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Development of a Tractor Reliability Optimization Model: a Review of Research and Rationale for the Components

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Abstract. This study reviews existing research on optimizing the reliability of agricultural tractors, with a focus on identifying the most critical factors influencing tractor performance. The methodological approach involved an expert assessment of factors affecting tractor reliability, which highlighted three key elements: the factory (inherent) reliability of tractors, the effectiveness of repair and maintenance practices, and the losses incurred from tractor downtime. The consistency of expert opinions was validated using an agreement coefficient. Based on these findings, the development of a mathematical model is proposed, enabling agricultural enterprises to make informed decisions when selecting tractors based on reliability and cost-efficiency indicators. This research represents the initial phase of a broader project, with future plans to create software that automates the optimization of tractor reliability and costs, ultimately improving the profitability of agricultural enterprises.

Keywords: tractor reliability, cost optimization, maintenance, failure-free operation, maintainability

1. Introduction

The purpose of acquiring technical equipment for agricultural producers is to maximize the effectiveness of their functional capabilities. Among these, the operational reliability of machine-tractor units is crucial, especially given the stringent requirements for both the duration and the quality of technological processes in crop production. Key indicators of reliability include the dependability and ease of maintenance of the machinery [1–3]. However, frequent tractor failures—tractors being the energy foundation of these units - along with the high labor demands for repair and maintenance, often result in a technical utilization rate of just 60 - 70% during peak fieldwork cycles. This makes the process of maintaining operability, with tractors as the central focus, the primary challenge in their acquisition.

Additionally, the substantial resources required for routine technical maintenance (TM) and repair activities lead to significant increases in the overall cost of maintaining tractor reliability. Over the standard operational period, these costs, which include labor, materials, and infrastructure development, often are several times higher than the initial manufacturing costs of the machinery itself [4–6].

Standards for mean time between failures (MTBF) and the labor intensity of repairs should align with the agronomic requirements for the duration and quality of crop production processes [7]. This underscores the need for deploying tractors with varying levels of reliability and maintainability, allowing for differentiation in these performance metrics within machine-tractor units.

The existence of an entire field of scientific research highlights the importance of this topic on both national and international scales. In English-language literature, the solution to this practical optimization problem falls under the field known as “life cycle engineering,” which focuses on optimizing the life cycle costs of technical systems [8–10]. Another commonly used concept is the “Total Cost of Ownership” (TCO), which evaluates the comprehensive costs associated with owning a product [11–13].

Several specialized international journals are dedicated to publishing the latest research in this area, such as *The International Journal of Life Cycle Assessment* [14], *Reliability, Availability, and Maintainability Aspects of Automobiles* [15], and book series like *Sustainable Production, Life Cycle Engineering, and Management* (*SPLCEM*) [16]. The emphasis on evaluating total costs of acquisition and usage arises from the fact that, for certain machines like agricultural tractors, the cumulative expenses for maintenance, repairs, fuel, and other operational needs over the machine’s lifetime can far exceed the initial purchase cost [17]. This gap widens further when factoring in downtime losses, which is particularly critical for tractors in crop production.

Unfortunately, these problems have not been adequately addressed to date. The outdated GOST R 53056-2008 [18], which closely mirrors GOST 23729-88 [19] from the planned economy era, remains in use. Many researchers are still forced to rely on these obsolete standards [18, 19] when calculating the economic performance of specialized machinery [20–23]. Consequently, Kazakhstan lacks modern methodologies for assembling machine-tractor units based on reliability, productivity, and efficiency metrics. As a result, agricultural enterprises often select equipment based on intuition, without a well-founded approach to minimizing costs and maximizing profitability.

More accurate guidelines for accounting cost components, including for tractors, can be found in earlier works, such as a detailed practical guide published in 1997 by Kansas State University [24]. This guide offers extensive reference data and methodologies for conducting such calculations. Similar approaches to evaluating the cost of ownership and operating expenses for agricultural tractors were presented in a 2009 publication by Iowa State University, which was reissued in 2011 and 2015 [25]. A shorter, more pragmatic guide by the University of

South Dakota [26], along with other works by international agricultural business experts, provides further insights. These studies emphasize that determining key components for calculating an optimal level of reliability requires forecasting changes in a machine's technical and economic characteristics over its entire lifespan, as highlighted in these foreign publications.

