Models for optimization the preventive maintenance schedules of mechanical systems in metallurgy

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Abstract
The optimization models for strategy of preventive maintenance are considered in this article. The possibilities of economic and statistical optimization models for maintenance and repair (M & R) of industrial enterprises mechanical systems were analyzed. The limited application of these models for maintenance of high-risk objects is shown. At transition to the maintenance on the technical condition, the accent in spending money on M & R is shifted from repair effects on diagnosing the technical condition, which solves the problem on the following dates and volumes of remedial actions. The relevance of planning of technical condition monitoring operations is growing.
On the basis of a review of models and algorithms for operational processes, this work aims to help practitioners to understand, which criteria should be followed when setting the particular equipment maintenance modes. Therefore, the objectives of this work are as an adaptation of known methods for determining the periodicity of controls to the engineering tool reliability, as well as analysis of preventive maintenance models capabilities for optimization of their modes.
Key words: MAINTENANCE, TECHNICAL CONDITION, RISK, SECURITY, CONTROL, MONITORING, FAILURE

The relevance of the problem and problem statement

Issues of maintenance and repair of mechanical systems of technological equipment have always been important to the industrial sector, but they have particular relevance to the metallurgical industry. This is due to several factors. The costs of raw materials and energy make up a major share of the prime cost of steel products (significantly more than 50%). The costs of maintenance and repair (M & R) also occupy a considerable share (about 10%). Taking into account that the share of other costs does not exceed this value (sometimes 3 times less), the surplus value of metallurgical production share of costs associated with the maintenance of equipment is stable of more than half, sometimes reaching 70% or more [1].

The share of maintenance staff can reach 35% of the total payroll of the metallurgical enterprise [1].

Even in the modern conditions of outsourcing the support services and optimization of staff structure, a number of repairmen does not fall below 20-25%, which is illustrated by the metallurgical plant “Evraz” in Dnipro. A similar situation is typical for foreign industrial production, as can be seen in the indices characterizing the state of M & R. Thus, the first index as a ratio of M & R costs to all costs for general industrial production is 5%, separately for the chemical industry the index is 6.8% and for the steel industry (metallurgy) it is 12.8%. In metallurgy, M & R costs amount to 8.6% of the investment in production (compared to 3.8% in chemistry) (third index) [2, 3].

Taking into account the particular relevance of M & R technologies for metallurgical production, in order to optimize costs of this item, the enterprises management gradually began to move away from the traditional planned - preventive maintenance systems with their tough schedule (preventive maintenance - PM, Figure 1). In some enterprises, tightness in money on M & R led to corrective maintenance strategy when remedying measures were made after the facts of failure (CM, Figure 1). As can be seen, in both strategies of money spending, *C* is far from optimal and the use of PM and CM-strategies can be justified only on the individual stages of the operation. Maintenance strategy according to technical condition (technical condition maintenance - TCM, Figure 1) contributes to minimizing expenditure on equipment and maximizing its readiness. This strategy assumes the use of a flexible schedule of repairs and it is characterized by the active use of methods of technical diagnostics, in foreign literature such strategies are referred to as proactive (predictive) maintenance [2, 3], imperfect maintenance [4]. Type of strategy with the reliability control (reliability centered maintenance - RCM) [2] is known and widely used in addition to considered types of maintenance with parameters control. There is the problem of evaluating the effects of failures that have led to the development of risk control and security strategy (RBI- risk based inspection concept).

Considering the information above, the producers of metallurgical equipment (e.g., SMS Meyer, SMS Siemag, Danieli, Eirich) has begun to equip it with integrated operation control systems, and, most notably, they offer after-sales service maintenance [5-7]. Essentially, this is a recommendation by dates of components replacement, which is carried out (sometimes in on-line mode) according to the results of technical condition monitoring. This trend is relevant, since taking into account the attention to outsourcing, the mechanics specialists are rejected from equipment, which they constantly watch over and the amount of information that characterizes the technical condition grows and becomes more complicated.

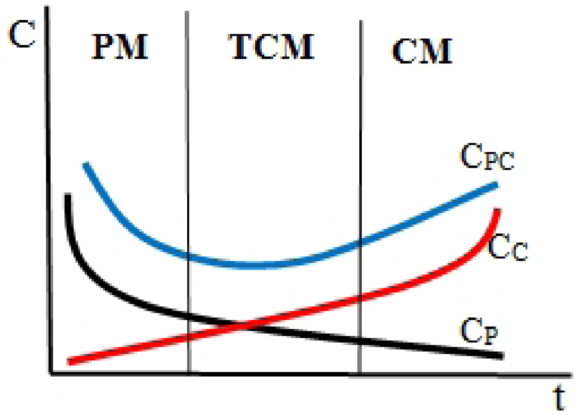

Figure 1. Charts of change in general maintenance costs (C_{PC}), expenditure on preventive (C_P) and after failure (C_c) repairs in time operation (t), and also compliance of their periods to strategies of M & R (PM- preventive maintenance, CM-corrective maintenance, TCM- technical condition maintenance)

At transition to a maintenance strategy according to technical condition, accent in money spending on M & R is shifted from repair operations on the diagnosis of technical condition, which solves the problem on the following dates of the volumes remedial action. Information about the operation of the equipment along with material resources is becoming a real factor of production influencing its effectiveness. In such a situation, the relevance of schedules of its examinations, inspections and controls of technical condition increases rather than that of equipment.

