System for material selection on the price and quality

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Abstract. This work suggests a methodological approach to selection of material according to the "price and quality" criterion on the basis of functional and mathematical definitions of indicators of reliability of machine parts. The reliability of components, as an indivisible element of the system, determines the reliability of the material proceeding from its quality.

1. Introduction
The present day level of development of industrial enterprises determines increased quality specifications pertaining to the products manufactured. Numerous research papers are devoted to defining the concept of “quality” [1, 2], beginning with Aristotle’s “quality is a specific difference covering the essence” and finishing with the present-day, where state standard defines quality as “a set of properties of a product that determine its capability of satisfying specific demands corresponding to its purpose”. Prof. V.N. Protasov [3] suggests using the concept of “consumer” quality, with the reliability of a product considered as one of its major properties. In addition, statistic analysis of the data provided in literature [4, 5] allows us to define reliability as a weightier indicator of quality (if compared with the other quality parameters: safety, workability, etc.). On the other hand, one of the leading specialists in the field of the reliability theory A.S. Pronikov notes that “Reliability is one of the major parameters of the products quality that manifests itself in the course of time and reflects the changes that occur within the machinery over the whole period of its operation” [6]. The reliability assurance systems that have been formed by now are completely substantiated in works [7, 8]. These systems are based upon thorough physical research accompanied by laboratorial and operational utilization of materials for components (machine parts) and units. Prof. V.G. Dazhin notes that the reliability of machine parts, units and assemblies is accomplished at the expense of materials [9]. It is logical to assume that if the reliability of machine parts (as elemental components of a system) is determined by the reliability of materials, then the reliability of materials, in its turn, is determined by the parameters of the component’s reliability.

The present day scientific-research and reference literature does not define the concept of “reliability of material” in a mathematical way. Therefore, the introduction of this concept and its mathematical description is an urgent task, from both theoretical and practical points of view.

According to GOST 27.002-2015, reliability is a complex property that may include various parameters: failure-free operation, maintainability, lifespan, and conservability or a certain combination of properties depending on the purpose of an object or the area of its application. So, when speaking of the reliability of machine components and materials for machinery, the most complete parameter for the assessment of reliability is a parameter that covers all above mentioned characteristics for specific working conditions.
As the classical theory of reliability lacks functional-mathematical dependencies for single parameters of component reliability and the reliability is considered for the machine as a whole, the system of these parameters should be developed in the first place.

This work suggests an approach to the formation of the complex parameter of reliability (efficiency retention factor) for primary units of machinery (parts of machines). This complex parameter is based on determining single parameters which in their turn are determined by the properties of materials. This allows us to introduce the concept of “reliability of materials and objectively assess materials against the price and quality criterion.

The most complete description of the formation of mathematical functions for single reliability parameters is provided in the works \[10,11,12\]. This work presents final formulas that determine major parameters (no-failure operation, maintainability, conservability and time-span) as well as the efficiency retention factor as a complex parameter of the component reliability (price and quality criterion).

2. Materials and Methods
According to GOST 27.002-2015, no-failure operation is the property of a unit (machine part) to continuously maintain operational capability for a certain running time. Major indicators of no-failure operation are: probability of no-failure running time; mean running time before failure; failure rate, etc. The following formula is suggested to calculate the no-failure operation

\[
K_{b1} = \frac{L_{t}}{L_{m}},
\]

where \(K_{b1}\) is a no-failure operation indicator of an initially installed component (machine part); \(L_{t}\) is the mean time before failure of the initially installed component (machine part); \(L_{m}\) is mean life of the system (machine).

From the physical point of view, no-failure operation indicator shows what part of the system’s (machine’s) life has been accomplished by an initially installed component (machine part).

It is worth noting that in this work the no-failure operation indicator of a component (machine part) determines the no-failure operation of a system (machine).

Taking into consideration the fact that no-failure operation is a statistic parameter, it is expedient to use the mean indicator of no-failure operation for calculations which is determined according to the formula below.

The mean indicator of no-failure operation of replacement components (machine parts) is the value inverse to the number of replacements from the difference \((1 - K_{b1})\)

\[
\bar{K}_{b1} = \frac{(1-K_{b1})}{N_{ap}},
\]

where \(\bar{K}_{b1}\) is an average indicator of the no-failure operation of replacement components (machine parts); \(N_{ap}\) is the number of replacements of components (machine parts).

According to GOST 27.002-2015, maintainability is a property of a component to maintain and restore workable condition by technical maintenance and repair. Maintainability indicators are: probability of repair; mean time to restore; restoration intensity; etc.