The relevance of this study lies in its potential to generalize and adapt existing international research for agricultural enterprises in Northern Kazakhstan, while incorporating the work of local scientists [27–29], including the authors of this publication [30–32]. The first study on this topic was authored by Gulyarenko A. A. in 2008, following research conducted since 2007, with over 50 related publications during this period [33]. An analysis of the literature shows that similar studies are conducted in other countries [9, 12–14, 17, 24–26, 34], but they largely contain statistical data and scattered mathematical models, lacking a comprehensive solution tailored to specific enterprises—particularly agricultural ones. This makes the hypothesis and objectives of this study both original and highly relevant, not only for Kazakhstan but also internationally. Moreover, this research aims to automate the calculation process by developing specialized software, allowing these models to be adapted for various agricultural enterprises across the Republic of Kazakhstan.

The most important factor in improving the efficiency of agricultural production is the increase of the quantity and quality of output. Producers around the world strive to ensure that their products meet high quality standards and are in demand by consumers. It is essential to remember that the quality of products affects demand, competitiveness, and their final price. To achieve growth in both quantity and quality, scientifically sound cultivation techniques, reliable high-performance equipment, and highly skilled personnel are required, which inevitably raises the price of the final product. However, despite these increased costs, it remains crucial to seek optimal solutions for achieving the best results, particularly in crop production. One such solution involves developing a model that ensures the reliability and maintainability of tractors, enabling the achievement of necessary performance metrics in mechanized processes.

In Kazakhstan, the available range of tractors varies significantly in terms of MTBF and the labor intensity of repair and maintenance. This variety allows for the selection of tractors with economically feasible levels of reliability and maintainability, tailored to the specific requirements of different crop production processes. In other words, it is possible to assemble machine-tractor units with differentiated values for reliability and maintenance needs. However, as the reliability of tractors increases, so does their price, making it essential to address this issue within the context of farm income and profitability [35]. Given the practical significance of this challenge, its scientific relevance is clear. Furthermore, improving the profitability of both small and large agricultural enterprises will have a profound impact on the agricultural sector, which is crucial to Kazakhstan's economy.

2. Materials and Methods

The methodological foundation of this study is based on the premise that a relationship exists between the MTBF, the labor intensity of repair and maintenance actions in machine-tractor units, and key factors such as the duration of technological processes in crop production, product losses, and resource costs required to maintain tractor operability. By studying and generalizing these dependencies, the goal is to solve this optimization problem for the specific conditions of agricultural enterprises in the Republic of Kazakhstan.

Given the wide range of factors influencing tractor reliability, the initial stage of the study focuses on identifying the most significant ones affecting tractor performance in crop production. The complexity of these interrelated factors is the main challenge in optimizing tractor reliability. This challenge can be effectively addressed using the expert assessment method.

To this end, an expert survey was conducted using a structured questionnaire that listed the key generalized factors affecting the reliability of mechanized processes on farms. Experts provided their understanding of each factor, clarifying any uncertainties if needed. They were then tasked with evaluating the weight of each factor and ranking them by significance. The questionnaire also allowed for the addition and ranking of unaccounted factors where necessary.

In our study, we interviewed 35 experts to assess the impact of various factors on the reliability of mechanized technological processes. As a result, eight key factors were identified as having the most significant influence on tractor performance during these processes. The factors, weighted by expert opinion, are as follows: tractor's factory reliability (X1), quality of maintenance (X2), quality of repairs (X3), availability of material and technical resources for maintenance and repair (X4), tractor workload (X5), operator proficiency (X6), storage and quality of fuel and lubricants (X7), and unfavorable environmental conditions (X8).

Once the survey was completed, it was necessary to analyze the results to determine whether the experts' responses were consistent and non-random. This involved calculating indicators that measure the degree of agreement among the experts. The primary metric used to assess this agreement was the concordance coefficient [37–39], which reflects the level of consensus across all the identified factors.

