Frequency of oil service operations regarding technical maintenance of combine harvesters

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Abstract. The present paper describes the method of frequency optimization for oil service operations regarding technical maintenance of combine harvesters RSM “TORUM-740”. Theoretical background for the estimation of optimal period for oil service that would minimize total losses is considered. When improving oil service, the failures belonging to the following groups are taken into account: strength breaks and predictive failures. The present paper is recommended for experts in agriculture, scientists, academicians, masters and students of agricultural engineering department of agricultural universities.

1. Introduction
The topic of the present research is relevant nowadays since no one of currently applied methods of frequency optimization for oil service operations regarding technical maintenance of combine harvesters and other farm machinery take into account the stochastic nature of performance of mechanization means.

The paper is aimed at improving reliability and efficiency of combine harvesters RSM-19 “TORUM-750”.

The subject of the research is a process of technical maintenance of combine harvesters in the context of agricultural sector of the Krasnodar Territory.

The study is focused on methods of improving reliability and efficiency of combine harvesters RSM-19 “TORUM-750” through optimization of frequency of oil service operations.

2. Materials and methods
The fleet of combine harvesters that are annually received by the farming sector of the Krasnodar Territory notably enlarges and meets the demands of agricultural production. However, the technical application rate of combine harvesters remains quite low. Combine harvesters stand idle for a long time (up to 10–20% of the working time) during scheduled and unscheduled repairs or while expecting them because of low operational reliability of parts, units or whole harvesters, as well as because of the decrease in the reliability of machines during their production and technical operation. Restoring combine harvesters demand large amount of materials and money significantly exceeding their initial cost [1].

In recent years, many studies have been conducted in the field of ensuring the reliability of combine harvesters. For instance, the works of academicians V.I. Chernovivanov, professors Yu. N. Artemyev and I.A. Mishin, and many other researchers can be regarded to works in the field of reliability of agricultural machinery.
However, the works of the authors mentioned above have not been adequately reflected and used in technical exploitation of agricultural machinery [2,3].

The reliability of combine harvesters, units and parts that are generally called “products” in the theory of machine reliability implies the harvester’s ability to remain functioning until the extreme limit state occurs under the given system of maintenance and repairs [4,5].

The reliability of combine harvesters largely depends on the right choice of their main parameters, quality of the production of harvesters and proper organization of their operation, which ultimately determines the economic efficiency of mechanization of agricultural works [6].

Therefore, along with measures to increase the reliability of combine harvesters, solutions are to be developed and implemented that will improve standards of operation, maintenance and repair of combines at certain planned operating time intervals [7,8].

The quality of maintenance and repairs is of great importance for ensuring the reliability and long service life of combine harvesters. It is achieved under conditions of centralized service at enterprises provided with modern equipment, control and measuring machines and experts performing these works and systematically studying reasons of defects and failures in the operation of combines.

Ensuring reliability when creating, developing and operating combine harvesters is a problem of state scale. A wide range of problems concerning the ensuring of reliability is associated with issues of optimization of various solutions [9,10].

Therefore, when determining a defect, identifying the causes of defects of combine harvesters as a complex technical system, one cannot act only intuitively or look through parts of a device, since it is expensive and unproductive.

Combine harvesters are known as machines having uncertainties and elements of randomness. This is because the made and operated harvesters become worn out and obsolete, which leads to a dispersion of their service lives, while inappropriate operation leads even to breakdowns. Due to the "imperfect" production processes and materials used, the quality of combine harvesters is heterogeneous and also has random scatter [11,12].

Many tasks related to the reliability of agricultural machines such as redundancy, determination of spare parts and components, problems of preventive maintenance, methods of optimal design and testing, human influence on the operation of combine harvesters as technical systems, turned out to be interconnected with many branches of mathematics, physics, mechanics, chemistry and other fundamental sciences.

