Dependability as criteria for bucket wheel excavator revitalization

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This study presents a model for dependability performance analysis of bucket wheel excavators using fuzzy sets. Dependability is overall indicator for quality of service, and considers simultaneously reliability, maintainability and maintenance support. As bucket wheel excavator is a technical system with a complex hierarchical structure, synthesis of information given in fuzzy form from the level of components to subsystems, functional systems and whole bucket wheel excavator is necessary. For synthesis processes, evident reasoning theory is used.

Keywords: Bucket wheel excavator, Dependability, Evidential reasoning, Fuzzy sets

Introduction
Bucket wheel excavators (BWE) are considered as one of the most complex machines and characterized by continual development and modernization during their lifetime. In Serbia, almost half of 30 BWEs that are in service on open step mines at Kolubara and Kostolac are over 30 years old, and significant resources are engaged in their modernization and revitalization. Bolotin reported few groups of methods for prediction of remaining service life of machines. Coefficient of time efficiency has been mainly used indicator of BWE quality of service. However, this indicator has not been suitable to find out reasons for inadequate quality of service of BWE, to make distinctions between downtimes due to problems in production management or BWE construction, or for identification of weak points in BWE structure. Dependability concept has been introduced through ISO-IEC standards as the most complete concept that presents the most complete quality of service measure. A model developed for dependability evaluation is based on fuzzy sets theory. However, complex, hierarchical structure of BWE has not been treated by this model, and synthesis of information from different hierarchical levels is not clear. In recent years, evidential reasoning approach has been applied to different fields such as selection of engineering design, organizational self-assessment, safety and risk assessment and supplier assessment, because it could preserve qualitative feature of subjective attribute during a process of aggregation.

This study presents Evidential Reasoning (ER) theory for synthesis of dependability performance (DP) from components to subsystems, functional systems and whole BWE.

Experimental Section
Analysis of BWE Components Dependability Performance based upon Fuzzy Sets Theory

DP can be calculated for any technical system or their components by utilization of fuzzy sets theory and fuzzy propositions rules. For analysis of dependability indicators [reliability (R), maintainability (M) and maintenance support (L)] of BWE components, fuzzy sets have to be defined. R is usually expressed as interval 0...1 or 0...100%. Same situation is with M. L is inherently linguistic, immeasurable variable. For representing a reliability performance, model of five linguistic variables (highly reliable, very reliable, averagely reliable, acceptably reliable and unreliable) is given as appropriate reliability fuzzy sets (Fig. 1). Fuzzy set “highly reliable” (Fig. 1) represented as triangular, in a way that its membership degrees to class 1 equal to 1 given as \( \mu_1 = 1 \), and membership degrees to class 2 equal to 0.25 (\( \mu_2 = 0.25 \)). This fuzzy set represents highest reliability, hence positioned in the range of first and second classes as those of highest quality, and is not spread over other classes (\( \mu_3 = \mu_4 = \mu_5 = \mu_6 = \mu_7 \)).
= 0). Other fuzzy sets are positioned in lower quality classes (closing with 7th class, Fig. 1).

Reliability is theoretically expressed as probability of operation without any failure during period $t$, as time function $R = f(t)$. Seven classes adopted for measuring units of reliability quality level could be easily split to cover time intervals between 0 and $t$, from $f(t) = 0$ to $f(t) = 1$. However, in that case, it would be necessary to complete research for reliability functions determination of considered BWE. In reliability examinations, a lot of significant information can be obtained as experts’ estimations and judgments. In proposed model, experts’ opinions can be used for determination of membership degrees ($\mu$) to classes. For example, if opinion of selected authority is that reliability performance of some BWE component can be estimated as average reliable, it means that reliability fuzzy set for that component is to be (Fig. 1):

$$R_{\text{aver.rel.}} = \{1/\mu(1), 2/\mu(2), \ldots, 7/\mu(7)\} = \{1/0, 2/0, 3/0.5, 4/1.0, 5/0.5, 6/0, 7/0\} \quad \ldots(1)$$

Fuzzy set average reliable is spread neither over the range of first and second classes, nor sixth and seventh ($\mu(1) = \mu(2) = \mu(6) = \mu(7) = 0$), but membership degree to third and fifth class is 0.5, and to fourth class is 1 ($\mu(3) = 0.5; \mu(4) = 1; \mu(5) = 0.5$).