Table 1. The influence of individual factors on the reliability of the implementation of a mechanized technological process and their significance according to expert survey data

Expert number	The weight of the factor, assigned by the i-th expert within the range from 0 to 1							
	Tractor's factory reliability	Quality of maintenance	Quality of repairs	Availability of material and technical resources for maintenance and repair	Tractor workload	Operator proficiency	Storage and quality of fuel and lubricants	Unfavorable environmental conditions
1	2	3	4	5	6	7	8	9
1	0.9	0.8	0.9	0.7	0.9	0.6	0.8	0.6
2	0.6	0.8	0.3	0.4	0.2	0.4	0.3	0.2
3	0.9	0.7	0.6	0.8	0.4	0.5	0.9	0.4
4	0.8	0.3	0.4	0.5	0.4	0.5	0.2	0,1
5	0.8	0.7	0.5	1.0	0.9	0.6	0.4	0.3
6	0.7	1.0	0.5	0.6	0.8	0.8	0.5	0.2
7	0.8	0.9	0.9	0.7	0.8	0.5	0.5	0.7
8	0.8	0.6	0.7	0.6	0.7	0.5	0.6	0.7
9	0.7	0.7	0.6	0.5	0.9	0.3	0.3	0.7
10	0.8	1.0	0.7	0.6	0.5	0.4	0.4	0.2
11	0.8	0.9	0.7	0.8	0.5	0.8	0.5	0.6
12	0.8	0.8	1.0	0.6	0.5	0.4	0.4	0.3
13	0.8	0.8	0.9	0.6	0.7	0.5	0.6	0.5
14	1.0	1.0	1.0	0.5	0.8	0.5	0.5	0,0
15	0.9	0.7	0.8	0.7	0.9	0.5	0.4	0.5
16	1.0	0.5	0.5	0.2	0.5	0.8	0.5	0.7
17	0.8	1.0	0.5	0.4	0.6	0.3	0.4	0.3
18	0.6	1.0	0.5	0.5	0.5	0.6	0.7	0.4
19	0.6	1.0	0.8	0.6	0.3	0.7	0.5	0.5
20	0.9	0.9	0.6	0.5	0.8	0.5	0.6	0.7
21	0.9	0.8	0.8	0.3	0.5	0.5	0.6	0.4
22	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.5
23	0.8	0.9	0.8	0.5	0.5	0.7	0.5	0.2
24	0.8	1.0	1.0	0.6	0.6	0.8	0.6	0.2
25	0.8	0.9	0.8	0.9	0.5	0.9	0.5	0.3
26	1.0	0.8	0.9	0.7	0.6	0.4	0.4	0,0
27	0.7	0.5	0.4	0.6	0.5	0.3	0.3	0.5
28	1.0	0.5	0.7	1.0	0.3	0.7	0.9	0.5
29	0.9	0.3	0.3	0.4	0.2	0.5	0.5	0.2
30	0.7	1.0	0.5	0.7	0.8	0.4	0.5	0.2
31	0.8	0.7	0.8	0.8	0.8	0.7	0.7	0.2
32	1.0	0.4	0.8	0.8	0.6	0.3	0.6	0.2
33	0.9	1.0	0.6	0.8	0.2	0.4	0.4	0.2
34	0.7	0.8	0.5	0.7	0.6	0.5	0.7	0.4
35	1.0	0.6	0.5	1.0	0.7	1.0	0.4	0.3

To calculate the value of the concordance coefficient, we first find the sum of the ratings (ranks) for each factor $\sum_{j=1}^{m} X_{ij}$, obtained from all experts, and then the difference between this sum and the average sum of the ranks ($\overline{X}$) using the formula:

$$\Delta_i = \sum_{j=1}^{m} X_{ij} - \overline{X} \tag{1}$$

The average sum of ranks is determined by the expression:

$$\overline{X} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} X_{ij}}{n} \tag{2}$$

where m is the number of experts;
n is the number of factors.

Next, the sum of the squares of the differences (deviations) S is calculated:

$$S = \sum_{i=1}^{n} \left(\sum_{j=1}^{m} X_{ij} - \frac{1}{2} m(n+1) \right)^2 \quad (3)$$

The value of S has a maximum value in the case when all experts give the same estimates.

After this, we directly calculate the concordance coefficient using the following formula:

$$W = \frac{12S}{m^2(n^3 - n) - m \sum_{j=1}^{m} T_j} \quad (4)$$

where

$$T_j = \sum_{j=1}^{J} t_j^3 - t_j \quad (5)$$

where J is the number of groups of related ranks;

t_j is the number of identical ranks in the j-th row.

To assess the significance of the coefficient of concordance W, we use the Pearson criterion:

$$x_p^2 = \frac{S}{\frac{1}{2} mn(n+1) - \frac{1}{n-1} \sum_{j=1}^{m} T_j} \quad (6)$$

For the agreement of expert opinions to be considered significant, it is necessary that the calculated value of the criterion x_p^2 was greater than the tabular x_m^2 [21], determined by the number of degrees of freedom $f = n - 1$ and the confidence level $y = 0.95$.