Queuing theory and mathematical statistics take a special part in the issue of reliability of machines. This is because the data obtained during testing, operation, and experimental studies convey nothing, since they still need to be well managed, which means to be analyzed and lead to right conclusions and generalizations corresponding the real flow of processes. It is impossible without scientific methods. Sound methods for testing and operating for subsequent data processing should also be developed.

The control and management of the quality and reliability of combine harvesters as in agricultural production are also important in farming production and technical operation. The purpose of quality control and management in agricultural production is to prevent the release of low-quality products, while in technical operation - is to prevent breakdowns. The issues raised above are considered in this thesis [13,14].

A number of research methods that are described in relation to the operation of combine harvesters as technical systems and development in the process of their creation allow determining the physical nature of the phenomena under consideration, establishing a quantitative relationship between stages of the operation and development process. These issues have not yet been fully resolved, therefore their solution will contribute to the progress of basic sciences.

Knowledge and understanding of what has been done and of current capability of agricultural engineering science is a prerequisite for the further development and improvement of other scientific areas and their applying.
The present research article discusses some theoretical and practical aspects, as well as methods that can be applied to ensure the reliability of combine harvesters.

The coverage of experimental material (from reliability assessments of combine harvesters and their parts, solving operational test problems, selecting maintenance and repair parameters to addressing the issues of organizing technical operation, machine repair) differs this research article from previously written papers on technical maintenance of combine harvesters.

The present study endures mathematically rigorous and accessible presentation of theoretical and experimental material, explains physical interpretations, gives practical applications of the obtained solutions and considers some problems of independent scientific and practical interest.

The main areas of research in the field of ensuring the reliability of combine harvesters should be further considered.

Scientific and technological progress has led to the intensive development of research in the field of increasing the reliability of combine harvesters as complex technical systems.

The use of mathematical methods is essential in ensuring reliability. Mathematical support is an integral part of the quality and reliability of combine harvesters at the stages of their design, manufacture and operation.

The most promising way of introducing the mathematical theory of reliability is the algorithmization of calculations of reliability ensuring, or in other words, the development of such mathematical methods that would enable uniform solution of wide spectrum of reliability theory problems in accordance with the given algorithm.

Developers, operators, control specialists are in daily contact with calculations of ensuring the reliability of combine harvesters. They have to sort through a large number of design options and possible modes of operation of the created and operated combines. Therefore, for any purpose of calculating reliability, it is necessary to have a flexible apparatus that makes it possible to compile the characteristics of a large number of combine harvester’s designs in a uniform manner, using the same set of algorithms.

The ultimate goal of ensuring the reliability of combine harvesters at the design stage is to find the optimal design solutions and parameters, the best operating conditions, and service strategies.

If taking into account the emerging tendency for more common use of statistical modeling methods in reliability calculations, then the importance of solving optimization problems of reliability theory by stochastic programming becomes understandable.

The working hypothesis of the study lies in the fact that theoretical analysis of the subject under the study allowed assuming that the distribution of failure-free time for combine harvesters RSM-19 "TORUM-750" can be approximated through the exponential distribution law.

The task of scientific research included:

1. The development of a mathematical model provided by the theory of reliability to optimize the frequency of oil service regarding the technical maintenance of combine harvesters RSM-19 "TORUM-750".
2. The conduction of experimental verification of the hypothesis put forward: on the basis of the analysis, the permissibility of applying the exponential distribution law is determined in order to describe the technical maintenance of combine harvesters.

3. Results and discussion

Following from elaborated methodological recommendations on the organization of technological complexes for grain harvesting in the agricultural enterprises of the Krasnodar Territory, a mathematical model was obtained to optimize the frequency of control and inspection operations during maintenance of Vector-420 combine harvesters

\[ t_{opt} = \frac{xT}{2(1+y)} \left( \sqrt{1 + \frac{4(1+y)}{x}} - 1 \right), \]  

(1)
where $t_{opt}$ is the optimal frequency of control and inspection operations during maintenance of combine harvesters Vector-420.