Initially, the domestic mechanics-scientists did not pay enough attention to the maintenance and repair (M & R) of equipment leaving this niche mainly to specialists in the organization of production and management [8-9]. Abroad, specialists in mathematical statistics are actively involved in this [10-14]. Therefore, mathematical and statistical reliability methods dominate on the basis of the majority of the technical condition models and in their estimation algorithms. They focus on economic criteria and are not related to the physical essence of degradation processes. In many ways, this contributed to the fact that the rapid development of the theory of reliability in the 50-ies years of the last century was due to its application to electronic systems. They are distinguished from the mechanical systems by a significant amount of relatively inexpensive items that justifies the use in such a situation of mathematical and statistical methods.

This fact played a positive role in the formation of the machines reliability theory. The impetus for its development served as the intensification of production in 60-ies years of the last century. Developed at the time direction of the reliability of the metallurgical equipment (hereinafter its methodology has been extended to technological equipment of other industries) is largely based on the results achieved by overall reliability theory. At the same time, the probabilistic methods of structural mechanics began to be applied to predict the resource [14-16]. The founder of this direction V. M. Grebenik explained reliability as a probabilistic strength, unfortunately, without showing the ways of its use to optimize the operation process of equipment [16]. Nevertheless, an extensive background literature on the issues of combining the questions of reliability, safety and operation of mechanical systems was developed all over the world [2-4, 10, 11, 17-21].

In the initial stages of development of M & R planning methods the issues of improving its efficiency were successfully solved within the framework of the organization of production. Modern M & R systems are characterized by updated forecasting of resources at the various phases of operation, evaluation of faults and defects development. Such problems cannot be solved only by management methods, which in this area have been exhausted. However, one of the main objectives of management is reducing the specific costs of maintenance and repair. It coincides with the main purpose of the mechanical service businesses – increasing equipment readiness. That is execution of a single task – readiness growth, which automatically leads to the solution of another problem - reduction of costs.

On the one hand, the combination of mathematical-statistical and probabilistic-physical approaches to the problem of the mechanical systems reliability enriches its toolkit making the complex problem. It attracts researchers of different profiles to this area. On the other hand, such an abundance of methods makes it difficult to find the optimal way for the practical use of the assessment results reliability. In particular, it refers to the stage of equipment operation, its maintenance from a set of rules has become a technology with its specific methods [22-24]. The terotechnology appears. It is interdisciplinary field of activity combining the impact of technological, technical, organizational and financial factors on the efficiency of use of the equipment [25]. It became a particularly relevant due to the widespread introduction in the production of means of technical diagnosing and widespread transition to a maintenance strategy according to the technical condition (TCM). Increasing the amount of information about the technical condition of the object leads to its incomplete use in order to predict the behavior of mechanical systems in operation. Therefore, along with the main task of TCM (reducing the cost on M&R) the experts develop approaches to the use of valuation techniques and maintaining of equipment conditions to improve the quality of metallurgical products [26], as well as to reduce the risk and safety of metallurgical production [27-31]. Thus, a more effective use of monitoring systems for the operation of the equipment is achieved.

In matters of periodicity of diagnosis, inspection, monitoring the technical condition the views of experts differ fundamentally: from a fundamental rejection of the diagnosis to the continuous monitoring of a significant number of parameters. The conflict of interests between maintenance staff and production management is well known in the domestic metal industry. But its presence is recognized also in the global industry, where repairers tend to excessive “care” over equipment (overmaintenance) and production workers do not see such a necessity (undermaintenance) [10, 32]. In theory of stimulation, this phenomenon is called moral hazard problem [9].

Despite the obvious relevance of periodicity monitoring, the technical condition of the metallurgical equipment, they do not find reflection in modern Russian textbooks on technical diagnostics and maintenance of machines [33-37].

This work based on a review of models and algorithms for operational processes aims to help practitioners understand what criteria should be followed when setting the technical maintenance modes for particular equipment. Therefore, the objectives of this work are an adaptation of the known methods for determining the periodicity controls to the engineering tool reliability and analysis of capabilities of preventive maintenance models for optimization of their modes.