Maintainability is related to adjustment of BWE design for maintenance actions. Maintainability performance can be evaluated as probability function $[M = f(t_0)]$ 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 of fuzzy sets, five expressions can be defined as follows: i) Optimal for maintenance % this linguistic variable is concerned to practically automated maintenance systems (without any additional utilization of tools, accessibility of locations are without influence at maintenance operation, etc.); ii) Easy maintenance % this linguistic variable practically includes the most favorable cases for complex mechanical systems; iii) Average maintainability % this is the most often case within complex mechanical systems. Compared with previous variable it implicated somewhat more complicated maintenance operation and/or more location that is inaccessible; iv) Complicate for maintenance % technologically more complicated but predictable maintenance operations (for example tendency to rust); and v) Hard for maintenance % beside high technological complexity, unpredictable situations during the maintenance operation can usually be expected.

At the same time, fuzzy set “optimal for maintenance” is spread over the range of first and second classes, so that to the first one it belongs with membership degree $\mu(1) = 1$, and to second class with $\mu(2) = 0.5$ (Fig. 2). Four remaining fuzzy sets are defined in the same way (Fig. 2). By analysis of maintenance conditions at Serbian open pit mines, four maintenance support systems can be identified as: i) Maintenance through services by producers or licensed organizations; ii) Maintenance developed by consumer; iii) Maintenance as per consumers’ request; and iv) Without organized maintenance.

According to four identified maintenance policy concepts, four linguistic variables (excellently developed maintenance support, well developed maintenance support, limited maintenance support and absence of maintenance support) for maintenance support can be introduced (Fig. 3). Again, classes are used as measuring units for representing maintenance support quality (in interval 1 ... 7). For two more efficient concepts, linguistic variables excellently developed and well developed are established 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 does not necessarily mean that maintenance support is excellently developed. For remaining two less efficient maintenance support options linguistic variables, limited and absent are introduced. These two maintenance policies are quite easier for distinguishing and strict identification with linguistic variables is evident. Also, outer linguistic variables excellently developed and absence are not mutually symmetrical (Fig. 3). Thereby, fuzzy set “excellently developed” covers highest quality first class ($\mu_{(1)} = 1$) and second class ($\mu_{(2)} = 0.75$), and remaining three fuzzy sets cover lower quality classes (Fig. 3).

Second step within dependability determination is to complete synthesis of estimations for $R$, $M$ and $L$ to dependability ($D$) level. Thereby, four dependability fuzzy sets are considered (excellent, good, average, and poor). Fig. 4 shows distribution of these fuzzy sets among classes, in a manner also described for fuzzy sets of $R$, $M$ and $L$. Synthesis has been done according to Max-Min fuzzy composition:

$$D = R \circ (M \times L) \ldots(2)$$

Conjunction “and”, which is product with operator ($\circ$), is used in cases when fuzzy sets and/or relations simultaneously exist and there is no functional conditionality between them. This product is used for integration of performance that describes times in operation ($R$) and failure ($M \times L$). Technological dependency between indicators of $M$ and $L$ certainly exists, but doesn’t exist for indictors of $R$ and ($M, L$). These two maintenance indicators can be even technologically dependent and Cartesian product ($\times$) is used for their integration.

Final expression for DP, at the level of selected component $i$ (considered as the lowest level in hierarchical structure of BWE), is obtained as

$$D_i = \{(\beta_{i1}, “poor”), (\beta_{i2}, “average”), (\beta_{i3}, “good”), (\beta_{i4}, “excellent”)\} \ldots(3)$$

**System Modeling and Synthesis of Dependability Evaluation by Hierarchical Evidential Reasoning (ER)**

Proposed model of DP can also be applied to hierarchically higher levels at the structure of BWE. However, in that case subjectivity of experts’ estimations will be more expressed and evaluated DP can be accepted with more reserve. Therefore, it is necessary to make a model that would synthesize dependability ratings from lower to higher levels in the hierarchical structure of entire BWE. It is going to be done by utilization of hierarchical ER algorithm.

