum_{i=1}^{4} \alpha_i} = 0.17911$$

Finally, B1 dependability in linguistic fuzzy form:
$\boldsymbol{D}_{B1}$ = {(β_4, "poor"), (β_3, "average"), (β_2, "good"), (β_1, "excellent")} =
= {(0,17911, "poor"), (0,21652 "average"), (0,39245, "good"),(0,21192, "excellent")}

For machines B2 and B3, dependability is (Fig. 11) :

$\boldsymbol{D}_{B2}$ = {(0,09655, "poor''), (0,10133, "average''), (0,11003, "good''),(0,69209, "excellent'')}
$\boldsymbol{D}_{B3}$ = {(0,16419, "poor''), (0,18100, "average''), (0,24820, good''), 0,40661, "excellent'')}

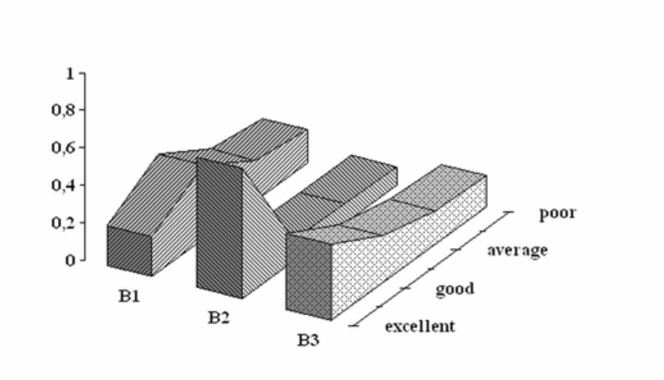

Fig. 11. Dependability performances of different bulldozers types

In this way, bulldozer with lowest dependability, i.e. availability, B1 has been identified. This bulldozer has mostly good dependability, while the two others are mostly excellent. Machine B1 also has the worst assessed maintenance support.

4. Conclusion

A new approach is proposed in this paper for maintenance support analyses in the framework of the dependability, based on rules of fuzzy algebra. In this approach, maintenance support is evaluated using expertise judgment and fuzzy sets. Thereby, it was necessary to differentiate between possible modes of organizing maintenance support, and to introduce measurement unit that represents quality level of maintenance support organization. The paper presents four possible organizing modes for maintenance support: maintenance through services by producers or licensed organizations, maintenance developed by consumer, maintenance by consumers' request and without organized maintenance. Each of them is conditionally defined, depending on classes as measurement unit. In order to get the necessary overview of the level of maintenance support organization, it is necessary to grasp it in the context of availability of the analyzed technical system, namely of dependability as a measure of availability.

Since dependability is influenced not only by maintenance support, but also by reliability and maintainability, which are usually represented as time functions, it is necessary to define fuzzification model, which will approximate in the best way these functions into a fuzzy form. That fuzzy form is complementary with fuzzy form of maintenance support. Fuzzification process is completed based on the principle of empirical scaling which as the assumption takes that Weibul distribution successfully covers all phenomena related to failures of realistic technical system, and introduces fuzzy set on the base of empirical study, apropos establish relation between measured times and their standard deviations and expected form of reliability/ maintainability fuzzy sets. In this way all necessary conditions are accomplished to calculate dependability using rules of fuzzy algebra.

Dependability assessment itself is of great importance for the identification of weak points from the standpoint of quality of maintenance and reliability. In addition, it is very important to find their interdependence and the influence on dependability. This article shows a methodology that effectively considers primarily the level of maintenance support and provides the ability to integration on the level of dependability, on the basis of actual working conditions as a result of empirical studies. The proposed methodology was tested on the example of three bulldozers of different manufacturers, working in a lignite mine.

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