Within the same work, the authors obtained a mathematical optimization model for adjustment and fastening operations of the maintenance system for combine harvesters Vector-420, which has the form

$$t = \frac{(a + bt_p) + \sqrt{(a + bt_p)^2 - 2blnP_g}}{b},$$

where $t$ is the frequency of adjustment and fastening operations of the technical maintenance system for combine harvesters Vector-420.

Based on the objectives of our study, first, a mathematical model for optimizing the frequency of oil service operations of the maintenance process of combine harvesters RSM-19 "TORUM-750" is to be considered.

Such operations as changing the oil in the fuel pump casing and in the regulator casing, adding grease, cleaning the air cleaner and oil centrifuge, descaling the engine cooling system of the RSM-19 "TORUM-750" combine harvester, etc. are taken as an example of calculation.

The frequency of the considered lubricating and charging operations (oil service) $t_{os}$ affects the resource of the assembly unit. The lifetime will be maximum when oils, greases, etc. are in working condition, which can be estimated by the probability of failure-free operation of the considered units and the value of $t_{os}$; the lifetime is minimum when oils, grease, etc. fail.

Thus, the efficiency of oil service is manageable; it can be increased by optimizing the sequence and frequency of operations.

The optimal frequency $t_{opt}$ of oil service operations is determined based on the cost analysis of service functions.

Let us assume that $c_{main} = c_{sb}t_{main}$ are costs associated with the standby of a combine harvester RSM-19 TORUM-750 during technical maintenance; $ac_{f} = c_{sb}t_{p}$ - costs of eliminating the failures of the combines, where $c_{sb}$ is the cost of one hour of standby for the RSM-19 "TORUM-750" combine harvester, etc. are taken as an example of calculation.

To make a chart of oil service performing, the sequence of non-negative numbers $\left\{ t_k \right\}_{k=0}^{\infty}$ should be determined where $t_0 = 0$. If $t_k = t_k$, then the service plan is periodic with the period $t_0$, i.e. harvesters should be serviced every $t$ hours if no failures occur. Other cases require the consistent maintenance strategy.

Then the average loss is defined. If combine harvesters RSM-19 TORUM-750 fail after the technical maintenance $(k-m)$ and before the $(k+1)$ one, then the losses equal $(k + 1) c_{main} + (t_{k+1} - t)c_{o}$, where $(k+1)c_{main} - losses due to machine standby during the technical maintenance.

\[
L = \sum_{k=0}^{\infty} \int_{t_k}^{t_{k+1}} [c_{main}(k + 1) + c_{o}(t_{k+1} - t)]dF(t),
\]

where $F_t$ is the distribution function of the failure-free operation of a combine harvester RSM-19 TORUM-750.
Any chart of oil service performing that minimizes function (3) further is called the optimal chart. Strictly periodic maintenance charts are optimal only for machines that have a constant failure rate.

When the failure rate of combine harvesters increases, the frequency of maintenance of such combines must be constantly reduced with the increase in operating time, as it is shown below.

The cases when oil service are performed every time units (operating time). Note that if a combine harvester failed at the moment $\tau$, $kt \leq t \leq (k + 1)t$, then the losses are $c_{main}(k + 1) + c_c[(k + 1)t - \tau]$.

The average losses in this case will be equal to

$$L = \sum_{k=0}^{\infty} \int_{kt}^{(k+1)t} [c_{main}(k + 1) + c_c[(k + 1)t - \tau)]dF(t) + c_{main}.$$  \hspace{1cm} (4)

It is assumed that the distribution of failure-free operation time for combine harvesters RSM-19 “TORUM-750” can be approximated by the exponential distribution law:

$$F(t) = 1 - \exp(-\omega t),$$  \hspace{1cm} (5)

where $\omega = at^m$ is the harvester failure flow parameter; $a, m$ – constants.

Taking into account (5), the average loss formula (3) takes the form

$$L = \frac{c_{main}\exp(\omega t)}{1 - \exp(-\omega t)} + \frac{c_c}{1 - \exp(-\omega t)} - \frac{c_o}{\omega} + c_{main},$$  \hspace{1cm} (6)

where $L$ is average loss, rubles.