Decomposition has to be implemented to as low constructive levels as it is possible, but parts and elements at considered levels has to have clearly defined function. Analysis of BWE DP should be carried out by taking into account hierarchical structure (Fig. 5). Partial evaluations of components’ DPs has to be aggregated to upper levels of subsystems, systems and finally to BWE DP. To provide a reasonable way of dealing with such problems, a hierarchical evaluation process has to be used. Evaluation process based on ER algorithm is based on evidence theory, which can model narrowing of hypothesis set with accumulation of evidence. In Eq. (3), whether dependability of a subsystem is ‘excellent’, ‘good’, ‘average’ or ‘poor’ would be regarded as a hypothesis. Obtained dependability evaluation of a component may be viewed as a single evidence part. If DP associated with a component has been evaluated, to a certain extent as ‘good’, then DP of associated subsystem would be to some degree ‘good’. Hierarchical evaluation process provides a systematic way of synthesizing such uncertain dependability evaluations of several components to produce an evaluation for related
subsystem dependability. Same procedure is used for evaluation of DP at higher hierarchical levels (Fig. 5).

To apply evidence theory, all linguistic variables for expression of DPs must be defined as distinct grades. Thus, if one of the variables is absolutely confirmed, no others must be confirmed at all. If > 1 variable is confirmed simultaneously, total degree of confidence must be 1 or < 1. Additionally, variables must cover all possible grades that dependability analyst may need to use for evaluation of DP. Linguistic variables as fuzzy sets satisfy requirements of exclusiveness and exhaustiveness. This enables to employ ER2\textsuperscript{11} algorithm in synthesis of uncertain DP evaluations generated for components using fuzzy sets. Such an evaluation is generated by synthesizing given DP evaluations of relevant components. In a similar way, DP evaluation of upper level in hierarchical structure of BWE (Fig. 5) can be determined based to DP evaluation of the first, previous lower level. Thus, ER algorithm is to be implemented to subsystems’ levels for evaluation of systems’ DP and it is to be implemented to the systems’ levels for evaluation of DP of entire system – BWE itself.

Results and Discussion
Case Study: Bucket Wheel Excavator SCHRS 630, Open Pit Mine Kolubara – Tamnava West Field, Serbia

BWE consists of large number\textsuperscript{12} of components assembled in functional systems, proper operation of which is necessary for efficient work of entire BWE. Proposed procedure of dependability analysis based upon fuzzy sets theory evaluates DPs for every component of BWE. Tanasijevic\textsuperscript{13} performed complete dependability analysis of all BWE SchRS 630 components. This study presents results related to belt conveyer drive unit at system for transport of materials. This BWE is employed at open pit mine Kolubara – Tamnava West Field (Serbia) and enquiry about $R$, $M$ and $L$ was realized by engineers at open pit mine.

Components in belt conveyer drive unit are electric engine (140 kW), clutch (hydraulodynamics + elastic), mechanical brake ($\Phi 500-160$), gear-box (cone – cylindrical) and locking assembly (between hollow shaft of gear-box and shaft of drive pulley, 4 x 130/180, model with four cones). For these components dependability indicators related to $R$, $M$ and $L$ are estimated (Table 1). Estimation was formed according to experts’ judgments, and their dominant orientation to some of proposed fuzzy sets (Figs 1-3) was adopted for introduction to model. In other words, fuzzy set that was accepted “in the greatest extent” was a little bit modified according to degree of acceptance. For example, when reliability of electric engine was being assessed, expertise judgments were asked from 10 engineers and technicians employed in production and maintenance of excavators. Five of them said that reliability is at the level between 4\textsuperscript{th} and 3\textsuperscript{rd} class (Averagely and Very reliable), while three of them said it is between 4\textsuperscript{th} and 5\textsuperscript{th} class (Averagely and Acceptable reliable) and two of them said it is only the 4\textsuperscript{th} class (Averagely reliable). Membership degree to fourth class (100%) is $\mu_4 = 1$, to third class $\mu_3 = 0.5$ and that to fifth class $\mu_5 = 0.3$. Using Eq. 1, this can be written as $R_{(el.eng.)} = \{1/0, 2/0, 3/0.5, 4/1.0, 5/0.3, 6/0, 7/0\}$. This equation is closest to fuzzy set average reliability...
Methods of collecting and processing of other data are reported. Based to max-min composition, dependability estimations of analyzed components are obtained and dependability fuzzy sets are determined by using best-fit method (Table 2). Clutch and locking assembly are components with best DP. DP of three other components is considerably lower and differences between grades of membership to different fuzzy sets are significantly lower. DP of mechanical brake is evaluated as excellent in greatest degree (33.0%). Grade of membership to “good” dependability fuzzy set is greatest in the case of gear-box, while DP of electric engine is evaluated equally as good and average.