Employment of the parameters suggested cannot be considered perfectly correct as after the component’s failure and dismantling from the system (machine), the component (machine part) becomes a separate individual unit functionally assigned for restoration of its working capacity. Major reason for component’s failure is wear-and-tear of its work surfaces. This can be restored through restoration of the component’s geometry, its special position and physical-mechanical properties.

Present day technologies and materials allow a wide range variability of wear resistance of restored work surfaces which is assessed by the ratio

\[
K_{b} = \frac{L_{b1}}{L_{na1}} = \frac{k_{bvt}}{k_{b1}},
\]
where $K_b$ is restoration ratio for no-failure operation $K_{NF}$; $L_{NF1}$ is the mean time before failure for first replacement component (machine part); $L_{na1}$ is the component’s (machine part) mean operating time to failure of the first replacement in the course of operation; $K_{BB1}$ is the indicator of faultlessness of a first replacement component (machine part); $K_{ba1}$ is the indicator of faultlessness of a new component (machine part) of the first replacement in the course of operation.

If we know the value of extended faultlessness, the indicator of maintainability is determined by the ratio of this value to the value of the remainder faultlessness after the initially installed component (machine part) has accomplished its faultlessness $(1 - K_{b1})$

$$K_p = \frac{K_v K_{ba1} \gamma (1 - \gamma^N)}{(1 - K_{b1}) (1 - \gamma)}$$

where $K_p$ is the indicator of maintainability of a component (machine part) $K_m$; $N$ is the predetermined number of restorations; $\gamma$ is the component’s no-failure operation restoration factor for the first replacement item.

From the physical point of view, maintainability factor shows the remainder of the system’s (machine’s) resource after the implementation of resource of the initially installed component (machine part) which is accomplished through N-repeated restoration of this component (machine part).

Having resolved the equation (4) with $K_p = 1$, relative to $K_v$ we obtain

$$K_{vp} = \frac{(1 - K_{b1}) (1 - \gamma)}{K_{b1} \gamma (1 - \gamma^N)},$$

$$K_{vp} = K_{RM}$$

where $K_{vp}$ is the design restoration factor of the component’s no-failure operation for the complete implementation of the system (machine) resource at the predetermined number $N$ of the component’s restorations.

According to GOST 27.002-2015, conservability is the property of an item to preserve the parameter values that characterize its capability to perform the required functions during its conservation and transportation within the frameworks of the predetermined limits; its parameters include: predetermined probability of the established conservation life; mean conservation life; failure rate during conservation period, etc.

After the failed component (machine part) has been dismantled from the system (machine), it becomes an individual component assigned for the restoration of its work capability. This restoration proceeds as follows: dismantling from the system (machine); conservation and transportation to the site of restoration; and the work process of restoration. Each sequence has a probability of preservation of the restoration capability of its own. In this case the probability of the component (machine part) restoration is determined by the product

$$P_v = P_a \cdot P_{xt} \cdot P_{pb}$$

where $P_v$ is the restoration probability for a component (machine part) $P_R$; $P_{EFA}$ is the probability of the absence of emergency failure; $P_{ST}$ is the probability of conservability of the component (machine part) during its storage and transportation; $P_{pb}$ is the probability of absence of spoilage in production when restoring component (machine part).

In this case it is expedient to calculate conservability indicator according to the following formula

$$K_C = \frac{P_v (1 - \gamma)[1 - (\gamma P_b)^N]}{(1 - \gamma P_a) (1 - \gamma^N)}.$$
replacement of the failed component (machine part); N is the number of restoration of the component (machine part).

From the physical point of view conservability indicator shows which part of the maintainability is preserved at the prescribed probability of N-fold restoration of the component (machine part).

GOST 27.002-2015 defines life span as a property of an item to preserve its working capacity until marginal state with necessary breaks for maintenance support and repairs. Life span parameters are mean life; gamma-percentile life; life-in-service, etc.

Life span of a component (machine part) as an individual item is determined by the total no-failure operation of the initially installed component (machine part) and by the extended no-failure operation at the expense of N-fold restoration taking into consideration probabilities of this restoration. Proceeding from the physical interpretation of the indicators of no-failure operation, maintainability and conservability of a component (machine part), the formula for life span looks as follows

$$K_d = K_{b1} + K_p \cdot K_C \cdot (1 - K_{b1}),$$

where $K_d$ is the life span parameter. $K_d = K_{LS}$

From the physical point of view the life span parameter shows what part of the system’s (machine) resource is implemented by the no-failure operation of the initially installed component (machine part) and its maintainability taking into consideration its conservability.