The optimal period for oil service performing that minimize total losses is obtained from the following condition

$$\frac{dL}{dt_k} = 0.$$  \hspace{1cm} (7)

Differentiating (7) and equating the derivative to zero, the expression is obtained for determining the optimal frequency of oil service regarding maintenance of combine harvesters RSM-19 “TORUM-750”.

$$\exp(\omega t) - \omega t - \omega - \frac{c_{main}}{c_o} = 1.$$  \hspace{1cm} (8)

Reliability is a property characterizing the quality of combine harvesters. The experimental assessment of reliability indicators of combine harvesters RSM-19 “TORUM-750” is the main way to determine many quantitative reliability indicators when developing and mass producing combine harvesters.

Therefore, the authors assume that many issues of processing the results of reliability tests are very important in terms of the general problem of ensuring the reliability of combine harvesters RSM-19 "TORUM-750".

Existing regulatory and technical documents governing operational methods for determining reliability indicators based on the results of controlled observations are based on the use of certain theoretical models of reliability (distribution functions).

The assessment of the operational reliability indicators of combine harvesters, as well as their test plans, can be significantly affected by the adoption of one or another theoretical model of reliability. If the distribution functions of mathematical statistics (or estimates of reliability indicators) are known, the planning of reliability tests and the evaluation of confidence intervals of reliability indicators of agricultural equipment are easily solved.

Table 1 and in Figure 2 show the sequence of oil service of combine harvesters RSM-19 “TORUM -750”.
Table 1. In addition to estimation of the optimal intervals for oil service.

| t, moto-h | 8   | 10  | 12  | 13  | 15  | 20  | 22  | 24  | 25  |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| y 10^{-2} | 0.2 | 0.4 | 0.6 | 0.8 | 0.2 | 0   | -0.4| -0.6|

Figure 2. Optimal intervals for oil service operations aimed to grain separator of the combine harvester RSM-19 "TORUM-750".

In this case, the form of the distribution function of the estimated reliability indicator (sufficient statistics) and, accordingly, the plans for controlled observations (tests) significantly depend on the selected distribution-to-failure distribution law (primary investigated statistics).

The optimal intervals between oil service operations within the framework of technical maintenance were similarly determined for the remaining parts of combine harvester RSM-19 TORUM-750 (table 2).

Table 3 shows the sequence of lubricating and refueling operations (oil service) for combine harvester RSM-19 "TORUM-750".

Then the program and methodology of the present study should be considered. The planned level of reliability of the RSM-19 "TORUM-750" combine harvesters is determined by the manufacturer and is reflected in the technical and operational documentation.

One of the objectives of the present work is to create a methodology for collecting and processing information on the reliability of combine harvesters RSM-19 "TORUM-750" under condition of actual operation with sufficient accuracy and minimum costs for practical assessments.

This program and methodology establish the rules and methods for collecting and processing information on the reliability of combine harvesters RSM-19 "TORUM-750" by conducting their surveys during operation.

Table 2. Determining the optimal interval for oil service operations of combine harvester PSM-19 “TORUM-750”.

| Names of parts and systems of combine harvester | Running hours to the failure for the group B, T, moto-h | Time spent, T₀, h | Optimal interval for oil service operations, t_{opt}, moto-h |
|-----------------------------------------------|--------------------------------------------------------|------------------|-------------------------------------------------------------|
| Engine                                        | 344                                                    | 7.4              | 30                                                          |
| Pickup unit                                   | 223                                                    | 2.7              | 20                                                          |
| Grain separator                               | 184                                                    | 1.0              | 22                                                          |
| Harvester stacker                             | 242                                                    | 0.58             | 30                                                          |
| Undercarriage                                 | 210                                                    | 1.18             | 25                                                          |
Table 3. Order of performing oil service operations of technical maintenance of combine harvester PSM-19 “TORUM-750”.

