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Analysis of the influence of product reliability on the cost structure of the manufacturer performing warranty repair of the released products

Analiza wpływu niezawodności produktu na strukturę kosztów producenta oferującego gwarancję konserwacji wytwarzanych dóbr

Abstract: In the modern conditions of the market economy, every enterprise struggles for its consumer. To attract and retain consumers of the manufactured products, enterprises develop and offer a wide range of extra terms which make their products more attractive. These are preferential terms and payment conditions, a flexible system of discounts for buyers and customers, as well as a system of warranty maintenance of the released products.
Keywords: cost structure, warranty maintenance, reliability level, fail-safe performance probability

Streszczenie: We współczesnej gospodarce rynkowej każde przedsiębiorstwo walczy o klienta. Żeby przyciągnąć i utrzymać klientów, firmy tworzą i rozwijają szeroki wachlarz dodatkowych ofert, które sprawiają, że ich produkty są bardziej atrakcyjne. Są nimi preferencyjne warunki płatności, elastyczny system obniżek cen dla klientów zbiorowych i indywidualnych, jak również systemy gwarancji i konserwacji wytwarzanych produktów.
Słowa kluczowe: struktura kosztów, gwarancja konserwacji, poziom niezawodności, prawdopodobieństwo niezawodnego działania

Introduction

The market has set a task for developers and manufacturers of innovative products to investigate the functioning of the products in the course of their operation, as this implies not only expenses for repair or replacement of failed products, but also the competitiveness of the manufacturer. Still, the manufacturer must take into account that a certain part of its products might fail while being used.

Economic models of products manufacturing are based on the category of their fail safety. At the same time, warranty for the product issued by the manufacturer must be correlated with the P_{tg} failure probability during the t_g warranty period, as this is the period when the manufacturer is responsible for the product being in working order.

Research method

The functional connection of the manufacturer's total costs from the probability of a faultless operation mathematically expresses the sum for manufacturing and repair. This model analysis enables finding the optimal value for probability of a faultless operation p_{opt}, where the manufacturer's expenses will be minimal.

If the cost of a product with the p probability of a faultless operation equals C, the cost of a similar product with a higher probability of a faultless operation $p_i >$ is $C_i > C$.

Modern practice lacks a trend of works on research and estimation of economic efficiency of increasing the faultless operation of products. And enterprises are not familiar with the issues of price formation with account of the increasing reliability of released products.

During the established warranty period, in the event of a product failure, the manufacturer must repair the product or replace it with a new unit.

The total expenses of the enterprise involve the C_{man} manufacturing costs and the cost of product repair or replacement.

The following can be assumed as models reflecting the dependence of the product cost on the probability of its faultless operation:

1. The higher the faultless operation the higher the cost of manufacturing, then $C_{man} = \alpha \times p^{\lambda}$, where α and λ are proportionality factors which characterise this product.

2. The higher the faultless operation of the product, the fewer repairs it requires during the warranty period. Hence, $C_{rep} = b/p\beta$, where b and β, are the corresponding coefficients characterising the reparability properties of the product.

Essence of Warranty Repair and Maintenance

A successful operation can hardly be achieved in modern conditions, if a manufacturer does not provide after-sale service of the released products.

Warranty maintenance of the released products is a set of works performed by the manufacturer for the purpose of technical and economic satisfaction and legal protection of the client-buyer as a result of using the acquired products.

The modern warranty maintenance principle is that a manufacturing enterprise undertakes a responsibility for supporting the working capacity of the released product throughout the entire period of its service life. High competitiveness of products is largely determined by high-quality warranty maintenance, and, therefore, manufacturers should not consider it a burden but, on the contrary, should strive towards its qualitative provision. When organised in the proper way, warranty maintenance services can not only influence the business reputation of the manufacturer, but can also become an important source of income.