M & R system with preventive repairs (PM - preventive maintenance) refers to the strategy of using the equipment according to the standard and represents sequence of periodically scheduled PM- repairs, which schedule failures randomly by conducted after-failure corrective repairs (CM-corrective maintenance). M & R model for this strategy was considered by Dillon [2, 3]. It is based on Markov processes of transition with λ, λ_p, μ, μ_p intensities of working-serviceable condition (G, Figure 2) to phase PM- or CM- repair (and vice versa).

Inspection at this strategy is intended to reduce the number of CM repairs taking on a part in M & R costs.

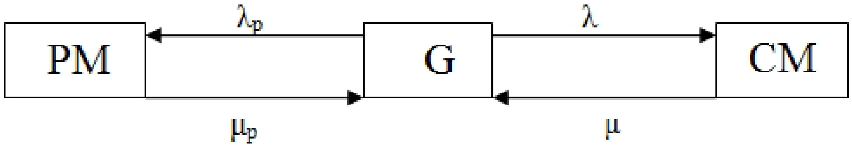

Figure 2. Scheme of preventive maintenance model

Minimizing of downtime

The total downtime can be expressed as follows:

$$TDT = n_i \cdot T_i + \frac{m \cdot T_b}{n_i}, \quad (1)$$

where n_i – the number of inspections per unit time (frequency of inspections),

T_i and T_b - time spent, respectively, on inspections and on failure recovery,

m - constant related to the peculiarities of the technical system.

It is obvious that the total downtime *TDT* is proportional to the frequency and time of the inspection (1, Figure 3). At first sight, it is not quite clear whereby the frequency of inspections contributes to the reduction of the TDT value (2, Figure 3). This can be explained by the above-mentioned decrease in the number of failures that is possible when the inspection (revision), along with the control of technical condition parameters is accompanied by urgent repair of replaceable elements. Such a situation is not certain for any technical system; in particular, this model is not always applied to the mechanical systems in metallurgy. For them, during inspection following measures should be done: replacement of lubrication, adjustment of units, tightening of fasteners, i.e. actions “mitigating” operating conditions. In this regulation, this model is suitable for mechanical equipment of industrial enterprises.

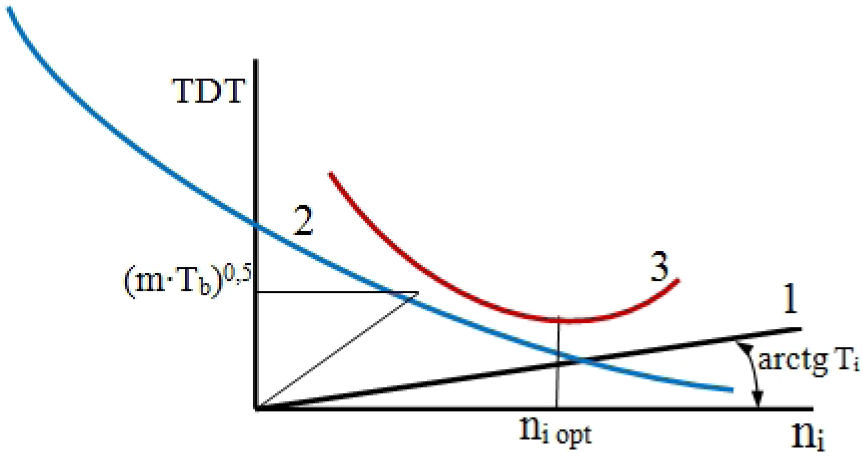

Figure 3. Graphic interpretation of downtime model (1)

Having studied *TDT(n_i)* function for a minimum (3, Figure 3), the optimum value of the inspections frequency is obtained [2]:

$$n_{iopt} = \sqrt{{m \cdot T_b}/{T_i}}. \quad (2)$$

Denoting the relative time repairs as $T_r = T_b/T_i$, the optimal interval between the inspections is obtained:

$$\delta_{opt} = (m \cdot T_r)^{-0,5}. \quad (3)$$

The second model of downtime proposed in [2] is the sum of the specific time for repair DT_b and on inspection DT_i: $TDT = DT_b + DT_i$. Whence

$$TDT = \frac{\lambda}{\mu} + \frac{n_i}{\theta}, \quad (4)$$

where θ - intensity of the output time from the inspection phase.

The graph of this equation is similar to graph 3 (Figure 3). Equating derivative to zero, we obtain the dependence to determine the optimal frequency of inspections:

$$\frac{d(TDT)}{dn_i} = 0$$

$$\frac{d\lambda}{dn_i}=\frac{\mu}{\theta}=\frac{T_i}{T_b}=\frac{1}{T_r}. \quad (5)$$

A relatively simple solution to this equation can be obtained for the exponential law of mean time between failures (MTBF), when its intensity is represented in the form [2]:

$$\lambda=\frac{1}{T_0}\exp(-n_i), \quad (6)$$

where T_0 – specified service life in the absence of M & R.