Gear box and electric engine are potential weak points at belt conveyer drive unit. Relatively insufficient reliability is main reason for low DP of electrical engine. Unpredicted number of rapid failures (overheating) of electric engines has been noticed during the last years. These failures are repeated regardless of repairs and maintenance. DP is not dominantly poor due to existence of workshop for electric engine maintenance at the open pit mine Kolubara and domestic production of electric engine itself. However, some modifications in design or changes of engine type are necessary. In case of gear-box, maintainability can be identified as the reason for lower dependability (Table 1).

Simplest way for verification of obtained results is statistical analysis of availability, like measure of DP, i.e. allocations of down-time by analyzed components. During 2003-2007, belt-conveyer failures have been a reason for 5.2% of total BWE SchRS 630 mechanical subsystems down-time. Sharing of drive unit failures have been 16% and for components, as follow: electric engine, 51.3%; mechanical brake, 19.8%; and gear-box, 28.9%. However, statistical analysis that proved DPs cannot help in identification of reasons for loses in availability, and nature of fuzzy approach is to offer such analysis.

According to different constructive and functional parts, decomposition of BWE has been done (Fig. 5). Systems for control and electro supply systems have not been included in dependability evaluation because of their significant difference in design. By application of proposed model for dependability synthesis based to ER algorithm, DP at the level of sub-system – drive unit has been determined as:

\[ D = \{ (0.1662, ‘‘poor’’), (0.1799, ‘‘average’’), (0.2063, ‘‘good’’), (0.4475, ‘‘excellent’’) \} \]
Drive unit, which is one of sub-systems in the system for materials transport, includes four sub-systems (rotating elements, main structure, rubber belt with steel core and lubrications system). DPs for these sub-systems were conducted similarly as in the case of drive – unit (Table 3); full analysis of all BWE’s components is reported\(^\text{13}\). DP for materials transport system was conducted by implementation of ER-algorithm as

\[D = \{(0.1334, \text{’poor’}), (0.1447, \text{’average’}), (0.2162, \text{’good’}), (0.5056, \text{’excellent’})\}\]

Same procedure was implemented\(^\text{13}\) to all BWE’s sub-systems and dependability fuzzy sets for mechanical BWE’s systems (Table 4). Finally, DP for BWE can be determined as

\[D = \{(0.1334, \text{’poor’}), (0.1447, \text{’average’}), (0.2162, \text{’good’}), (0.5056, \text{’excellent’})\}\]

Graphical interpretation of obtained dependability (Fig. 6) is excellent indicator for dependability trend, which for selected BWE comes toward excellent. Such evaluation of overall BWE SchRS 630 dependability is in correlation with measured availability of this machine according to ratio of up time and downtime. For present BWE, this parameter is 0.47 on the average, what is over the usual values for other BWEs at Serbian lignite mines\(^\text{14}\). If proposed procedure for BWE evaluation is applied simultaneously to several BWE, obtained results could be used as criteria for comparison and definition of sequence of their revitalization.

Beside DP evaluation for whole BWE, proposed approach provides information about impacts of BWE’s functional systems’ DP to overall estimation. Fig. 7 represents graphical interpretation of Fig. 4. Obviously, that system for digging is “critical” at BWE structure as its DP is “average” as dominant, namely DP is at its fullest extent of 0.7420 (practically at the level of 74.20% regarding overall assessment) on average, which is a fuzzy set that (Fig. 4) refers to lower quality classes of same dependability. Other systems on BWE are at fullest extent either “good” or “excellent”. For example, accessory and main structure are at fullest extent 0.8299 assessed as “excellent”. Detail inspection of system’s sub-systems and further, their components could be implemented to find “weak” point or points at BWE.

