Analysis of necessary investments in the production and warranty service of innovative products considering the necessity of their backup

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Abstract

Redundancy is one of the commonly used methods to improve the reliability of industrial products and is used in various designs. Another way to increase the reliability is to use more reliable components during the production. This work provides a feasibility study of the redundancy during the manufacturing as well as a comparative analysis of the conditions under which one or another methods are chosen to improve the reliability of a product as a function of its value.

Key words: costs structure, warranty service, reliability level, probability of no-failure operation of products

1 Introduction

Nowadays there is tough competition in the market, competition for customers, for cost-cutting of the production process and issues of reliability of the made products are as relevant as ever. It is no secret that there is an enormous amount of products, the reliability of which does not influence the person's safety and their premature failure only harms the image of its producer. But there are some types of products that must not be unreliable. The issues of reliability require special attention in the production of innovative component parts, assemblies and mechanisms of vehicles. Their sudden failure can result in catastrophic consequences and not only economic losses or loss of the business reputation of the producer but also the unmitigatable death of people. At the same time, the increase in the reliability of products entails a cost escalation for the producer. Thus, it is necessary to solve the contradiction between a desire to reduce the price of the production process of a product and maintain a certain level of reliability.

2 Essence and key reliability indices

If we speak about the fact that the made products must offer a certain level of reliability, it is necessary to define the essence of the concept of reliability and state its characteristic indices.

Reliability is a system or component property which performs the set functions, providing fail-free operation, durability and serviceability [1, 3, 4].

Depending on the conditions of the current task, one and the same item can be named a system or component. Under the term system we understand an aggregate of the jointly operating components (spare parts, associated parts, devices), performance of the set functions.

In order to evaluate the reliability properties (fail-free operation, serviceability, storageability, durability), it is necessary to introduce quantitative reliability indices.

Quantitative reliability indices of nonrepairable items:

1). The probability of no-failure operation *P(t)*. Under the probability of no-failure operation of an item we understand that within the limits of the set operating time the item will not fail. Mathematically this index can be determined as the probability that time *T* of no-failure operation is a random variable and will exceed the set *t* [2]:

$$P(t) = \frac{N_0 - n(t)}{N_0}, \quad (1)$$

where N_0 – total number of products;
n(t) – number of failed products till the beginning of the interval of time under investigation.

2). Failure probability *Q(t)*. Here failure probability means the probability that failure of an item will happen during a period of time not exceeding the set value *t* [2]:

$$Q(t) = I - P(t). \quad (2)$$

3). Rate of failures $\lambda(t)$ – rate of failure of a nonrepairable product in a unit of time after the current moment upon the condition that the failure could not happen till that moment [2]: The probability of no-failure operation will be determined in the following way:

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$$P(t) = e^{-\lambda t}. \quad (3)$$

4). Mean time to failure T_0 – mathematical expectation of the running time of a product till the first failure [2]:

$$T_0 = M[T] = \frac{\sum_{i=0}^{N} \tau_i}{N_0}. \quad (4)$$

On the whole, the task for the calculation of reliability: determination of fail-free operation indices of a system, consisting of non-repairable items, according to data on component reliability and interactions between them.

In turn, the purpose of the calculation of reliability is a choice of one or another structural solution, as well as the determination of possibility and, mainly, the economic efficiency of backing up.

3 Costs structure for production and post-sale maintenance of innovative products

When evaluating necessary investment amounts, first of all, it is necessary to determine the cost value of the enterprise when planning to implement the investment project. If such an investment project represents the industrial production of an innovative product, we can state that the total costs of the enterprise in manufacturing the innovative product on the one hand, include the costs of its development, production, sale and post-sale maintenance, i.e. maintenance of use, but on the other hand, these costs depend on the degrees of reliability of the innovative product characterised by the probability of no-failure operation *P(t)*.

Formally combined costs of the whole above-stated process can be presented as follows:

$$C_\Sigma = C_{prod} + C_{use} = f[P(t)], \quad (5)$$

where C_{prod} – costs of development and production of the innovative product; C_{use} – costs of maintenance of use of the innovative product.