Here the basic position of the first model on the positive impact of inspections is supported: with increasing their frequency the failure rate decreases, and operating time increases. As it is for the first model, it should be noted that this statement is not true for all the degradation processes, but only for those which are controlled by direct diagnostic feature (wear, vibration). The accumulation process of fatigue damages is controlled by indirect indications, so in this case a positive influence of inspection weakens.

From equation (6) we obtain:

$$n_{iopt}=\ln\left(\frac{\theta}{\mu\cdot T_0}\right) \text{ or } \delta_{opt}=\left(\ln\frac{T_r}{T_0}\right)^{-1}. \quad (7)$$

This form is convenient because it allows to obtain a relative interval δ^r_{opt} when taking $T_0=1$ (the model is valid for $T_r/T_0>1$).

Minimizing the expenditure intensity on M & R

Assessing the total losses of downtime per time unit c_m, the costs intensity balance is represented as follows [2]

$$c=c_m-\frac{c_m\cdot n_i}{\theta}-\frac{c_m\cdot\lambda}{\mu}-\frac{n_i\cdot c_i}{\theta}-\frac{c_{pc}\cdot\lambda}{\mu}, \quad (8)$$

where c_i and c_{pc} – specific costs of a single act of inspection and repair, respectively.

The value located in the left side of this equation is a not considered part of the intensity losses and, in fact, it is a characteristic of the operation risk associated with the missed profit and social consequences [29].

After differentiating the equation (8), we denote the relative cost of the repair costs as $c_r=(c_m+c_{pc})/(c_m+c_i)$ and obtain optimal interval between inspections:

$$\delta_{opt}=\frac{1}{\ln\frac{T_r\cdot c_r}{T_0}}. \quad (9)$$

It is clear that intervals defined by (7) and (9) do not coincide. Taking into account that $T_r>1$, $c_r>1$, the optimum interval between inspections determined by model minimum costs intensity will be less than the value of δ_{opt} determined by the minimum downtime model. However, such a ratio as will be shown below is observed not for all models.

The connection of between inspection interval with a specified service life T_0 was found in [38] from the condition of constancy of the costs intensity on M & R c_1 for the exponential law of reliability:

$$\delta_{opt}=\left(2T_0\frac{c_i}{c_1}\right)^{1/2}. \quad (10)$$

Taking into account that the share of expenditures on inspection c_i is insignificant in the total expenditures c_1, using the adopted conventions this formula can be converted to a form suitable for comparison:

$$\delta_{opt}=\left(\frac{2T_0}{c_r}\right)^{1/2}. \quad (11)$$

From the graphs of dependencies (9) and (11) for relative periods δ^r_{opt} we can assume that the difference between the two models is insignificant (Figure 4). The more expensive the repair, the less the cost of inspection, the more it can be conducted. When values $c_r>20\text{-}30$ optimal relative value of between the inspection period is no longer depend strongly on this factor.

For objects defining the production safety, which have high relative cost of repairs $c_r>80\text{-}100$, the optimal relative interval is $\delta^r_{opt}=0.15\text{-}0.20$. Thus, for the mechanical systems of industrial production following these models, 3-6 inspections for the entire service life can be recommended. A similar result was also obtained for the models based on probabilistic and physical interpretations of the degradation process [39].

In his first TDT-model (1) - (4) Dillon did not explain how to choose the constant *m*. From the comparison of the two models, it is clear that it has the dimensions of a square of operational events frequency depending on the frequency of inspections n_i. Consequently, the use of the model (1) is problematic for the mechanical systems, which have significant downtime from failures when $T_b>>T_i$.