There are several types of warranty maintenance:

- *Pre-sale service* aims at meeting consumer demand and anticipates that a manufacturer studies the needs of potential buyers regarding the manufactured products from all aspects. Personnel of the department involved in warranty maintenance participate in design works, tests and their evaluation, and in the preparation of documentation. Upon delivery of products to the site, employees of the manufacturer can eliminate deficiencies that occur during transportation, install the equipment and prepare it for operation.
- *After-sale service* includes the services provided to secure efficient functioning of the manufactured products in the existing conditions throughout their entire life cycle. After-sale warranty maintenance is performed both before and after the sale of a product and includes the following main activities:
  - ✓ Determining the requirements of the consumers to the after-sale service of the manufactured product at its development stage (jointly with the main consumers);
  - ✓ Determining the list of services provided to the consumer after selling the products;
  - ✓ Determining the after-sale service procedure for the consumer in the process of discussing the product supply agreement;
  - ✓ Preparation of the personnel to perform the maintenance and repair works;
  - ✓ Preparation of the required documentation;
  - ✓ Preparation of the required infrastructure to secure the after-sale service;
  - ✓ Development of the system of product replacement with a new model, utilisation of the old model.

After-sale service is subdivided into warranty and post-warranty maintenance according to a purely formal characteristic – whether the maintenance works are performed 'for free' or for payment. This characteristic is formal as the cost of the work, its spare parts and materials during the guarantee period is included in the sale price or other (post-warranty) services.

During the warranty period, the manufacturer tries to undertake all works which are required to secure the faultless operation of a machine, equipment, a separate block or component of a mechanism.

During the after-warranty period, the manufacturer performs planned preventive works and repairs, provides spare parts and renders consultations regarding the most efficient operation. All of these works are performed pursuant to the concluded conformity agreement, the fulfilment of which is beneficial to both parties, due to a decrease in the idle standing of the equipment, longer life between overhauls, less defective goods and the increased safety of operating the equipment. All of these enhance the prestige of the manufacturer, allow reference to real examples of high quality works in advertising and bring apparent benefits to the seller, due to enhancing its position as a reliable supplier with regard for the buyers of its products.

Regardless of how perfect the innovative products are, they are certainly subjected to certain repair and service impacts in the process of operation.

Thus, warranty maintenance and repair are the most important resource-saving measures anticipated by the design of modern innovative products. In all cases, the manufacturer bears full responsibility for the process and results of warranty maintenance, the value and provision quality of which are most important for the consumers.

1. Cost planning for warranty maintenance and repair of the released products

Thus, as mentioned before, the warranty maintenance system can include the complete replacement of a faulty product or its repair.

However, issues related to the increase in the involved expenses come to the foreground for a manufacturer who offers warranty maintenance of the released products, as well as determining the warranty maintenance term when the service expenses are economically expedient.

The only alternative for warranty maintenance of faulty products with regard to the considered case (complete replacement of the faulty product) is repair (restoration). In this case, the total manufacturing and operation costs will be:

$$C_{\Sigma} = C_{man} + C_{rep}, \tag{1}$$

where C_{man}, C_{rep} – costs of manufacturing and repair of faulty units correspondingly.

In turn,

$$C_{rep} = C_s + C_p, \tag{2}$$

where C_s – expenses for salary of equipment repairers;
C_p – cost of spare parts used for the repair.
As a result,

$$C_{\Sigma} = C_{man} + C_s + C_p. \tag{3}$$

The last model is deliberately restricted with summands C_{man}, C_s, C_p, as all additional summands which are not presented here, like the cost of the repair workshop rental, the cost of the equipment depreciation, etc., will change only the quantitative part of the solution constituents and will not alter its principal side.

If a batch of products is released in the N_1 amount, then

$$C_{man} = N_1 C_1, \tag{4}$$

where C_1 – cost of manufacturing one unit.

During the warranty obligations period t_g of the manufacturer, one worker repairs $12nt_g$ of units, where n – number of units repaired by one worker during a month.