3. Results

As it has been noted above GOST 27.002-2015 defines reliability as the property of an item to preserve its working capability within time frameworks under stated operation conditions, technical maintenance and repairs. The reliability is a complex property. Depending on the purpose of an item, the reliability is assessed by simple parameters (no-failure operation, maintainability, conservability and life span) or complex: availability factor; operating efficiency factor; efficiency retention factor, etc.

From the economical point of view, efficiency retention factor as an indicator of the component’s (machine part) reliability is assessed by the replacement costs of failed components (machine parts) within the frameworks of operation when implementing the resource of the system (machine).

In this connection, the efficiency retention factor (ε “price and quality” criterion) of the component (machine part) is determined as

$$K_n = \frac{c_n}{c_n + N_{NC}(c_n + c_d) + N_{RC}(c_v + c_d)},$$

where $K_n$ is the efficiency retention factor of the component (machine part); $C_{NC} C_{HI}$ is the cost of a new component (machine part); $C_{RC} C_{HI}$ is the cost of the restored component (machine part); $C_{R&IH}$ is the cost of replacement of the component (machine part) within the frameworks of operation and losses from idle hours of the system (machine); $N_{NC} N_{HI}$ is the number of new components (machine parts) replaced within the frameworks of the operation; $N_{RC} N_{HI}$ is the number of restored components (machine parts), replaced within the frameworks of operation.

Let us introduce the concept of relative costs:

$$\alpha = \frac{c_n}{c_n}; \beta = \frac{c_d}{c_n},$$

where $\alpha$ is the relative cost of the component (machine part) restorations; $\beta$ is the relative replacement costs of the failed component (machine part) during operation.

Finally we obtain
From the economical point of view, the complex indicator determines the share of the cost of an initially installed component (machine part) in the overall operational costs to replace failed components (machine parts) while accomplishing the resource of a system (machine).

Operational costs for the replacement of failed components is determined by the formula

\[ Z_a = C_{K} - 1 \cdot \Delta C_a \] (12)

where \( Z_a \) is the operational costs for the replacement of failed components. \( Z_a = C_0 \)

Saving rate from the change in the complex parameter of reliability is determined by difference in the costs

\[ C_{af} = \left[ \left( \frac{1}{k_{n1}} - 1 \right) \cdot C_{n1} - \left( \frac{1}{k_{n2}} - 1 \right) \cdot C_{n2} \right] \] (13)

where \( R_S \) is the saving rate from changing efficiency retention factor; \( K_{ER1} \) \( K_{H1} \) is the initial value of efficiency retention factor of the component (machine part); \( K_{ER2} \) \( K_{H2} \) is efficiency retention factor of a component (machine part) after restoration and strengthening; \( C_{NC1} \) \( C_{H1} \) is the cost of new component (machine part) before strengthening; \( C_{NC2} \) \( C_{H2} \) is the cost of the new component (machine part) after strengthening.

4. Discussion

In order to determine the functional and mathematical dependencies for simple reliability indexes and the efficiency retention factor, which determines the reliability of the component (machine part), it is expedient to designate the properties and the characteristics of the material that make for the implementation of these parameters (no-failure operation, maintainability, conservability and life span).

It is also worth taking into consideration that the manufacture material is chosen for a specific component under specific working conditions.

Let us consider as an example the procedure of selecting material for hammer mill beaters for fine coal grinding. The latter are used at the heat electropower stations to improve the efficiency of coal firing and to decrease the abuse on the environment. The material is chosen on the “price and quality” criterion (efficiency retention factor, as an indicator of reliability). The beater is a 10 kilogram cast product of the 110G13L steel. With the working surface wear of 4 kilograms on the average, the complete set (120 items) are replaced until the hammer mill exhausts its life span which is determined by the maximum deterioration of its armour.

No-failure operation (i.e. prefailure life). As the beater works under the conditions of percussive and abrasive wear, we consider as its failure the maximum changes in the geometry of the beater’s work surface connected with wear resistance, impact strength and hardness (or their various combinations). In the process of operation, wear resistance of the material plays a major role. Material wear resistance depends upon the material’s chemical composition, thermal treatment or certain processing impacts, therefore any improvements or deteriorations in this property of the material will influence the no-failure operation of the component itself.

The no-failure operation parameter of the initially installed component (machine part) can be expressed as

\[ K_{n1} = \frac{L}{1 + K_m} \] (14)

where \( K_m \) is the wear resistance index (WRI) of the material, determined as a ratio of masses of the material and the standard after testing for equal periods of time and equal loads.
\[ K_1 = \frac{M_m}{M_a} \]  
(15)

where \( M_m \) is the mass of the material of the component; \( M_{St} \) is the mass of the standard (in this particular case the standard is made of steel 110G13L).

