RELIABILITY RESEARCH OF FEED PREPARATION AND DISTRIBUTION EQUIPMENT AS "HUMAN-MACHINE" SYSTEM UNDER CONDITION OF "HUMAN" COMPONENT DEVELOPMENT

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Abstract. In modern conditions of development of animal husbandry, in the world practice for preparation, transportation, distribution and dosing of fodder, means for preparation and distribution of fodder are widely used. The purpose of the presented article is to assess and enhance the operational reliability of the mixer-feed dispenser by improving the 'human-operator' component of the complex technical system "human-machine". The article reveals the methodological approaches to the formation and provision of reliability indicators of the mixer-feed dispenser. The presented results are a continuation of previous studies and are aimed at improving the efficiency of use and ensuring the reliability of means for preparing and distributing feed. A graph of states and transitions of the mixer-feed dispenser as a complex technical system has been developed depending on the aging of the 'machine' and 'human-operator' components. An additional fictitious state has been introduced in the graph, which provides for the improvement of the 'human-operator' component. A system of Kolmogorov dynamic balance differential equations for probabilities of states and transitions of a complex technical system 'man-machine' was compiled and solved using Laplace transformations. After a series of transformations, the algebraic equations are solved according to the Cramer's rule. To revert to the original, the fractional-rational function has been decomposed into elementary fractions using the method of undetermined coefficients. For this, the determinant is decomposed into linear factors. An analytical dependence was obtained for calculating the probability of failure-free operation of the mixer-feeder depending on the failure rates and repair rates. One of the promising approaches to improving the reliability of the "human-machine" system is enhancing the professional level of the human-operator, including upgrading the qualifications of the personnel.

Keywords: non-failure, mixer-feeder, human-operator, graph of states.

Introduction

In the last decade, precision animal husbandry, precision farming, smart farming and Industry 4.0 are shaping innovations in modern agricultural production. Leading countries, large global organizations and international agricultural companies use the presented innovative directions as the main indicators for sustainable and effective development of animal husbandry [1]. Global experience in the development of the livestock sector demonstrates that the primary equipment for feeding cattle consists of trailed [2] and self-propelled [3] machines for feed preparation and distribution. The articles [2; 3] indicate that the efficiency of the livestock sector largely depends on the specifics of preparing and distributing balanced feed mixtures for different animal groups [1; 4]. The author of study [2] presented the results of modeling and optimizing the parameters of shredding-mixing mechanisms of feed mixer-distributors. The articles establish that the auger speed and mixing time of the material have a significant impact on the quality of the feed mixture. The results obtained in [3] enable the analysis of the characteristics of shredding, mixing, distributing, and dosing of feed mixtures, allowing for the selection of optimal performance parameters under various operating modes of the equipment.

The authors of scientific articles [4] have proposed dynamic and mathematical models of feed preparation units, which have made it possible to study the nature of load variations in the mechanisms. Justification of the design and optimization of the parameters of the mixer-feed dispenser will ensure shredding and mixing of roughage with minimal specific energy consumption.

Based on the analysis of literary sources and patent searches from previous studies, the authors of work [5] developed and manufactured an improved design of the screw working elements. To study the force parameters and characteristics of the enhanced screw, an experimental setup for transporting bulk agricultural materials was created. This setup is relevant and can be utilized for improvement of feed mixer-distributors.

The authors of the scientific paper [6] proposed to represent mechanized processes in agricultural production as a marked state graph and used Markov random processes with discrete states and continuous time to describe them. Based on the results of the research on accident-prone processes [6], the authors determined the event flow intensities that condition individual states of the graph and the marginal probabilities of objects being in those states.

In operational conditions, the technical state of the feed preparation and distribution equipment changes as part of the “human-machine” system [7], with the influence on the probability of failure-free operation being considered for two components: the ‘human-operator’ and the ‘machine’. The use of the complex technical system “human-machine” has shown changes in the reliability indicators of the technical component – the feed mixer-distributor, as a period of parametric failures arises [7]. The second component of the complex technical system “human-machine” is the human-operator. This component also undergoes changes, as the reliability indicator of the operator [7] changes, such as the probability of error-free operation and the probability of error correction.