Whereas the total number of repaired units with the fail-safe performance probability $P = P(t_g)$ equals to $(1-p)N_1$. As a result, the number of workers required for performing warranty maintenance $(1-p)N_1$ of units per the warranty period t_g will be:

$$\frac{(1-p)N_1}{12nt_g} = \frac{(1-e^{-\lambda t})N_1}{12nt_g}. \tag{5}$$

If the salary of one repairer is LVL C_{s1} per month, the total expenses for salaries of all repairers during the warranty maintenance period t_g will equal to:

$$Cs = \frac{(1-p)N_1}{12nt_g} C_{s1}. \tag{6}$$

Finally, if the cost of spare parts per one unit is C_{p1}, the total cost of spare parts used in the repair is:

$$C_p = C_{p1}\,(1-p)N_1 \tag{7}$$

A simultaneous solution of the equations (6) and (7) gives the expression for determining the total cost of manufacturing and warranty repair of the units, with account of the fail-safe performance probability of the unit:

$$C_\Sigma = N_1C_1 + \frac{(1-p)N_1}{12nt_g} C_{s1} + C_{p1}(1-p)N_1. \tag{8}$$

When performing warranty repair of faulty units, the manufacturer does not make additional units, but forms spare parts for the repair of the faulty ones.

Therefore, the first summand in the equation (8) does not contain the multiplier $(2-p)$, as it is in the event of replacement of the faulty product with a new one.

Let us present the equation (8) as:

$$C_{\Sigma rep} = N_1C_1 + \frac{(1-p)N_1C_1}{12nt_gC_1} C_{s1} + K_0C_1N_1(1-p). \tag{9}$$

As $N_1C_1 = C$, then

$$(C_\Sigma/C)_{rep} = 1 + \frac{1-p}{12nt_gC_1} C_{s1} + K_0\,(1-p) = 1 + (1-p)\left(\frac{C_{s1}}{12nt_gC_1} + K_0\right) \tag{10}$$

Let us introduce the designation $A = C_{s1}/nC_1$. As $p = exp\,(-\lambda t_e)$, the equation (10) will take the form:

$$(C_\Sigma/C)_{rep} = 1 + (\frac{A}{12t_g} + K_0)\,(1 - e^{-\lambda t_\Gamma}). \quad (11)$$

Initially, we will restrict the solution of the task by the case of the high reliability of the product:

$$e^{-\lambda t_g} \cong 1 - \lambda t_g \quad (12)$$

This correlation is correct, starting from the value of the failure-free operation of not less than $P = \exp(-\lambda t_g) \geq 0{,}9$, i.e. when $\lambda t_g \leq 0{,}10$.

In most cases the summand $A/12t_g$ is considerably less than the K_0, value, i.e. $A/12t_g << K_0$. Under this condition, the equation is transformed into a simple dependence:

$$(C_\Sigma / C)_{PEM} \cong 1 + ЛK_0\lambda t_g \quad (13)$$

If the salary of a repairer considerably exceeds the monthly cost of repaired units, the value A is commensurable to the K_0 value or exceeds it.

In this case, the $A/12t_g$ summand must not be neglected.

The correlation between expenses of the manufacturer, the duration of the warranty maintenance period and the reliability of the released products

The dependence of the total expenses $(C_\Sigma / C)_{REP}$ on key indicators K_0, λ and t_g is very obvious in the equation $(C_\Sigma / C)_{REP} \cong 1 + ЛK_0\lambda t_g$:

- The higher the K_0 share of the cost of spare parts with regard to the cost of the unit, the more the intensity of failures λ of the unit and the warranty term t_g are and the higher the total expenses of the manufacturer are.

In a general case, the dependence of the value $(C_\Sigma / C)_{REP}$ on the duration of the warranty maintenance period t_g is non-linear and it is presented in Fig. 1 according to the data of Table 1 received for A=0.5, K_0 = 0.2 and λ =10^{-5} 1/p.