Maintainability. Scientific and technical literature, regrettably, does not provide a definition of his concept as applied to materials. Safety margin, as a rule, exceeds basic strength of the material 2-3 times, which results in the increase in the components size as well as in its cost. At the heat electropower stations, beaters are consumable items and their wear exceeds critical values, and their wear exceeds critical values, therefore the majority of heat electropower stations do not provide for repairs. As a consequence of this situation, few works are devoted to restoration of work surfaces. This causes the need to conduct assessment measures in this field. In this work, the computational number of restorations according to [12] is determined with the formula

\[ N_p = \frac{\ln\left[1 - \frac{1}{K_{b1} \gamma} \ln \gamma\right]}{\ln \gamma}, \]  
(16)

The actual number of restorations is determined by [12] formula

\[ N_f = \frac{(1-K_p K_c)(1-K_{b1})}{K_p K_{ba}}, \]  
(17)

Conservability. Literature lacks definitions of material properties. In such a case, conservability can be understood as the probability of the fact that the material is capable of preserving its properties during its storage and transportation as well during the component replacement during operation. As an example, we shall use probability of material conservability equal to 0.95.

Life span. Literature sources define life span of the material as the component’s period of work to the first crack (definition of strength under major cycle of loads). The calculations in this case are reduced to determining of resistance of materials under different loads. Following the approach suggested the life span/useful life of material is supposed to be determined by the sum of the indexes of no-failure operation, conservability and maintainability according to the formula (5.1).

The material for the manufacture of hammer mill beater was chosen employing the price and quality criterion among the following variants:

1- standard new beater of steel 110G13L; 2- new beater of steel 110G13X2BRL; 3 – new beater of steel 80GSL, thermostrengthened; 4 – beater of steel 80GSL strengthened with welding wire Sv-08XM Cb -08XM through alloying plate with 20% content of tungsten carbide, silicon carbide, etc.; 5 – standard new beater of steel 110G13L, strengthened according to the technology 4; 6 – new beater strengthened with welding wire Sv-08XM through alloying plate with carbides content of 40%.

Initial data for determining economic parameters and reliability indexes of the beater with consideration of [12] are presented in Table1. Results of calculations are presented in Table 2.

**Table 1.** Initial data.

| Variants of beater manufacture | Component reliability indexes |
|-------------------------------|-------------------------------|
| \( K_{b1} \) | \( \gamma \) | \( N_a \) | \( K_{ba} \) | \( K_b \) | \( K_p \) | \( N_p \) | \( Kc \) | \( Kd \) | \( N_f \) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.3 | 0.9 | 3 | 0.23 | 1 | 0.39 | 3 | 0.95 | 0.56 | 1 |
| 2 | 0.33 | 0.9 | 3 | 0.22 | 1 | 0.44 | 2 | 0.95 | 0.61 | 1 |
| 3 | 0.29 | 0.9 | 3 | 0.24 | 1 | 0.37 | 3 | 0.95 | 0.53 | 1 |

* Initial data \( L_m = 1200 \) hours; \( L_n = 360 \) hours; \( L_{na} = 324 \) hours.

**Table 2.** Consolidated Table of economic parameters and reliability indexes for manufacture of the beater.

| Beater reliability indexes | \( C_{ba} \) | \( C_{af} \) |
Analysis of Table 2 shows, all variants under consideration are equivalent on the reliability factor. Nevertheless, when considering the economic sides of the issue, one can see that less alloyed material is more cost efficient for production of beaters. And the saving rate increases if a possibility of strengthening work surfaces is additionally provided.

The algorithm for material assessment against the price and quality criterion, that we suggest in our work, allows us to define the concept “reliability of material” as a complex of properties and characteristics that ensure item’s simple reliability indicators (no-failure operation, maintainability, conservability or their various combinations) under stated operation modes or certain working conditions.

5. Conclusions
- We suggest using functional and mathematical simple reliability parameters of a component (machine part), such as no-failure operation, maintainability, conservability and life span (useful life), to determine the indicator “quality” for materials.
- The suggested methodology for assessment of materials against “price and quality” criterion allows us to introduce and to formulate the concept “reliability of material”.
- The use of the suggested approach has been demonstrated on the example of determining the reliability of material for manufacture of the beater for the hammer mill for fine coal grinding employed at the heat electropower stations.

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