The purpose of the presented article is to evaluate and increase the operational reliability of the mixer-feeder by improving the ‘human-operator’ component of the complex “human-machine” technical system.

Materials and methods

The article proposes a mathematical model of the reliability of the PROFILE mixer-feeder (Fig. 1) as a complex technical “human-machine” system during the warranty and post-warranty periods. The influence of the main components of the system on the dynamic characteristics of reliability with the gradual loss of their initial parameters by two components has been revealed. The component systems were based on close interaction between the human operator and the machine. They are sufficiently complex for study and physically exist in different stages of operation, ranging from the accumulation of potential capabilities to aging. The basis of the research was the methodology for calculating the reliability of the mixer-feeder based on the analysis of the marked state graph of the process of functioning of the “human-machine” system [7].

a) b)

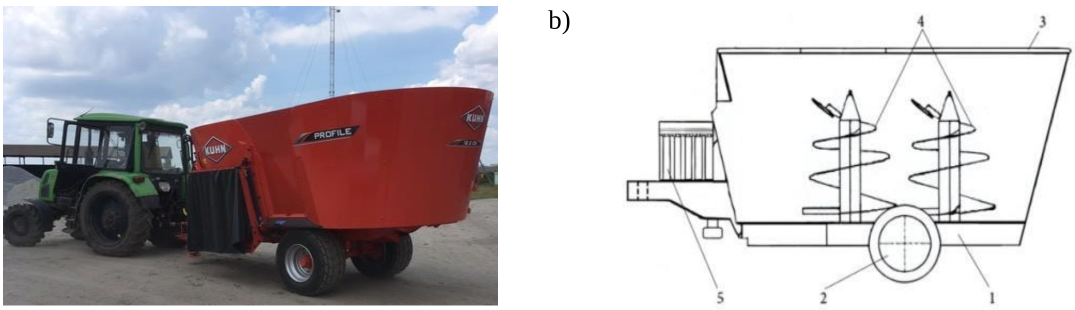

Fig. 1. **Feed mixer-dispenser PROFILE 14.2 DS:** a – under operational conditions; b – scheme of the device; 1 – frame; 2 – chassis; 3 – hopper; 4 – shredding-mixing mechanism; 5 – feed mixture unloading mechanism

The proposed methodology is a continuation of research into complex technical systems, provided that its components, the mixer-feeder and the human operator, age and lose their efficiency as a result of the accumulation of failures [7]. The failures of the feed mixer-distributor and the operator were recorded throughout the life cycles in non-standard situations that occurred during the installation, operation, maintenance, and repair of the equipment. The failures of the operator controlling the machine were characterized by a loss of attention due to the accumulation of fatigue and a decrease in reaction time, which affected the ability to make correct operational decisions.

The presented article conducts a study of reliability of a complex technical system under the condition of improving the ‘human-operator’ component (Fig. 2). To describe the developed mathematical model, Kolmogorov differential equations of state and transition probabilities were used, which were solved using Laplace transforms [8]. The scientific interest lies in introducing intermediate fictitious states to simplify calculations and provide a mathematical description of the system’s functioning, converting the non-Markovian processes of its transitions into Markovian ones: “aging” of the machine; “aging” of the operator; improvement of the operator. After a series of transformations of differential equations, algebraic equations were obtained, which were solved using Cramer’s rule. To return to the original form, the fractional-rational function is decomposed into elementary fractions using the method of undetermined coefficients. For this purpose, the determinant is decomposed into linear factors. An analytical dependence was obtained for calculating the probability of failure-free operation of the system depending on the intensities of failures and restorations in the development of the authors' research [7; 9].

Results and discussion

The graph of states and transitions of the "human-machine" system for an "aging" machine and an operator who improves his level can be presented in Fig. 2. For the presented system, the time to failure decreases, and the failure intensity increases accordingly, transferring the system from a working state to an inoperable state.