Table 1.

t_r	2	3	4	5	10
$(C_\Sigma / C)_{REP}$	1.035	1.049	1.063	1.075	1.1956

As follows from the equation $(C_\Sigma / C)_{REP} = 1 + (\frac{A}{12t_g} + K_0)(1 - e^{-\lambda t_g})$,

when K_0=$0.2t_g \to \infty$ $(C_\Sigma / C)_{REP}$=1.2.

In a general case:

$$(C_\Sigma / C)_{REP} = 1 + K_0 \tag{14}$$

According to the data of Table 1, when t_g = 10 years $(C_\Sigma / C)_{REP}$ = 1.2.

In particular, it follows from the correlation $(C_\Sigma / C)_{REP} = 1 + K_0$ that, in the event of considerable warranty periods t_g, the share of the cost of spare parts from the cost of the repaired unit is the value which determines the correlation $(C_\Sigma / C)_{REP}$ characterising the total expenses of the manufacturer for the programme of production and warranty repair of the faulty units.

With the increased fail-safe performance probability from level P to level P_1, the cost of the unit will increase from value C_1 to value $C_1^{"}$, as well as the cost of spare parts per one unit from value C_{D1} to the level $C_{D1}^{"}$ and the total cost of manufacturing and repair with account of the fail-safe performance probability of the unit will be determined as follows:

$$C_\Sigma^{"} = N_1 C_1^{"} + \frac{(1-p_1)N_1}{12nt_g} C_{S1} + C_{D1}^{"}(1-p_1)N_1 \tag{15}$$

The cost of spare parts per one unit constitutes a part of the unit cost, i.e. $C_{Д1}^{"} = K_0 C_1^{"}$, where K_0<1, and we will consider that K_0 - *const*. With account of this condition,

$$\begin{aligned} C_\Sigma^{"} &= N_1 C_1^{"} + \frac{(1-p_1)N_1 C_1^{"}}{12nt_g C_1^{"}} C_{S1} + K_0(1-p_1)N_1 C_1^{"} = \\ &= N_1 C_1^{"}[1 + \frac{1-p_1}{12nt_g C_1^{"}} C_{S1} + K_0(1-p_1)] \end{aligned} \tag{16}$$

This equation for $C_\Sigma^{"}$, with account of the aforementioned correlation, will look like

$$C_\Sigma^{"} / C = [1 + K^1(\frac{a}{K})][1 + \frac{1-p_1}{12nt_g C_1[1 + K^1(\frac{a}{K})]} C_{S1} + K_0(1-p_1), \tag{17}$$

where $C = N_1 C_1$.

$$A = C_{S1} / nC_1, \tag{18}$$

where nC_1 – cost n of units restored by one repairer during a month.

As a result,

$$C_{\Sigma}^{"} / C = [1 + K^{1}(\frac{a}{K})][1 + \frac{(1 - p_1)A}{12t_g[1 + K^{1}(\frac{a}{K})]} + K_0(1 - p_1) \qquad (19)$$

Thus, the value of the relation $C_{\Sigma}^{"} / C$ is a function of a number of parameters:

$$C_{\Sigma}^{"} / C = f(p_1, \frac{a}{K}, A, K_0). \qquad (20)$$

The values a / K, A and K_0 can change within noticeable limits. The value $K^1 = \ln p / \ln p_1$ is unambiguously determined by the value of the fail-safe performance probability of the unit with the initial value of the fail-safe performance probability.

Table 1 provides values of the relative cost $C_{\Sigma}^{"} / C$ for the warranty maintenance period which equals 2 years for the products when A=0.5 and the base value of the fail-safe performance probability is 0.5, which is further used to evaluate the increase in reliability of the unit.

In this case, the value of growth of the cost of failure-free operation a / K changes within the limits of 0.02 to 0.2 for each of the values K_0 = 0.2; 0.4; 0.6.