3. Results and Discussion

Table 2 presents the results of calculating the consistency of expert opinions regarding the impact of individual factors on the technical performance of tractors.

Table 2. Assessment of the agreement of expert opinions

Index of expert consensus	The weight of the factor, assigned by the *i*-th expert within the range from 0 to 1							
	Tractor's factory reliability	Quality of maintenance	Quality of repairs	Availability of material and technical resources for maintenance and repair	Tractor workload	Operator proficiency	Storage and quality of fuel and lubricants	Unfavorable environmental conditions
Sum of ranks X_{ij}	78	101	136	152	164	202	185	240
Deviations from the average sum of ranks Δ_i	−79	−56	−21	−5	7	45	28	83
Squares of deviations S	6241	3136	441	25	49	2025	784	6889
Tied ranks index T_i	2923	1368	1272	1128	1197	1764	1860	1428
The weight of the factor φ	0.82	0.76	0.67	0.62	0.58	0.50	0.55	0.36

Based on the obtained data, the concordance coefficient for the entire set of factors ($n = 8$) was $W = 0.40$. This positive value, distinct from zero, indicates a significant level of agreement among the expert opinions. The actual value of x^2 ($x_p^2 = 17.22$) is much greater than the critical table value ($x_m^2 = 2.17$), further confirming sufficient agreement across all factors.

The analysis of the survey results shows that among the eight factors, the greatest impact on the reliability of mechanized processes comes from the factory reliability of tractors ($\varphi = 0.82$), followed by the quality of maintenance ($\varphi = 0.76$), and the quality of repairs ($\varphi = 0.67$). Future research should prioritize these key components, as they have the most significant influence on tractor reliability.

Existing methods for determining optimal tractor reliability indicators can be categorized based on the types of operational costs they account for:

1) Methods that consider both repair and maintenance (MOT) costs as well as the costs of energy materials (fuel, lubricants, electricity, etc.).
2) Methods that account only for the repair and maintenance costs of machines.
3) Methods that focus solely on the costs of spare parts, metal consumption, and related materials.
4) Methods that account for losses due to unplanned machine downtime caused by technical faults, alongside the costs of repair and maintenance.

An analysis of the methods leads to the conclusion that, when using tractors in crop production, their reliability should generally be justified by minimizing the total cost function:

$$\sum C = C_F + C_{repair} + C_{maintenance} + C_{salary} + C_{fuel/lubricants} + C_{PR} \to \min \quad (7)$$

where C_F represents the cost of purchasing the tractor (first-order indirect costs of manufacturing at the factory, in tenge);
C_{repair} are the costs of repairing the machine, in tenge;
$C_{maintenance}$ includes maintenance and storage costs, in tenge;
C_{salary} is the wage expenditure for tractor operators, in tenge;
$C_{fuel/lubricants}$ are the fuel and lubricant costs, in tenge;
C_{PR} represents the complex costs from production losses and underutilization of labor due to machine downtime, in tenge.

The analysis of research materials and expert survey results shows that, to determine the required level of factory reliability for tractors within machine-tractor units, it is sufficient to account for the following: the initial purchase cost of tractors, the costs of maintaining and restoring operability, and the costs arising from mechanized process disruptions due to downtime. The behavior of these costs is highly influenced by the initial reliability of the machine and the conditions under which it is operated. Therefore, the cost function can be simplified as:

$$\sum C = C_F + C_{PMA} + C_{PR} \to \min \quad (8)$$

where C_{PMA} represents the costs of preventive maintenance and repairs.

Each component of the total costs consists of variables that are characterized by their variability and the presence of numerous price-determining factors. To identify the priority indicators of the objective function, it is necessary to examine the mechanisms that influence the formation of these cost components. However, based on current findings, we can assert that the initial cost of purchasing the machine, particularly the investment in higher factory reliability, is critical. This initial expense significantly impacts the other cost components during the machine's operation and forms the foundation for optimizing the total cost function (Figure 1).