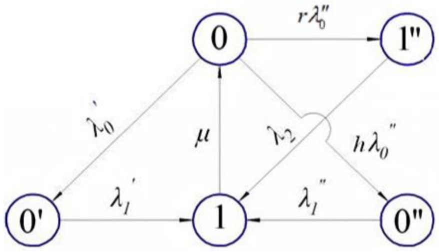

Fig. 2. **Graph of states and transitions of the "human-machine" system for an "aging" machine and an operator who improves his level:** "0" – working state; "1" – inoperative state (operator failure recovery and machine failure recovery); "0′ " – intermediate (fictitious state) of "aging" of the machine; "0″" – intermediate (fictitious state) of "aging" of the operator; "1″" – intermediate (fictitious state) operator improvement; λ'_0, λ''_0, λ'_1, λ''_1, λ_2, $r\lambda''_0$, $h\lambda''_0$ – failure rate; μ – repair intensity

Based on the constructed state and transition graph, differential equations of dynamic balance have been formulated for the state probabilities of the "human-machine" system [8]:

$$\begin{cases} \frac{d}{dt}P_0(t) = \mu P_1(t) - \lambda_0' P_0(t) - h\lambda_0'' P_0(t) - r\lambda_0'' P_0(t) \\ \frac{d}{dt}P_0'(t) = \lambda_0' P_0(t) - \lambda_1' P_0'(t) \\ \frac{d}{dt}P_0''(t) = h\lambda_0'' P_0(t) - \lambda_0'' P_0''(t) \\ \frac{d}{dt}P_1(t) = \lambda_1' P_0'(t) + \lambda_2 P_1''(t) + \lambda_1'' P_0''(t) - \mu P_1(t) \\ \frac{d}{dt}P_1''(t) = r\lambda_0'' P_0(t) - \lambda_2 P_1''(t) \end{cases} \quad (1)$$

where $P_0(t)$ – probability of the system being in working condition;

$P_0'(t)$ – probability of the system being in an intermediate state (fictitious state) – "aging" machines;

$P_0''(t)$ – probability of the system being in an intermediate state (fictitious state) – "aging" of the operator;

$P_1(t)$ – probability of the system being in an inoperable state;

$P_1''(t)$ – probability of the system being in an intermediate state (fictitious state) – for the condition of the operator improving his level.

For the system of differential equations (1), we write a normalizing condition that represents the sum of the probabilities of the states of the "human-machine" system:

$$P_0(t) + P_0'(t) + P_0''(t) + P_1(t) + P_1''(t) = 1.$$

Let us impose the condition that in the initial period of operation for preparing and distributing feed the 'man-machine' is operational and can perform the specified functions according to the requirements of the regulatory and technical documentation. That is, for the system (Fig. 2) we can write:

$$P_0(t) = 1; P_0'(t) = 0; P_0''(t) = 0; P_1(t) = 0; P_1''(t) = 0.$$

Based on the Laplace transforms, the system of differential equations (1) can be represented in the following form:

$$\begin{cases} S\varphi_0(S) = -r\lambda_0''\varphi_0(S) - \lambda_0'\varphi_0(S) - h\lambda''\varphi_0(S) + \mu\varphi_1(S) + 1; \\ S\varphi_0'(S) = \lambda_0'\varphi_0(S) - \lambda_1'\varphi_0'(S); \\ S\varphi_0''(S) = h\lambda_0''\varphi_0(S) - \lambda_1''\varphi_0''(S); \\ S\varphi_1(S) = \lambda_1'\varphi_0'(S) + \lambda_1''\varphi_0''(S) - \mu\varphi_1(S) + \lambda_2\varphi_1''(S); \\ S\varphi_1''(S) = r\lambda_0''\varphi_0(S) - \lambda_2\varphi_1''(S). \end{cases} \quad (2)$$

According to the Laplace transform, the normalization condition will take the following form:

$$S\varphi_0(S) + S\varphi_0'(S) + S\varphi_0''(S) + S\varphi_1(S) + S\varphi_1''(S) = 1.$$