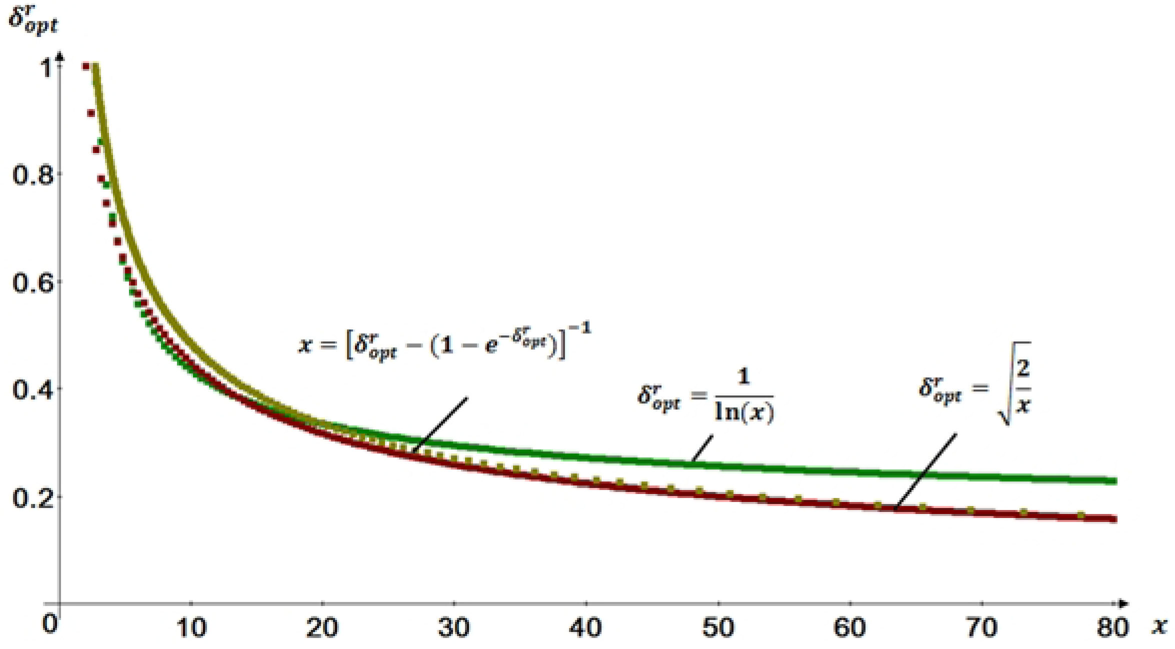

Figure 4. Graphs for the optimal relative between inspection intervals δ^r_{opt}, obtained for model (9) ($x= T_r \cdot c_r$), (11) ($x=c_r$) , and for model (21) ($x=c_r$)

Probability-cost models to optimize M&R modes

In many operational practices inspections, diagnostic monitoring and revisions are an integral part of prevention actions, under which a system restore is performed. Periodic inspections determine the amount of preventive maintenance. In this situation, the frequency of repairs and inspections is coincided and the known solutions for finding intervals of prophylactic (preventive) repairs can be used.

Probability-cost model is generally the sum of the productions $P_k(t_j)$ residence of the system in a phase of technical condition at the moment of control time t_j and "cost" of the system being in this phase C_k:

$$C(t) = \sum^{k} P_k(t_j) \cdot C_k \qquad (12)$$

Changing in time probability $P_k(t_j)$ plays the role of the weighting coefficient. Because it is associated with the time (in fact, having the dimension probability/time), the costs C found by (12) obtain meaning of unit costs c, i.e. the operation costs t_j.

In the statistical aspect, the function of time distribution of the object location in an appropriate phase of technical condition is inverse to the function $P_k(t_j)$. So, for the reliability function, inverse function is that of distribution of $T(P)$ or of durability distribution T_p. However, to determine the costs function C by function $(T_p)^{-1}$ put in the formula (12) instead of $P_k(t_j)$ is basically possible if only the operating model is represented by no more than two phases of technical condition forming a complete group of events. Although, the calculations results will not be the same.

If not to interpret the technical condition by its various phases, the ratio $c(t)=C_\Sigma/T_p$ is used to calculate the unit costs; in the numerator overall remediation costs are located [1]. In addition to the limited application among the inconvenience, a posteriori nature and the implicitness of extremum availability should be noted. It is not clear how the number of after failure repairs and their cost increase while extending service life will. This approach is suitable for evaluating of optimal operational strategies but not for optimizing the M&R modes parameters.

In the most common case, the state of the technical system is described by two phases: preventive repair with unit costs c_p, and corrective repair with unit costs c_c, which reflect consequences of failure.

As compared with a scheme of preventive maintenance model shown in Figure 2, in this case the phase G (operative condition) and PM (prevention) are combined. Therefore, for them value $P_p(t_j)$ is the probability of the system work without failure $P(t)$ and the probability of being in a phase of correction repair $P_c(t_j)$ correspond to the probability of failure, i.e. $P_c(t_j)=1- P(t)$. Then, (12) will be of the following form:

$$C(t) = C_p(t) + C_c(t) = P(t) \cdot C_p + [1 - P(t)] \cdot C_c \qquad (13)$$

In order to obtain the desired for optimization cost intensity function, this expression should be divided by the mean time between failures for the interval from 0 to a maximum set time of operation T_0, as that for this task the overhaul (between inspection) interval δ is selected [17, 38]:

$$c(t) = c_p(t) + c_c(t) = \frac{P(t)\cdot C_p + [1 - P(t)]\cdot C_c}{\int_0^{\delta} P(t)dt} \qquad (14)$$

The value of the integral in the denominator of this expression is somewhat less than the upper limit of δ, and for specified time $\lambda t<2$, it can be taken equal to δ.

