Integrated system of criteria for determining operational maintenance of forest and agricultural machinery

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Abstract. Maintenance of forestry and agricultural machines, in addition to their configurations, is facing many challenges, one of them being extensive fragmentation over territories, which creates conditions for multiple practices to keep equipment operational, starting with field conditions and ending with specialized enterprises. The choice of the most efficient option in terms of location and technology (with due account for varying structural complexity of functional units) in order to ensure the best quality and cost-effectiveness of maintenance and repair is an important task in improving the efficiency of operating conditions, and, therefore, of the entire production that rests on them. The paper discusses a set of interrelated provisions to provide a rationale for factors characterizing the efficiency of practices to keep forestry and agricultural machines in satisfactory operational condition. The paper focuses on a comparative assessment of the ease with which these machines can be maintained and repaired while being in operation, as well as on predictions of maintainability indicators at the design stage to ensure their competitiveness and economic efficiency.

1. Introduction
The wider objective set by modern management of agricultural and forestry production is to maximize profit. The amount of profit is generally determined by cost and price difference. The cost of maintenance of equipment used account for up to one third in the cost of a product [1]. The least costly maintenance requires monitoring the factors it is affected and subsequent effective decision making [2]. In modern market conditions, those machines and equipment are more in demand, which are maximally adapted to maintenance, repair and operations (MRO) that are time-, labor- and money-consuming [3-6]. To produce forestry and agricultural machines that meet these requirements, it is necessary to assess the level of operational availability and maintainability of existing machines with the identification of directions for improving it [7–10].

Operational maintainability of a machine is referred to as a set of properties that determine its adaptability to achieving optimal costs in the production, maintenance and repair of machines [8, 10, 11].

Operational maintainability (OM) is the ability of a machine, under stated conditions of cost of labor, materials, time and funds, to be retained in or restored to a state in which it can perform its required functions [9]. What is more, operational maintainability depends on the conditions for all types of maintenance and repairs, which determine the economic efficiency of operational conditions of machines [1, 10, 11].
Today, the flow of imported equipment that is rather costly is significantly increasing. Obtaining an economic effect from the use of this equipment depends on the state of factors and indicators influencing its operational maintainability, the assessment of which will allow the selection of the most efficient machines [11].

The development of domestic forestry and agricultural machinery, the level of operational adaptability of which should not be lower than the level of foreign OA, is relevant. Imported equipment is reliable, efficient and in demand in the market, despite its high cost. Obtaining an economic effect from the use of this machinery by individual enterprises often leads to huge economic losses at the state level, caused by shutdowns of domestic machine-building enterprises, staff redundancy, an increase in the export of raw materials for purchased foreign equipment [3].

Benchmark analysis of operational maintainability of products (OMP) across the entire range of factors is relevant and important for both the manufacturer and the consumer [8, 10].

Operational maintainability of machines, like other properties they feature, is a function of design, production and operational factors. The profile of each of these groups of factors, their effect on OM characteristics are determined by the purpose and design properties of machines, operational conditions, maintenance and repair [7, 8, 10].

Let us consider these factors as exemplified by logging machines (LM), presenting them in a form of an “Aims and tasks tree for assessing and improving the OM and improving the efficiency of LM” in Fig. 1.

The paper deals with a study and assessment of the effect that one of the operational factors has on operational maintainability of an item through one-way analysis of variance (one-way ANOVA).

2. Material and methods

A study into the significance of the effect each factor has on a target attribute (property) involves partitioning the total variance that characterizes variability of an attribute resulting from changes in a set of factors, into a sum of variances caused by the effect of each factor.

The total variance can be expressed in the following form [9,11]:

$$
\sigma_t^2 = \sum_{i=1}^{l} \alpha_i \sigma_i^2 (Y) + \sigma_{\epsilon r}^2 (Y),
$$

where $Y$ is an attribute addressed (maintainability, as a sign of operational availability);

$\sigma_i^2 (Y)$ is the total variance, characterizing variability of the attribute $Y$;

$\sigma_i^2 (Y)$ is the variance characterizing variability of attribute resulting from a change in an $i$-th factor;

$\alpha_i$ is an index depending on the observations;

$\sigma_{\epsilon r}^2 (Y)$ is the variance characterizing an observational error.

Significant factors are selected by the value of the dispersion ratio and by comparing this value with that of the F-criterion (Fisher criterion) [12], defined at the significance level $\alpha$ and the number of degrees of freedom corresponding to the variance of the numerator and the denominator, that is:

$$
F_i = \frac{\sigma_i^2 (Y)}{\sigma_{\epsilon r}^2 (Y)} > F_{\alpha} (f_i; f_j),
$$

where $\sigma_i^2 (Y)$ is the variance with which the variance of the numerator is compared to reveal the significance of the factors under consideration.