From the analysis of system (2) we see that the most rational way to further solve this system is to replace its first equation with a normalizing condition, and therefore we obtain:

$$\begin{cases} S\varphi_0(S) + S\varphi_0'(S) + S\varphi_0''(S) + S\varphi_1(S) + S\varphi_1''(S) = 1; \\ S\varphi_0'(S) = \lambda_0'\varphi_0(S) - \lambda_1'\varphi_0'(S); \\ S\varphi_0''(S) = h\lambda_0''\varphi_0(S) - \lambda_1''\varphi_0''(S); \\ S\varphi_1(S) = \lambda_1'\varphi_0'(S) + \lambda_1''\varphi_0''(S) - \mu\varphi_1(S) + \lambda_2\varphi_1''(S); \\ S\varphi_1''(S) = r\lambda_0''\varphi_0(S) - \lambda_2\varphi_1''(S). \end{cases} \quad (3)$$

We will solve the system of linear algebraic equations (3) using the Cramer's rule [8]:

$$\varphi_0(S) = \frac{\Delta_0}{\Delta};\ \varphi_0'(S) = \frac{\Delta_0'}{\Delta};\ \varphi_0''(S) = \frac{\Delta_0''}{\Delta};\ \varphi_1(S) = \frac{\Delta_1}{\Delta};\ \varphi_1''(S) = \frac{\Delta_1''}{\Delta}; \quad (4)$$

where Δ – main determinant of a system of equations (3);
Δ_0, Δ'_0, Δ''_0, Δ_1, Δ''_1 – determinants for determining unknowns $\varphi_0(S)$, $\varphi'_0(S)$, $\varphi_0(S)$, $\varphi''_1(S)$, $\varphi''_1(S)$ accordingly.

Having written the system of equations (3) in a form convenient for applying the Cramer's rule, we find the main determinant of this system of equations:

$$\Delta = \begin{vmatrix} S & S & S & S & S \\ -\lambda_0' & (S+\lambda_1') & 0 & 0 & 0 \\ -h\lambda_0'' & 0 & (S+\lambda_1'') & 0 & 0 \\ 0 & -\lambda_1' & -\lambda_1'' & (S+\mu) & -\lambda_2 \\ -r\lambda_0'' & 0 & 0 & 0 & (S+\lambda_2) \end{vmatrix}. \quad (5)$$

As it can be seen from (5), this determinant is a square matrix of the fifth order. The determinant Δ_0 can be written in the following form:

$$\Delta_0 = \begin{vmatrix} 1 & S & S & S & S \\ 0 & (S+\lambda_1') & 0 & 0 & 0 \\ 0 & 0 & (S+\lambda_1'') & 0 & 0 \\ 0 & -\lambda_1' & -\lambda_1'' & (S+\mu) & -\lambda_2 \\ 0 & 0 & 0 & 0 & (S+\lambda_2) \end{vmatrix}. \quad (6)$$

After calculating the determinants Δ and Δ_0, using expression (4) and a series of transformations, we obtain:

$$\varphi_0(S) = \frac{\Delta_0}{\Delta} = \frac{(S+\lambda_1')\cdot(S+\lambda_1'')\cdot(S+\mu)\cdot(S+\lambda_2)}{\lambda_0'(S+\lambda_1'')\cdot S\cdot(S+\lambda_2)\cdot(S+\mu+\lambda_1') + (S+\lambda_1')\cdot\left\{\begin{matrix} h\lambda_0''\cdot S\cdot(S+\lambda_2)\cdot(S+\mu+\lambda_1'')+ \\ +(S+\lambda_1'')\cdot S\cdot\begin{bmatrix}(S+\mu)\cdot(S+\lambda_2)+ \\ +r\lambda_0''(S+\mu+\lambda_2)\end{bmatrix}\end{matrix}\right\}} \quad (7)$$