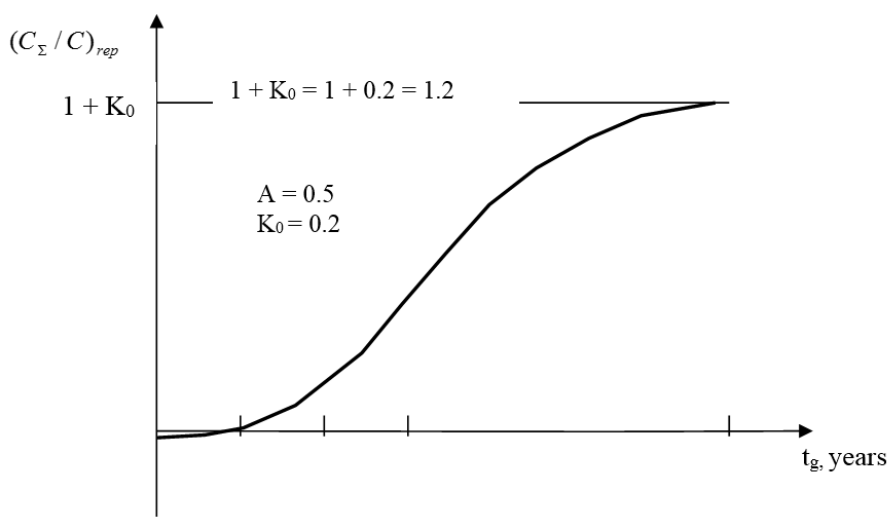

Fig. 1. Dependence of the total costs of an enterprise on the duration of the warranty maintenance period when repairing faulty units

Source: own study.

Table 2.

$C_{\Sigma}^{"} / C$ **values when t_g = years; A=0.5; P=0.5**					
		P_1			
K_0	a/K	0.6	0.7	0.8	0.9
0.2	0.02	1.120	1.107	1.160	--
	0.05	1.162	1.169	--	--
	0.10	1.24	1.27	--	--
	0.20	1.38	1.48	--	--
0.4	0.02	1.20	1.17	1.15	1.18
	0.05	1.247	1.235	1.252	1.384
	0.10	1.326	1.344	--	--
	0.20	1.48	1.56	--	--
0.6	0.02	1.28	1.232	1.194	1.202
	0.05	1.333	1.301	1.298	1.411
	0.10	1.417	1.415	1.472	--
	0.20	1.585	1.644	--	--

Source: own study.

Fig. 2 provides the nature of the change of the relative value $C_{\Sigma}^{"} / C$ depending on the growth of reliability for different values of K_0 and a / K. It follows from the data of Table 2 and Fig. 2 that the dependence of a change in the cost share of spare parts from the unit cost considerably influences the programme of the cost of the manufacturing and repair of faulty units. And, as could be expected, the total expenses $C_{\Sigma}^{"} / C$ increase with the growing cost of the fault-free operation of the unit a / K. Moreover, it follows from the data of Table 2 and the curves on the figure that, similarly to the case of replacing the faulty parts with new ones, with the growing cost of the increase in reliability for each fixed value of K_0 (0.2, 0.4, 0.6), the optimum value of the fault-free operation probability, which secures the condition of minimum expenses, moves to the area of lower values of the fail-safe performance probability.

As to the value K_0, the growth of this value moves the value of the optimum fail-safe performance probability to the area of higher values. However, with the growth of K_0 the amount of total expenses of the manufacturer for the production and repair of faulty products also grows. Let us turn to the dependence of the change of the warranty period value t_g and A value of the share of salary of one worker on the cost of units repaired by him during one month by the value of the relative cost of total expenses $C_{\Sigma}^{"} / C$. For this purpose, let us consider the following summand of the equation (19):

$$\frac{(1-p_1)A}{12t_g[1+K^1(\frac{a}{K})]},$$

which practically does not influence the total expenses $C_{\Sigma}^{"} / C$.