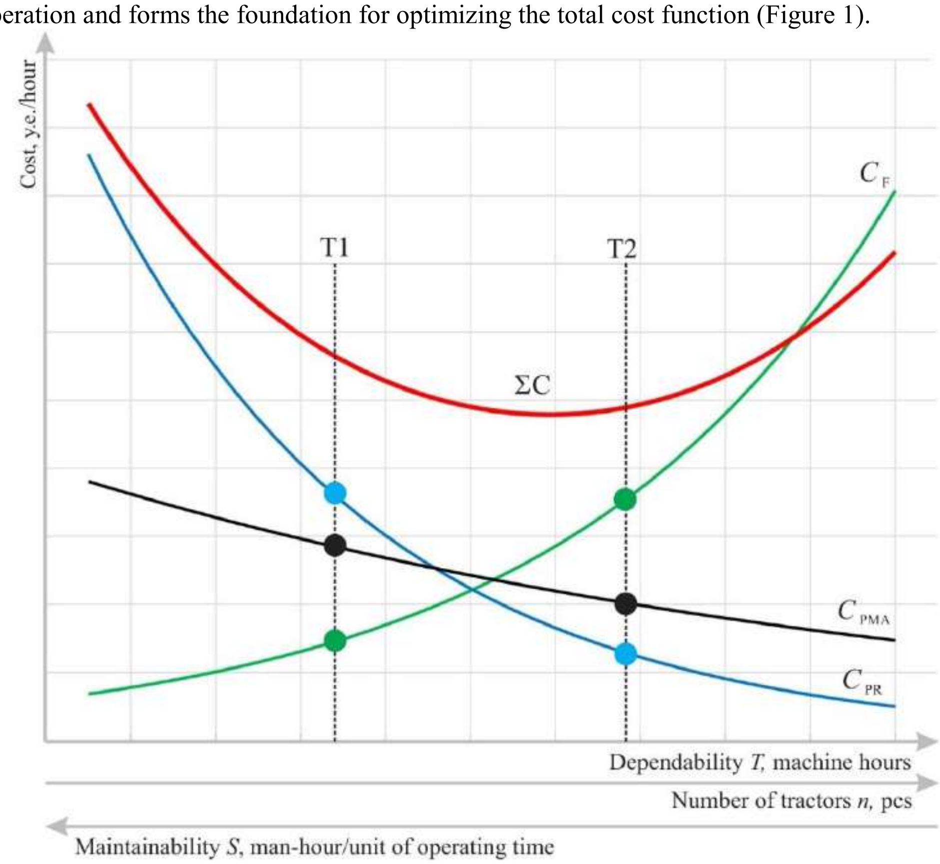

Fig. 1. - Change in the minimum of the total cost function depending on the costs of increasing the level of factory reliability of agricultural tractors C_F, the costs of maintaining and restoring their operability in operation C_{PMA} and complex costs due to losses of crop production C_{PR}.

In Figure 1, two hypothetical tractors are depicted: T1, a cheaper but less reliable tractor, and T2, a more expensive tractor with excessive reliability. This comparison illustrates the balance between cost components. The key to maximizing profit in crop production lies in minimizing total costs ($\sum C \rightarrow$ min). When viewed from a profitability standpoint, delays in crop production (as shown in Figure 1) can lead to losses in both the quantity and the quality of the harvest, resulting in financial losses. At the same time, the reliability of tractors directly correlates with financial costs for manufacturing and maintaining equipment in working condition.

Conclusions

The essence of determining the optimal levels of reliability and maintainability for agricultural tractors lies in identifying rational operational indicators where the total costs - including acquisition, operation, and downtime losses due to malfunctions - are minimized over a given service life (e.g., per 1,000 engine hours, work cycle, etc.). The goal is to achieve the lowest possible cost per unit of work performed.

Increasing factory reliability reduces product losses C_{PR}, but it also raises manufacturing costs and the price of tractors. Product losses depend on factors such as workload, crop yield, and the tractor's factory reliability level. During operation, various reliability and maintainability indicators can be used to assess tractor performance. For instance, tractors of the same class from different manufacturers may be compared using metrics such as mean time between failures and specific labor intensity of maintenance. The point at which the curves of increased factory reliability costs intersect with the cost of losses indicates the minimum total cost function ($\sum C$) and helps determine the optimal range of reliability indicators on the x-axis.

Prospects for Further Development

This article represents the first stage in substantiating the key components of a mathematical model to differentiate tractor reliability indicators. In the next stage, theoretical dependencies will be established, and the three main components of the objective function (from Formula 8) will be analyzed. This will be followed by collecting and evaluating data on tractor performance under real-world operating conditions. In the third stage, experimental data will be used to refine the theoretical models. Ultimately, this will result in a reliable mathematical model for optimizing tractor reliability indicators, tailored to the specific operational conditions of agricultural enterprises.

Foundings

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