To return to the original, we decompose the fractional-rational function (7) into elementary fractions using the method of undetermined coefficients. To do this, it is necessary to decompose the denominator of the fraction (7), i.e. the determinant Δ, into linear factors. Therefore, the next step will be to perform the necessary transformations of the determinant Δ and introduce the following notations:

$$A = \lambda_0' + h\lambda_0'' + \lambda_2 + \mu + r\lambda_0'' + \lambda_1'' + \lambda_1';$$

$$B = \lambda_0'\mu + \lambda_0'\lambda_1' + \lambda_0'\lambda_2 + \lambda_0'\lambda_1'' + h\lambda_0''\mu + h\lambda_0''\lambda_1'' + h\lambda_0''\lambda_2 + h\lambda_2 + r\lambda_0''\mu + \\ + h\lambda_0''\lambda_2 + \lambda_2\lambda_1'' + \mu\lambda_1'' + r\lambda_0''\lambda_1'' + h\lambda_0''\lambda_1'' + \lambda_2\lambda_1' + \mu\lambda_1' + r\lambda_0''\lambda_1'' + \lambda_1''\lambda_1';$$

$$C = \lambda_0'\lambda_2\mu + \lambda_0'\lambda_2\lambda_1' + \lambda_0'\lambda_1''\mu + \lambda_0'\lambda_1''\lambda_1' + \lambda_0'\lambda_1''\lambda_2 + h\lambda_0''\lambda_2\mu + h\lambda_0''\lambda_2\lambda_1'' + \mu\lambda_2\lambda_1'' + \\ + r\lambda_0''\mu_1\lambda_1'' + r\lambda_0''\lambda_2\lambda_1'' + h\lambda_0''\mu\lambda_1' + h\lambda_0''\lambda_1''\lambda_1' + h\lambda_0''\lambda_2\lambda_1' + \mu\lambda_2\lambda_1' + r\lambda_0''\mu\lambda_1' + r\lambda_0''\lambda_2\lambda_1' + \\ + \lambda_2\lambda_1''\lambda_1' + \mu\lambda_1''\lambda_1' + r\lambda_0''\lambda_1''\lambda_1';$$

$$D = \lambda_0'\lambda_1''\lambda_2\mu + \lambda_0'\lambda_1''\lambda_2\lambda_1' + h\lambda_0''\lambda_2\mu\lambda_1' + h\lambda_0''\lambda_2\lambda_1''\lambda_1' + \mu\lambda_2\lambda_1''\lambda_1' + r\lambda_0''\mu\lambda_1''\lambda_1' + r\lambda_0''\lambda_2\lambda_1''\lambda_1'.$$

Given the introduced notation, the determinant Δ can be written in the following form:

$$\Delta = S \cdot \left(S^4 + AS^3 + BS^2 + CS + D\right). \tag{8}$$

The coefficients C and D in expression (8) can be neglected, since the terms they consist of are products of three and four numbers, respectively, from the set $\{\lambda'_0, \lambda'_1, \lambda''_1, \lambda_2, r\lambda''_0, h\lambda''_0, \mu\}$, therefore they are quantities of a high order of smallness. As a result, expression (8) will take the following form:

$$\Delta = S^3 \cdot \left(S^2 + AS + B\right). \tag{9}$$

After determining the roots of equation (9), expression (7) will take the following form:

$$\varphi_0(S) = \frac{\Delta_0}{\Delta} = \frac{(S+\lambda_1')\cdot(S+\lambda_1'')\cdot(S+\mu)\cdot(S+\lambda_2)}{S^3(S-S_4)\cdot(S-S_5)} = \frac{K}{S^3} + \frac{P}{S^2} + \frac{N}{S} + \frac{Q}{S-S_4} + \frac{R}{S-S_5}. \tag{10}$$

where S_4 and S_5 – roots of the equation (9);
K, P, N, Q, R – unknown coefficients, which are determined by the method of uncertain coefficients.