For example, when forming the data of Table 2, this value changes within the limits of 0.0015 to 0.008, which is next smaller to other summands in the equation

$$C_{\Sigma}^{"} / C = [1 + K^{1}(\frac{a}{K})][1 + \frac{(1 - p_1)A}{12t_g[1 + K^{1}(\frac{a}{K})]} + K_0(1 - p_1)\,. \qquad (20)$$

Besides, in accordance with the data of Table 1, with the growing fail-safe performance probability, the value $K^{1} = \ln p / \ln p_1$ grows fast, which leads to a noticeable reduction in the value of the considered summand. As a result, the general equation can be presented as:

$$C_{\Sigma}^{"} / C \cong [1 + K^{1}(\frac{a}{K})][1 + K_0(1 - p_1)]\,, \qquad (21)$$

i.e. the total expenses for the repair of faulty items depends on the product reliability, the cost share of spare parts from the unit cost and the growing cost of the fault-free operation of the unit. In this case, as follows from the last equation, the value $C_{\Sigma}^{"} / C$ practically does not depend on the duration of the warranty maintenance period and the share of salary of one worker on the cost of units repaired by him during one month, i.e. on A value.

Thus, when determining the total expenses for manufacturing and warranty repair of faulty units, instead of the

$$C_{\Sigma}^{"} / C = [1 + K^{1}(\frac{a}{K})][1 + \frac{(1 - p_1)A}{12t_g[1 + K^{1}(\frac{a}{K})]} + K_0(1 - p_1)$$

formula, one should use a simpler correlation

$$C_{\Sigma}^{"} / C \cong [1 + K^{1}(\frac{a}{K})][1 + K_0(1 - p_1)]$$

in the aforementioned conditions. The results of the calculation for these equations practically coincide.

Thus, pursuant to the aforementioned, one can make a conclusion that the minimum expenses of an enterprise can be obtained for production and warranty maintenance, but the level of reliability of released products does not meet the available requirements, i.e. is in the area of inadmissibly low values. And such quality of warranty maintenance can entail not only a loss of competitiveness but can also influence the safety of transportation, when transport enterprises are involved, which is also important.

As a result, it can be stated that the depth of warranty maintenance, i.e. the fail-safe performance probability is one of the determining factors of costs of a manufacturing enterprise in market economy conditions.