The graphs making up the cost intensity functions $c_p(t)$ and $c_c(t)$ are symmetrical to horizontal line passing through the point $0.5c_p$ when $c_p = c_c$, i.e. if the relative costs, which in this case are conveniently to denote as $c_r = c_c / c_p$, are equal to one (Figure. 5). In this situation, the cost function is constant ($c_c=c_p=c=const$) and it is not subject to optimization. In fact, for the mechanical systems $c_p<c_c$, functions $c_p(t)$ and $c_c(t)$ decrease and increase with different intensities, and their sum function will have a minimum at a point of their intersection, which corresponds to δ_{opt}. The greater the value c_r, the lower the interval δ_{opt} and the steeper ascending branch of the graph $c(t)$. In general, at $c_p << c_c$ situation when $\delta_{opt}\rightarrow 0$ is possible.

If in the integral (14) the upper limit is not restricted by its use, it is possible to find the average resource T_0, which is implemented for the maintenance-free system:

$$T_0 = \int_0^{\infty} P(t)dt. \qquad (15)$$

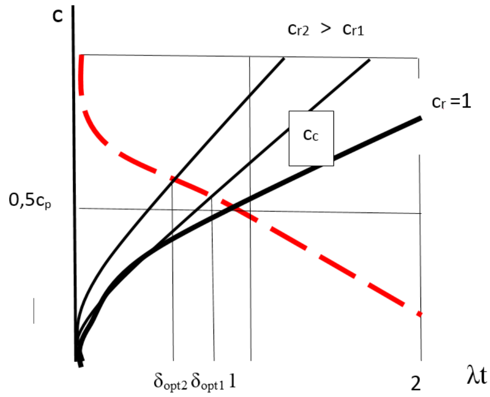

Figure 5. The graph of costs intensity on preventive (dotted line) and after-failure (continuous) recovery for different relative costs c_r

If the system is serviced periodically with an interval δ, its resource increases in accordance with the expression [2]:

$$T_{0p} = \frac{\int_0^{\delta} P(t)dt}{1 - P(\delta)}. \qquad (16)$$

The probability of system failure by the end of the interval between the inspection is located in the denominator of this expression. The less this value, the higher the resource of regularly restored system.

In order to experience the efficiency of the above models, let us consider a system of two parallel and simultaneously working elements, one of which is sufficient for operation of the facility. The intensity of failure flow is $\lambda=0.1\ years^{-1}$, and the relative cost of unscheduled repairs is $c_r=20$. The reliability function for the system of such a configuration will be:

$$P(t) = 2\exp(-\lambda t) - \exp(-2\lambda t). \qquad (17)$$

Approximation of the integral in (14) gives the mean time between failures during the life-cycle (by the end of interval δ), which has a form:

$$T_{\delta} = \frac{3}{2\lambda} - \frac{2}{\lambda}\exp(-\lambda\delta) + \frac{1}{2\lambda}\exp(-2\lambda\delta). \qquad (18)$$

Then, for maintenance-free systems $T_0=3/(2\lambda)$.

Solutions for a minimum of function $c(t)$ using reliability function as Veybulla- Gnedenko law were tabulated for a relative interval δ^r_{opt}. They are available in specialized literature [38]. In general form, the minimum is determined by graphical plotting of function $c(t)$. The optimal interval obtained in this way for a considered example is $\delta_{opt}=3\ years$ [17]. The probability of failure-free operation will be $P_p=0.929$, resource maintenance-free system will be $T_0=15\ years$, and served with the optimal interval it will be $T_{0p}=43\ years$. Consequently, the optimal relative interval is $\delta^r_{opt}=3/15=0.2$, that corresponds to the recommendations given above. If we increase δ to 8 years, the intensity of the costs will be increased by 1.24 times while the serviced resource will decrease to $T_{0p}=23.4\ years$. Thus, the optimal strategy for M&R provides not only a reduction of the costs, but also helps to extend the lifetime of the system, which is even more profitable.