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### Table 3 — Dependability estimation for sub-system at System for transport of materials

<table>
<thead>
<tr>
<th>Sub-system</th>
<th>(D)</th>
<th>(\lambda)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive unit</td>
<td>{(0.1662, ‘poor’), (0.1799, ‘average’), (0.2063, ‘good’), (0.4475, ‘excellent’)}</td>
<td>λ=0.30</td>
</tr>
<tr>
<td>Rotating elements</td>
<td>{(0.1715, ‘poor’), (0.1829, ‘average’), (0.2108, ‘good’), (0.4348, ‘excellent’)}</td>
<td>λ=0.60</td>
</tr>
<tr>
<td>Main structure</td>
<td>{(0.1715, ‘poor’), (0.1829, ‘average’), (0.2108, ‘good’), (0.4348, ‘excellent’)}</td>
<td>λ=0.80</td>
</tr>
<tr>
<td>Rubber belt</td>
<td>{(0.0478, ‘poor’), (0.0498, ‘average’), (0.0557, ‘good’), (0.8466, ‘excellent’)}</td>
<td>λ=0.40</td>
</tr>
<tr>
<td>Lubrications system</td>
<td>{(0.1029, ‘poor’), (0.1285, ‘average’), (0.6532, ‘good’), (0.1154, ‘excellent’)}</td>
<td>λ=0.25</td>
</tr>
</tbody>
</table>

where \(\lambda\) is normalized relative weight, \(0 \leq \lambda \leq 1\)

### Table 4 — Dependability estimation for system at BWE

<table>
<thead>
<tr>
<th>System</th>
<th>(D)</th>
<th>(\lambda)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System for digging</td>
<td>{(0.0867, ‘poor’), (0.7420, ‘average’), (0.0938, ‘good’), (0.0774, ‘excellent’)}</td>
<td>λ=0.76</td>
</tr>
<tr>
<td>System for transport of materials</td>
<td>{(0.1334, ‘poor’), (0.1447, ‘average’), (0.2162, ‘good’), (0.5056, ‘excellent’)}</td>
<td>λ=0.67</td>
</tr>
<tr>
<td>System for transport of excavator</td>
<td>{(0.1727 ‘poor’), (0.2497, ‘average’), (0.3815, ‘good’), (0.1960, ‘excellent’)}</td>
<td>λ=0.60</td>
</tr>
<tr>
<td>System for boom lifting</td>
<td>{(0.1428, ‘poor’), (0.1550, ‘average’), (0.5221, ‘good’), (0.1799, ‘excellent’)}</td>
<td>λ=0.80</td>
</tr>
<tr>
<td>System for slewing of superstr</td>
<td>{(0.0864, ‘poor’), (0.1029, ‘average’), (0.7134, ‘good’), (0.0971, ‘excellent’)}</td>
<td>λ=0.70</td>
</tr>
<tr>
<td>Main structure</td>
<td>{(0.0530, ‘poor’), (0.0553, ‘average’), (0.0616, ‘good’), (0.8299, ‘excellent’)}</td>
<td>λ=0.80</td>
</tr>
<tr>
<td>Accessory structure</td>
<td>{(0.0530, ‘poor’), (0.0553, ‘average’), (0.0616, ‘good’), (0.8299, ‘excellent’)}</td>
<td>λ=0.20</td>
</tr>
</tbody>
</table>
structure. At the end of that inspection chain are $R$, $M$ and $L$ performances for every component.

**Conclusions**

Proposed model for evaluation of DP of components at BWE, based on fuzzy sets and ER theory, completely tries to absorb expertise opinions and judgments given in linguistic forms. This form is found as the most suitable for introduction of knowledge and experiences accumulated during BWE design, operation and maintenance, as well as related to BWE structure and its logistic characteristics. The model output is within linguistic, continual form and thus, provides a multidimensional character to evaluation of BWE. Presented model can be used as a simple tool for fast estimation of quality of service for BWE, based to experts’ judgments and estimations, but also for its in-depth analysis regarding to design, constructive, maintenance and logistic characteristics. Proposed synthesis process could be useful in weak point identification at BWE, in comparison of several BWEs at the same mine or in decision about sequence of BWE revitalization.

**References**