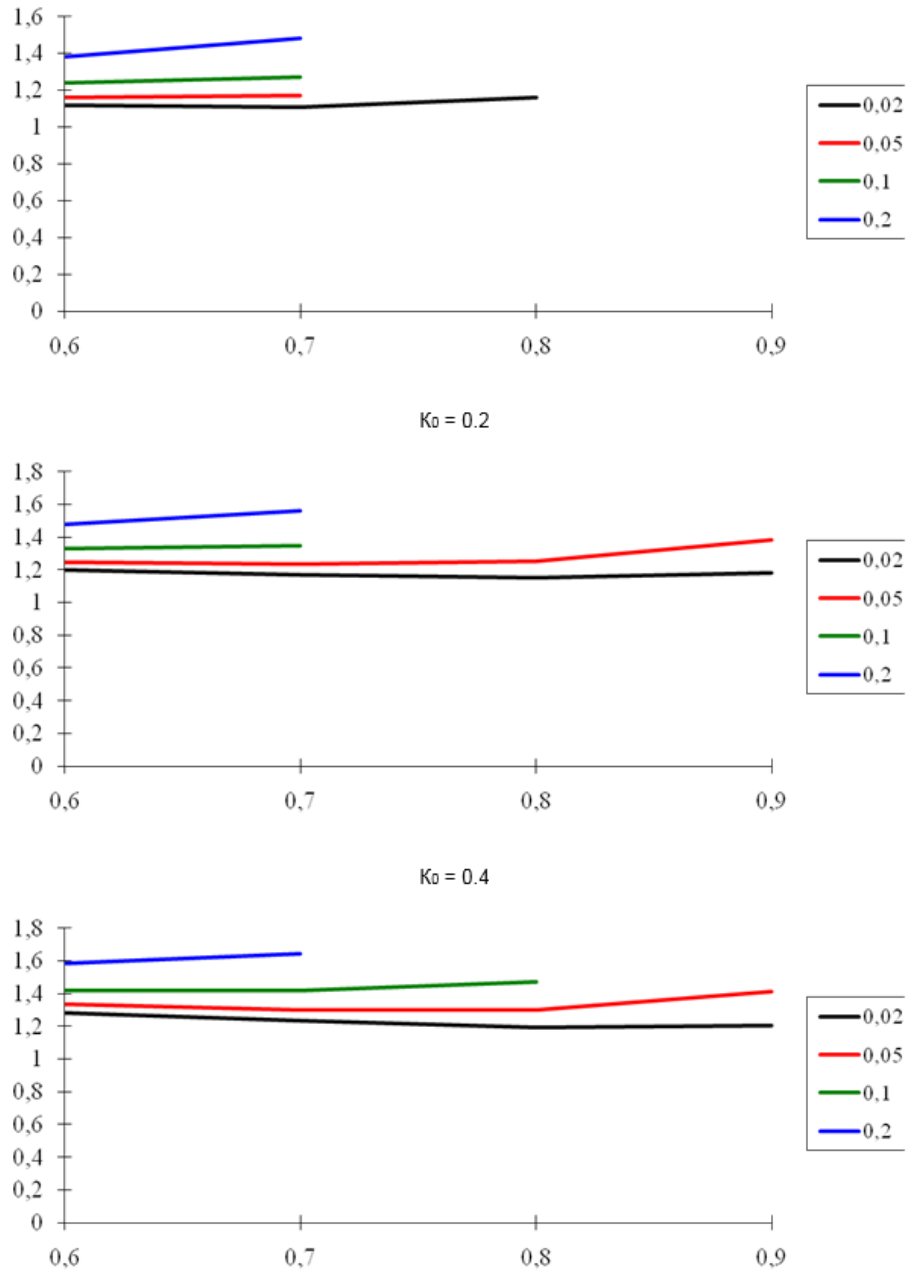

Fig. 2. Dependence of total expenses of an enterprise on the level of the fault-free operation of the units
Source: own study.

Conclusion

It is becoming more obvious that the chief feature of modern innovative production must focus on a long-term perspective, the performance of fundamental research, diversification of operations and maximal satisfaction of requirements of consumers. One of the chief factors of achieving a high level of competitiveness is the provision of warranty maintenance by the manufacturer. Having analysed this subject, the following conclusions can be made:

1. Warranty maintenance of the released products is a set of works performed by the manufacturer for the purpose of technical and economic satisfaction and legal protection of the client-buyer as a result of using the acquired products. Manufacturers of innovative products must secure the provision of a service involved in their operation, for which warranty maintenance and repair are performed, the value and quality of which have the highest value for consumers.
2. The increase in quality and the warranty maintenance period is one of the conditions for actually satisfying the requirements of buyers. The integrated index of warranty maintenance of the released products must include a set of exponents which characterise the warranty maintenance period, the level of reliability of the released products, the quality of after-sale service, etc.
3. Consequently, the topicality of the performed research is substantiated which is aimed at determining costs, which occur at the manufacturers in the production and warranty maintenance of the released innovative products. The obtained results certify that the minimum expenses of an enterprise can be obtained for the production and warranty maintenance, but the level of reliability of released products does not meet the set requirements, i.e. is in the area of inadmissibly low values. And such quality of warranty maintenance can entail not only a loss of competitiveness of the manufacturer on the market but is also related to the safety of people, when the released innovative products are used as components of vehicles. As a result, it can be stated that the depth of warranty maintenance, i.e. the fail-safe performance probability, is one of the determining factors of costs of a manufacturing enterprise in market economy conditions.

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