Model "standby time"

This inspection model (backup model) is proposed for M & R strategies, wherein three phases of the technical state are considered, one of which (B-phase) is located between the workable (G-phase) and unworkable (D-phase) [40-43]. In fact, here the operation of the technical system in the intermediate phase, the model for which was proposed in 60s by Barlow, is assumed [11]. To evaluate if the object belongs to the B-phase or G-phase is possible only by the control check, so when M&R technical diagnostics is widely used. Therefore, the relevance of control procedures (checking) is increasing, as well as their costs are growing C_i. It is assumed that the existing defect leads to a technical malfunction of the system, but it can operate in this phase for some backup time (literally - reverse - backward time). Then, in this situation, it is possible to save money on repair costs having intensity c_c (loss cost). Knowing the mean time between failures T_0, repair costs must be equal to the value of $c_c T_0$. The balance of costs $C(t)$ is due to constant linear growth of the planned repair costs together with the costs on control C_i and savings of these costs on time interval of $\delta = t_j - t_{j-1}$ between inspections j, which is constrained by the probability of failure $F(j\delta)$ [40] :

$$C(t) = (C_i - c_c \cdot \delta)\sum_{j=1}^{\infty} F(j\delta) + c_c \cdot T_0 \ . \qquad (19)$$

Based on these prerequisites, 3 variants of inspection modes are offered: periodical, with decreasing between inspection intervals (serial) and randomized. For the first two modes, the model inspection parameter is the ratio C_i/c_c, which has the dimension of time. For the periodic mode, optimal interval δ is constant and when the exponential law of reliability, it is determined from the following equation:

$$\delta = T_0(1 - e^{-\delta/T_0}) - C_i / c_c \ . \qquad (20)$$

This equation can be written as:

$$\frac{\delta}{T_0} - (1 - e^{-\delta/T_0}) = \frac{C_i}{c_c \cdot T_0} = \frac{1}{T_0 \cdot c_r} \ , \qquad (21)$$

from which at $T_0=1$ the optimal relative interval δ^r_{opt} can be found. Graphical interpretation of this model shows that its use provides results similar to models (9), (11) (Figure 4).

For serial mode between the inspection interval $\delta_j = t_j - t_{j-1}$ is determined from the equation:

$$\frac{F(t_j) - F(t_{j-1})}{f(t_j)} = t_j - t_{j-1} - \frac{C_i}{c_c} \ , \qquad (22)$$

where $F(t)$ and $f(t)$ - the probability and the probability density of distribution of mean time between failures respectively.

A similar model, although out of other preconditions was obtained in [38]. For the first interval between inspections $t_{j-1}=0$, and $\delta_1 = t_1$. Considering that under the exponential law of distribution of time between failures

$$f(t) = \frac{\exp(-t_j / T_0)}{T_0} \ ,$$

this model for δ_1 becomes identical to the model of strictly periodical inspections (20). According to the result of the use of the algorithm, it follows that the date of the first inspection is $\delta_1 = (0,2 - 0,4)T_0$, increasing with growing of its cost C_i [40, 43].

Randomized inspection algorithm is applied for multi-mode operating conditions [42].

Possibilities of economic and statistical optimization models for the M&R of mechanical systems of industrial production (conclusion)

Economic and statistical models, where the optimization criteria are maximizing the availability function and minimizing the downtime and the unit cost on M&R, which are widely studied in the literature dedicated to the reliability [2-4, 17, 18, 20, 21]. Despite this fact, they still do not find their proper application in practice of M&R of technological equipment, leaving a place for more comfortable, but more expensive system of scheduled preventive maintenance (SPM). To some extent, its prevalence is related to the organizational factors: the SPM system allows carrying out the repairs simultaneously for all equipment of technological complex, which is important for continuous production processes. At this time the rigid planning schedule is kept. The use of optimization models suggests a departure from this principle, and their effectiveness within the SPM system is expressed by the reduction in the M&R costs of the several tens of percent. It is more efficient to use them according to technological condition maintenance system. However, it is necessary to build equipment for a similar maintenance. One of the requirements is redundancy of the technical system elements. Due to this, M&R is carried out for the individual subsystems based on the decision of optimization models. In addition, the correct use of the studied models is assumed, which has several aspects.

1. The inspection procedure assumes that found during the control process of the technical system defective element will be replaced in case of inspection [44]. In this formulation, Dillon models are working. It is actual for small, but relatively frequent failures.

It is unlikely that such a short-term replacement of the expensive element is possible, which failure is associated with significant consequences (high risk). In particular, these defects of varying degree of danger occur in the equipment diagnosis process.

2. The basic premise making possible the optimization procedure is associated with a monotone increase since operation time of the probability of failure and similar reduction in the probability of failure-free operation. The functions of intensity after failure and preventive restorations behave themselves similarly.

3. Due to interference of competing maintenance processes, the function of total costs *c(t)* is not monotonous with a minimum corresponding to the optimal range of restorations. With an increase in the relative cost of after-failure restoring, which is a parameter of the function *c(t)*, optimal recovery interval decreases. This can lead to a situation where advisability of optimization is not needed.