The analysis of variance is used to select the variances $\sigma_i^2 (Y)$, corresponding to each of the factors addressed. Due to the fact that the values of theoretical variances are unknown, when identifying significant factors, instead of variances $\sigma_i^2 (Y)$ and $\sigma_j^2 (Y)$, their estimates $S_i^2 (Y)$ and $S_j^2 (Y)$ are used, defined as mean squares of the corresponding sums of squared deviations, that is:

$$
S_i^2 (Y) = \frac{Q_i}{f_i},
$$

where $Q_i$ is the sum of squared deviations attributable to the $i$-th factor;

$f_i$ is the number of degrees of freedom corresponding to the target mean square.
Figure 1. Aims and tasks tree for assessing and improving OM and increasing the efficiency of LM. Definitions: FL – fuel and lubricants; MTU – mobile technical unit; CMF – central maintenance facility; MRS – mechanical repair shops; SS – service station; REW – repair and engineering works; SP – spare parts
Source data for estimated calculations. The objects of research were gearboxes (GB) in two arrangements used in tractors manufactured by the Omega Tractor Plant (OTP) and in logging machines based on these tractors. The first option is a design with movable gear blocks. The second upgraded version is a constant mesh gearbox. Once being maintained and repaired, KPs were observed at some reference points arranged to study the reliability of logging machines utilized by the three logging enterprises under the Karellesprom association.

Both types of gearboxes were repaired by four (I–IV) groups of mechanics (a = 4) with the same rate, but with different work experience: I – 10 years, II – 12 years; III – 15 years; IV – 20 years.

The task is to assess the effect of employment history (work experience) of a mechanic on the duration of maintenance activities.

Each group of mechanics repaired five gearboxes (n=5; N=20). Gearboxes were removed from LMs and drive shaft bearings were replaced in a repair shop. The observation results are shown in Tables 1 and 2.

| GB No. | Group of mechanics |
|--------|-------------------|
|        | I | II | III | IV |
| 1      | 59| 55| 39 | 43 |
| 2      | 60| 56| 43 | 41 |
| 3      | 55| 61| 46 | 39 |
| 4      | 56| 60| 45 | 42 |
| 5      | 62| 52| 45 | 45 |

Table 1. Time for replacing gearbox bearings with movable gear blocks (min)

| GB No. | Group of mechanics |
|--------|-------------------|
|        | I | II | III | IV |
| 1      | 58| 61| 47 | 43 |
| 2      | 59| 62| 45 | 40 |
| 3      | 61| 56| 50 | 44 |
| 4      | 52| 57| 40 | 46 |
| 5      | 63| 55| 42 | 45 |

Table 2. Time for replacing GB bearings with constant mesh gears (min)

3. Results and discussion

Analysis of variance and assessment of target factor impact. To conduct an analysis of variance, you should first make sure that the variances in each of the four groups of observations are homogeneous. For ease of calculations, all values of time required for replacing \( y_{lk} \) will be reduced by 50, i.e. we represent them in coded form. The computing results are shown in Tables 3 and 4.

The values of \( S_i^2(Y) \) are determined by the following expression [10]:

\[
S_i^2(Y) = n^2 \left[ \frac{1}{n} \sum_{k=1}^{n} y_{lk}^2 - \left( \frac{1}{n} \sum_{k=1}^{n} y_{l,k} \right)^2 \right]
\]

Due to the fact that the volume of observations in each group is the same (n1=n2=n3=n4=5), then to test the hypothesis about the homogeneity of \( S_i^2(Y) \) we use the Cochran criterion – \( G \). The hypothesis is not rejected under certain condition:

\[
G = \frac{i e a \max S_i^2(Y)}{\sum_{i=1}^{n} S_i^2(Y)} < G_a(n, a)
\]

For the data shown in Table 3, we have:

\[
G = \frac{13.7}{8.3+13.7+7.8+5.0} = 0.393
\]

For the data shown in Table 4, we have:

\[
G' = \frac{11.8}{8.6+11.8+8.2+6.7} = 0.334
\]
Table 3. The coded results for GB with movable blocks

| GB No. | Group of mechanics | I      | II     | III    | IV     | Sum |
|--------|--------------------|--------|--------|--------|--------|-----|
| 1      | 9                  | 5      | -11    | -7     | -      | -   |
| 2      | 10                 | 6      | -7     | -9     | -      | -   |
| 3      | 5                  | 11     | -4     | -11    | -      | -   |
| 4      | 6                  | 10     | -5     | -8     | -      | -   |
| 5      | 12                 | 2      | -5     | -5     | -      | -   |

Computing results

\[\sum_{i=1}^{s} y_{ik} = 42 \quad 34 \quad -32 \quad -40 \quad 4\]

\[\sum_{i=1}^{s} y_{ik}^2 = 386 \quad 286 \quad 236 \quad 340 \quad 1248\]

\[\left(\sum_{i=1}^{s} y_{ik}\right)^2 = 1764 \quad 1155 \quad 1024 \quad 1600 \quad 5544\]

\[S_i^2(y) = 8.3 \quad 13.7 \quad 7.8 \quad 5.0 \quad -\]