Having determined the coefficients K, P, N, Q and R, we obtain:

$$\varphi_0(S) = \frac{N}{S} + \frac{Q}{S-S_4} + \frac{R}{S-S_5}. \tag{11}$$

By performing the inverse Laplace transform, we will obtain a dependence for determining the probability of failure-free operation of the "human-machine" system in conditions of a decrease in its performance level and improvement of the 'human-operator' component. The analytical dependence consists of three parts, the first of which characterizes the condition when $t \to \infty$, and others can be neglected. The probability of failure-free operation of a complex "human-machine" system for such a case will be:

$$P_0(t) = K_2(t) = \frac{\lambda_2\mu +' \lambda_1''\lambda_2 + \lambda_1''\mu + \lambda_1'\lambda_2 + \lambda_1'\mu + \lambda_1'\lambda_1''}{S_4 S_5}. \tag{12}$$

The analysis of components (12) and the use of the results given in [7] make it possible to construct graphs of the dependence of the change in the probability function of failure-free operation of the 'man-machine' system on the operating time when the intensity of restorations changes. To assess the correspondence of theoretical results to real ones, the results of operational trials of PROFILE 14.2 DS feed mixers were used [9]. The results are presented in Fig. 3.

There are several reasons for the transition of the 'human operator' component, which serves the mixer-feed dispenser, into an inoperable state. First of all, during the process of installation, adjustment and commissioning of new means for preparing and distributing feed or in case of complex failures, the operator becomes familiar with its design, features of use, maintenance and repair [7; 9] (Fig. 3, a). In the process of "aging" of equipment, failures become more complicated, the time for their restoration increases, there is a need for long-term advanced training or training for 90-100 hours, which increases the probability of failure-free operation to 0.94.