The concept of inspection combining examination of object and its preventive repair is successful, primarily for the electronic technical systems, where the small elements of low operating risk are regularly out of order, their repair is operative and do not require many months of preparation. Also, such a concept is relevant to technical systems, which are restored by adjustments and settings. In this situation, Dillon idea to extend the initial resource at the expense of regular maintenance is undeniable. Of course, to maintain the required parameters of gearings contributes to the long-term operation of the gear-reduction box. However, it is difficult to imagine how regular check-ups (even diagnosis) may affect the accumulation of fatigue damages in the structure power elements.

The above economic and statistical models are applied to the mechanical systems, in which failures of irresponsible elements are dominated leading to a fault condition. Such elements usually are not calculated when designing, but they are constructively selected. This category also includes junctions, which performance is difficult to predict in calculations. For example, these are elements of lining and cooling systems, working units of machines for processing of bulk materials (crushers, mills, mixers, etc.).

The basis of the models is a function of reliability, which is usually obtained by studying the object in operation (posteriori). It is associated with span time and additional costs on material resources, which are not always taken into account in the optimization algorithms.

4. The appearance of a minimum on the graph of function of M&R costs is largely due to the bathshape of function of failure intensity rate *λ(t)* [38], where there are three characteristic sections: *I* - decrease of failure intensities (sometimes called “burning” phase - burn-in), *II* - the steady phase, *III* - failure intensity acceleration (a catastrophic phase of wear - wear-out) (Figure 6). This behavior of function *λ(t)* is certain for electronic engineering systems, as well as for technical systems in which failures are caused by an S-shaped kinetic of damaging processes. In particular, these include the wear processes. The wear curve has an initial section of running-in where the wear rate is higher than in the steady portion, but lower than at catastrophic wear. On this basis, bathshape of the curve *λ(t)* was extended to the mechanical-technical systems that allowed applying mathematical and statistical models obtained for the electronic systems. Subjective factors of the availability of the initial section of intensive failures are low-quality assembly of machine (defects are eliminated during the operational phase) and the unpreparedness of staff (for a new type of equipment errors in the operation rules may occur).

Specialists involved in the general theory of reliability paid attention to the difference in the behavior of the operating parameters of electronic and mechanical systems. For the latter, there may be an exponential shape of curve *λ(t)* (Figure 6) [17, 45, 46]. It is caused by serious failures, which occur as a result of damaging processes with monotone kinetics (fatigue, overloading).

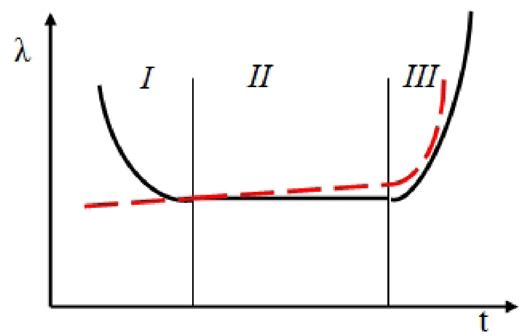

Figure 6. Phases of failure flow rate for electronic (continuous) and mechanical (dotted line) systems [46]

3. Optimization algorithms are based on theorems of renewal theory on monotonic increase of the intensity of post-accident repairs (CM) and a monotonic decrease of the preventive maintenance intensity (PM) [38]. Markov model transients correspond to this the most satisfactory providing 2 phases of the technical condition (workable - unworkable, regularly - faulty), as well as discrete transition from one phase to another [39].

4. It assumes a sudden failure. In fact, almost all

failures are gradual. However, the main drawback of this approach is that when following it, the remaining service life depends only on the latest state of the object, and does not depend on the operating history that is not fully justified. [14]

To sum up the above, it should be noted that most of the economic and statistical models to optimize the service life or inspections are of probabilistic nature. They are fair, if the losses from downtime are comparable to the cost of repairs and the cost of inspection is much smaller. The emergence of failures is allowed. It is only important that their rate should be economically justified. At the same time, in mechanical systems of industrial production there are basic and important elements, which failure is undesirable (unacceptable) since it is associated with the consequences that is operated with a high risk. The use of these elements to their regulatory service life is economically disadvantageous since more than half of the service life is usually undeveloped. It is advisable to use them until pre-failure state by controlling its diagnostic parameters. If in the models studied in the specified aspect of the cost-probability proportion is changed, the model for solving the optimization problem will be considered unsuitable (insensitive). In addition, economic and statistical models operate with the parameters of the reliability of the entire system (in general), and it is necessary to obtain information about the residual life of individual elements and then combine them into a single comprehensive measure.

Another motive limiting the effect of economic and statistical models is due to the complexity (and sometimes impossibility) to obtain a representative sampling in order to determine the type and parameters of law of the time distribution to failure. All of this confirms the need for the transition to M&R models based on probabilistic and physical approaches that take into account the nature and parameters of the degradation process.

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