Table 4. The coded results for GB with constant mesh gears

| GB No. | Group of mechanics | I      | II     | III    | IV     | Sum |
|--------|--------------------|--------|--------|--------|--------|-----|
| 1      | 8                  | 11     | -3     | -7     | -      | -   |
| 2      | 9                  | 12     | -5     | -10    | -      | -   |
| 3      | 11                 | 7      | 0      | -6     | -      | -   |
| 4      | 2                  | 6      | -10    | -4     | -      | -   |
| 5      | 13                 | 5      | -8     | -5     | -      | -   |

Computing results

\[\sum_{i=1}^{s} y_{ik} = 43 \quad 41 \quad -26 \quad -32 \quad 26\]

\[\sum_{i=1}^{s} y_{ik}^2 = 439 \quad 375 \quad 198 \quad 206 \quad 1053\]

\[\left(\sum_{i=1}^{s} y_{ik}\right)^2 = 1849 \quad 1681 \quad 676 \quad 1024 \quad 5230\]

\[S_i^2(y) = 8.6 \quad 11.8 \quad 8.2 \quad 6.7 \quad -\]

The table value of the criterion at \(\alpha = 0.05\) is equal to: \(G_{0.05}(5;4) = 0.544\), and since \(G = 0.393 < 0.544\) and \(G' = 0.334 < 0.544\), the hypothesis of homogeneity of target variances is not rejected.

Let us determine the sum of squared deviations required for further calculations [13]:

\[Q = \sum_{i=1}^{s} \sum_{k=1}^{s} y_{ik}^2 - \frac{1}{N} \left(\sum_{i=1}^{s} \sum_{k=1}^{s} y_{ik}\right)^2 = 1248 - \frac{4^2}{20} = 1247.2\]

\[Q' = \sum_{i=1}^{s} \sum_{k=1}^{s} y_{ik}^2 - \frac{1}{N} \left(\sum_{i=1}^{s} \sum_{k=1}^{s} y_{ik}\right)^2 = 1053 - \frac{4^2}{20} = 1019.2\]

\[Q_1 = \frac{1}{s} \sum_{i=1}^{s} \left(\sum_{k=1}^{s} y_{ik}\right)^2 - \frac{1}{N} \left(\sum_{i=1}^{s} \sum_{k=1}^{s} y_{ik}\right)^2 = \frac{5544}{5} - \frac{4^2}{20} = 1108.08\]
\[ Q_1' = \frac{1}{n} \sum_{i=1}^{n} (\sum_{k=1}^{5} y_{ik})^2, \quad Q_2 = \frac{1}{N} \sum_{i=1}^{n} (\sum_{k=1}^{5} y_{ik})^2 = \frac{5230}{5} = 1046; \]
\[ Q_2' = \frac{1}{n} \sum_{i=1}^{n} (\sum_{k=1}^{5} y_{ik})^2 = 1248-1108.8 = 139.2 \]
\[ Q_2'' = \frac{1}{n} \sum_{i=1}^{n} (\sum_{k=1}^{5} y_{ik})^2 = 1053-1012.2 = 40.8 \]

In the case under consideration, these sums of squared deviations correspond to the number of degrees of freedom: \( f_1 = a - 1 = 3; f_2 = N - a = 16; f_3 = f_1 + f_2 = 19 \).

The mean squares of corresponding sums of squared deviations will be:
\[ S_1^2 = \frac{Q_1}{f_1} = \frac{1108.8}{3} = 369.3; \]
\[ S_1'^2 = \frac{Q_1'}{f_1} = \frac{1012.2}{3} = 337.4; \]
\[ S_2^2 = \frac{Q_2}{f_2} = \frac{1392}{16} = 8.71; \]
\[ S_2'^2 = \frac{Q_2'}{f_2} = \frac{40.8}{16} = 2.55. \]

We estimate the significance of the factor (work experience of mechanics) using the following typical expression:
\[ F = \frac{s^2(Y)}{s^2_{er}(Y)} > F_0(f_1; f_2) \]

At specific values of the source parameters: \( a = 0.05; f_1 = 3; f_2 = 16 \) we have:
\[ F = \frac{s^2(Y)}{s^2_{er}(Y)} = \frac{369.3}{8.71} = 42.4 > F_{0.05}(3; 16) = 3.24; \]
\[ F' = \frac{s^2(Y)'}{s^2_{er}(Y)'} = \frac{337.4}{2.55} = 132.3 > F_{0.05}(3; 16) = 3.24. \]

4. Conclusions

It seems crucial to assess factors and indicators for operational maintainability of forestry and agricultural machines. The paper presents a quantitative assessment of the effect that one of the operational factors – work experience of mechanics – has on the duration of maintenance and repair procedure (using the example of nodes – GB in forestry machines). The findings showed that the significance of work experience influencing the duration of repair activities to keep the advanced gearbox operational (with constant-mesh gear) is higher than that on the gearbox with movable gear blocks.

Further activities involve the assessment of other factors of operational maintainability of forestry and agricultural machines, presented by the “Aims and tasks tree for assessing and improving the OM and increasing the efficiency of LM” can be used to select the most efficient and competitive machines.

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