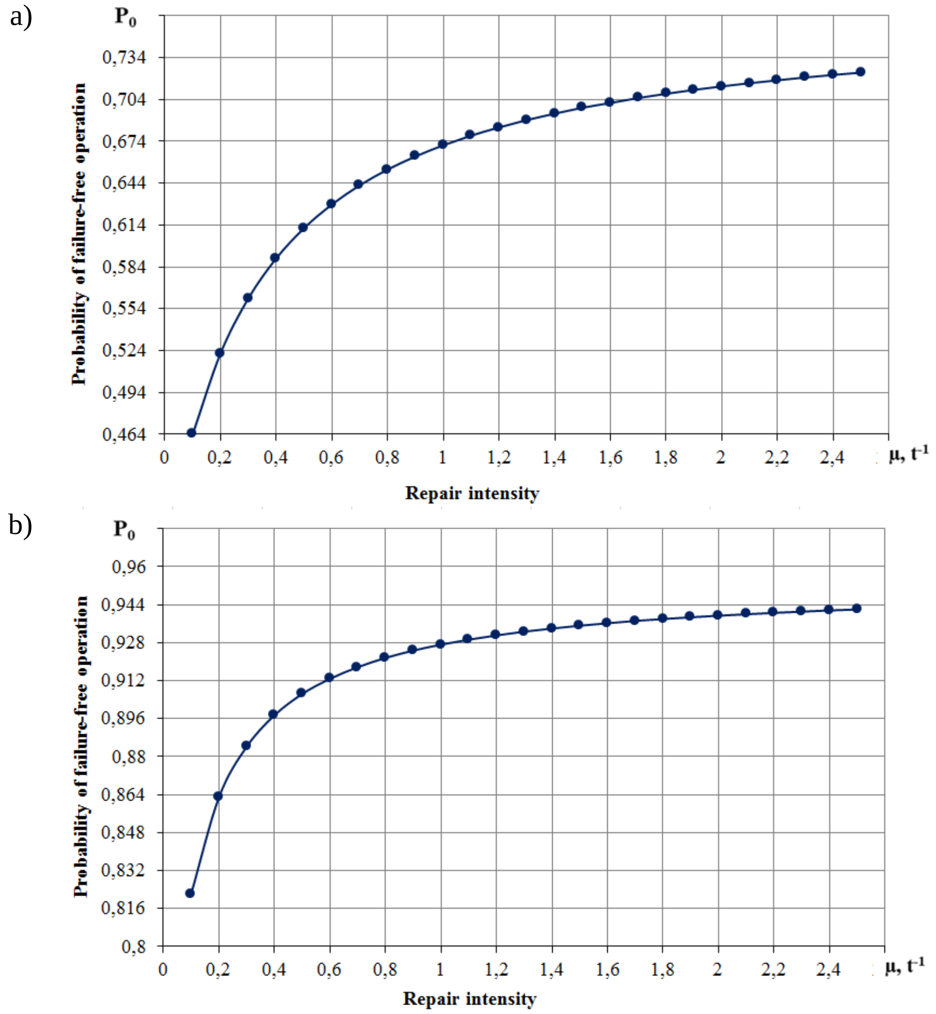

Fig. 3. **Graphs of dependence of probability of failure-free operation of the system upon operator qualification improvement:** a – long-term; b – short-term

If the operator's qualifications are insufficient or if they frequently change their type of work, the 'man-machine' system will lose its operational capacity much more often, primarily due to the influence of the 'man-operator' component (Fig. 3, b). However, a short training period of up to 10 hours only provides a probability of failure-free operation up to 0.72. Improving the qualifications of the personnel positively affects the probability of failure-free operation and reliability of the 'man-machine' system through long-term qualification enhancement and improvement of the professional level of the personnel has increased from 0.72 to 0.94.

The authors of [10] note that the efficiency of using feed loaders is determined by the ergonomics of the machine and the professionalism of the staff. The article [10] mentions that the efficiency of operators ranges from 5.48% to 12.23%, which negatively affects not only the quality of the feed mixture but also the productivity and health of animals. In the presented scientific paper, the authors propose to increase the reliability of personnel and ensure the operational capability of the system by constantly maintaining the professional level of machine operators.

The article [11] confirms the importance of combining the functions and activities of the operator and service personnel, who have sufficient knowledge, skills and abilities for effective development of 'man-machine-machine' systems. Since Industry 4.0 is implemented through innovative approaches, in order to increase the efficiency of the use of resources, monitoring should be combined with the use of systematic research methods and operator reliability.

The authors of study [12] investigated the maintainability indicators of the vertical auger drive mechanism in the feed mixer-distributor. The practice of restoring the operational capability of the research object [12], along with the findings from study [9] and the authors' own research, confirm the impact of the operator on the choice of restoration technology and the duration of the repair.

The scientific study [13] established that the power of the feed loading equipment from storage facilities depends on the operator's experience and professional skills, as well as a thorough assessment of the technical condition of working components and mechanisms.

Conclusions

1. The global experience in the development of the livestock industry shows that the main equipment for feeding cattle is mixer-feeders. During operation, the means for preparing and distributing feed gradually lose their effectiveness due to "aging" of the components and parts. The loss of operator efficiency occurs due to insufficient qualification and decreased attention.
2. The model of the "human-machine" system can be represented as a labeled graph of states and transitions with stochastic differential equations for the balance of probabilities, using Kolmogorov's equations. The operating conditions of the system are reduced to Markovian time distribution flows for operation and recovery by introducing additional fictitious states. The main determinant of the system of equations, which describes the transitions of the mixer-feeder into various possible states, is the combination of failure and recovery intensities, which are necessary computational components for reliability calculations.
3. Improving personnel qualifications positively impacts the probability of failure-free operation of the mixer-feeder as a "human-machine" system. The reliability of the "human-machine" system increased from 0.72 to 0.94 due to prolonged qualification improvement and enhancement of the professional level of the personnel.
4. Studies of the influence of the age and length of service of the operator on the reliability of the human-machine system may be promising.

Author contributions

Conceptualization, A. N., I. G.; methodology, A. N.; validation, A. N., I. G., O. B. and Y. N.; formal analysis, A. N. and V. M.; data curation, O. B., Y. N.; writing – original draft preparation, O. B. and Y. N.; writing – review and editing, A. N. and I. G.; visualization, O. B.; project administration, A. N.; funding acquisition, A. N., I. G., O. B. and Y. N. All authors have read and agreed to the published version of the manuscript.

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