| Number of operation | List of operations                                                                 | Optimal interval of oil service operations, $t_{\text{opt}}$, moto-h |
|---------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------|
| 1                   | Add oil to the engine crankcase, fuel to the main engine tank, coolant to the radiator, distilled water to the battery, oil to the fuel pump case and engine regulator | 30                                                               |
| 2                   | Add: brake fluid to the brake reservoir and hydraulic clutch reservoir, oil to the hydraulic reservoir Lubricate the friction joints according to the lubrication schedule: - receiving and intermediate beater bearings; - right finger-type beater bearing; - upper beater bearings; - eye bearing of a lever with a spring block; - eye bearings of the left and right levers of feeder house; - bearings connecting the frame with rods; - the cavity of the lever of the counter drive of the cutter; - lever cavity of a beater of feeder house; - lever cavity of the upper beater of feeder house; - the axis of the lever of the tension pulley counter-drive of feeder house; - cavity of the lever of the tensioner of the grinding rotor; - the lever cavity of the tension sprocket of the upper shaft of the grain elevator; - cavity of the lever of the pulley of the tension counter-drive of the grain group; - cavity of the counter-drive lever of the unloading device; - bearing of the driven shaft of the reducer of the conical loading auger of the hopper; - bearing parts of counter-drive feeder house; - cutter rotor shaft bearings. | 25                                                               |
| 3                   |                                                                                     | 20                                                               |

The onetime inspection implies the assessment of the condition of a harvester or obtaining the necessary information through the polling of combine operators on failures and operating conditions during a certain period passed.

The information obtained during onetime inspection is intended to provide solutions to the following tasks:

– analysis of theoretical and experimental research data;
– obtaining and processing experimental information on the results of tests of combine harvesters RSM-19 “TO-RUM-750” for failure-free operation;
– determining analytically and graphically the form of the distribution law and its parameters, as well as checking this distribution law according to the Pearson “chi-square” criterion of consent;
– deducing the nomenclature, frequency of occurrence and (if possible) causes of structural, technological (production) and operational failures that significantly reduce the reliability level.
The duration of operation of combine harvesters RSM-19 "TORUM-750" and their running hours are measured in motor-hours and determined with the counter and the duration of operation in units of calendar time (months, years), or by the volume of work performed (ha, t), or by fuel consumption.

In the process of primary processing of materials, all these data should be reduced to moto-hours. Calendar time is converted into moto-hours based on the average annual load of combine harvester RSM-19 "TORUM-750" in the given region (the Krasnodar Territory), taking into account the seasonality of work.

The conversion factors of relative sample hectares (r s ha) and liters of spent fuel into motor hours are given in the reference literature.

For machines of new brands, the values of the conversion factors are set by analogs having identical purposes, traction class and the closest possible performance.

The terminology concerning reliability used in this work is regulated by Russian State Standard GOST R 53480-2009.

Organization of the collection of information should be carried out as follows. One-time inspections of RSM-19 "TORUM-750" combine harvesters are carried out in places of their direct operation.

Surveying places (district, farm) are determined by the program of work and are selected proceeding from the conditions of the greatest possible concentration of combines, that forward information, and restrictions on travel (transportation) expenses.

In particular, the collection of information on the reliability of combine harvesters RSM-19 "TORUM-750" was carried out under ordinary operating conditions at PAO Plemzavod named after Chapaev V.I. of Dinsky district of the Krasnodar Territory.

Workers performing one-time inspections of combines should be well aware of the design, technical operation rules and work technology. Before conducting the survey, all workers should be instructed by the supervisor, who should inform the performers about the work program and its methodological features.

Information on the reliability of combine harvesters RSM-19 "TORUM-750" and operating conditions is collected by interviewing operators of harvesters (mechanical engineers, team leaders, engineers), inspecting the machines and reading accounting and warehouse documents.

Obtaining the necessary information is carried out using questionnaires.

Harvester operator’s polling is divided into two stages – preliminary and subassembly. The preliminary polling involves creating a psychological attitude and obtaining independent information from the operator on the reliability and use of a combine harvester RSM-19 “TORUM-750”.

The purpose of the subassembly polling is to identify failures that occurred during the previous period of operation.

For the psychological mood of the operator, it is recommended to start a conversation on general topics (marital status, earnings, health, job satisfaction, etc.) in order to create a confidential atmosphere and conditions for an easy conversation.

Preliminary information is an arbitrary story about the work on the reliability of combine harvester RSM-19 "TORUM-750" and its technical condition. Listening to these data, it is necessary to clarify certain points: the external manifestation of the failure, the time and conditions of its occurrence, the reason, method of elimination, etc.

General issues also include identifying the organization of maintenance, the characteristics of the repair base, the causes and duration of downtime.

In a subassembly polling, questions about failures are posed sequentially by units and systems (engine, clutch, gearbox, drive axles, hydraulic system, etc.). In this case, the most probable failures are probed.

At first, it is advisable to ask indirect questions about the adequacy of power, ease of operation, slipping, extraneous noise and knocking and other possible violations of the machine. Then these questions develop in the direction of the reasons for the refusals, if any follow from the answers.
In conclusion of the polling, it is necessary to listen to suggestions and a general assessment of the reliability of combine harvester RSM-19 "TORUM-750", primarily in terms of its reliability and the conditions for its use.

The results of the survey of the combine should be supplemented by a conversation with a mechanic (foreman, engineer), from whom it is desirable to obtain more complete information about the causes of failures, maintenance of the machine and other data characterizing both reliability and operating conditions.

Based on the results of the polling, a consolidated statement of failure accounting is drawn up.

In this study, the sample amount (the total number of failures of five combine harvesters RSM-19 "TORUM-750") $N = 42$.

When conducting one-time examinations, it is necessary to collect information about combine harvesters RSM-19 "TORUM-750" and their failures.

Data on the machine: brand, utility number, year of manufacture, producer factory, month and year of entering into farm; running hours to the day of the examination; the period (in months and motorcycle hours) of collecting information.

Moreover, it is advisable to obtain additional data on the completeness of combine harvesters received by the farm, the quality of pre-sale preparation, information about the seller and the form of payment (prepayment, leasing, etc.), as well as feedback from harvester operators on the quality of operational documentation.

Failure information should contain:
- operating time of the combine harvester up to the moment when a failure occurred;
- name of failed parts;
- brief description of the failure, the alleged cause (according to the combine operator or mechanical engineer);
- method of elimination and replaced parts;
- downtime (in days) due to failure (according to the combine or according to the data of economic accounting).

The terms used to characterize failures are given in GOST R 53480-2009.

In accordance with this standard, a failure is an event that occurred during operation, which consists in a malfunction of the machine and requiring its stop for repair or unscheduled maintenance.

Violation of the operability of combine harvesters RSM-19 "TORUM-750" is characterized by the following conditions:
- for technical reasons, the combine harvester cannot fulfill the functions assigned to it (obvious failure);
- the value of one or more parameters characterizing the operability of the combine has exceeded the limits specified in the technical documentation (parametric failure);
- an event had occurred that was detected by external inspection, listening, or with the help of diagnostics, which, if the operation is continued, can lead to serious technical or economic consequences or cause a threat to people's safety (gradual failure).

4. Conclusion

Based on the analysis of methods for solving problems associated with increasing the reliability of combine harvesters, the authors elaborated theoretical aspects of increasing the failure-safety of combine harvesters RSM-19 “TORUM-750”.

The mathematical model was developed to optimize the frequency of oil service regarding maintenance process of combine harvesters RSM-19 “TORUM-750”.

The theoretical and experimental research data were analyzed. Experimental information on the results of tests of combine harvesters RSM-19 “TORUM-750” for failure-free operation was received and processed.

The study showed that the exponential distribution law could be used as a probabilistic model for describing the maintenance process of combine harvesters. The substantiated indicators of the
frequency of oil service operations are verified by experimental data, which allowed proving the hypothesis put forward.

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