Obviously, the higher the probability of no-failure operation of the product, the higher its price. It is possible to accept the following expression as a model of this dependence:

$$C_{prod} = a \cdot P^{\alpha}, \quad (6)$$

where *a* and α are corresponding factors, determining C_{prod}, *P* – *P(tr)* – probability of no-failure operation during the warranty period *tr*.

The model of dependence for operating costs can be presented as follows:

$$C_{use} = b \cdot (1/P)^{\beta}. \quad (7)$$

Quite often the made products can be used in devices requiring enhanced reliability due to a direct influence on the safety of vital activity security or high importance of performed tasks. As an example it is possible to mention sea, air, rail and road transport, where switching of the systems responsible for vital activity security to backup ones should be carried out with a probability close to 1.

Therefore backing up is presently one of the most in-use methods for the increase in no-failure operation of innovative products, especially for nonrepairable (impossible to repair) devices.

But in this case of backing up a problem regarding the contradictions between mass-dimensional and cost limitations often appears, as well as a question about the economic efficiency of such a decision, especially with the creation of an innovative product. The practical possibility of backing up at the level of components, associated parts and devices on the whole meets the challenge of the increase in fail-free operation of a device thanks to backing up of the weak component of the basic kit.

It is generally known, that the failure of a product happens due to the breakdown of one or several components of this product. Thus, as experience shows, in the vast majority of cases other components work smoothly for quite a long period. In this context, duplication of a product on the whole means, that for the sake of one or several failed components we include one more of the same product with the same component with a high probability of failure. Therefore, the larger the product is, the less confidence we have in the justification of the backup. The price is too high to pay for not-knowing which component of the device exactly will fail during its use.

Therefore, first of all, it is necessary to discuss the economic model of the cost of duplication of products as the simplest and most widespread type of backing up.

4 Evaluation of the economic efficiency of the increase in reliability of an innovative product by means of backing up

The working efficiency of systems without backing up requires working efficiency of all of the components of the system. In complex technical devices, without backing up, it is never possible to reach a high level of reliability even in the case of using components with high fail-free operation indices. System with backing up is a system with a redundancy of components, i.e. with backup parts, which are redundant in relation to the minimum necessary (main) construction and executing the same functions as the main components. In systems with backing up, the operation of the system is guaranteed while there are enough backup components that can start their work when the original components fail.

It is necessary to state that failure of the main component or component duplicating the main one, does not mean failure of the duplicated device in general. If a backing up device is in standby mode, it is easy to show that the total probability of no-failure operation of the whole duplicated device of $P_g(t)$ will be as follows:

$$P_g(t) = 1 - [1 - P(t)]^2 = P(t)[2 - P(t)], \quad (8)$$

where $P(t)$ – probability of no-failure operation of the main or backing up device.

Duplication of a product prolongs its fail-free operation, i.e. $P_g(t) > P(t)$. Thus, it is obvious, that the cost of the duplicated device exceeds the cost of the main or backing up device by at least two times and, naturally, it is necessary to expect that the total expenses will be, at least, two times higher compared to the expenses for the creation of non-backed up devices. However, this seemingly obvious conclusion requires deeper analysis and, as it will be presented, it is not always justified.

Let us explain the relevance of raising the issue of the economic efficiency of the backing up of devices using an example of the simplest case of backing up duplication.

For example, the probability of no-failure operation of the developed innovative device considering the fail-free operation of the existing components base, is evaluated at the level of $P = P(t_g) = 0.9$ for a guaranteed period of time t_g, but the required reliability value of this device for the same period of time is $P = P_{required}(t_g) = 0.99$.

There are two obvious solutions to this issue.

The first way represents an increase in the fail-free operation value of the device due to the increase in reliability of its components without backing up of the components or the device in general, i.e. thanks to using a more expensive and more reliable component base, more attentive selection of components, more careful input and output control, etc.

The second way is duplication of the device, which also represents a solution to the set problem, because the probability of fail-free operation $P_g = P_g(t_g)$ of the duplicated device according to expression (2) and the probability of no-failure operation $P(t_g) = 0.9$ set above, will be equal to the required value.

$$P_g = 1 - [1 - P]^2 = 1 - 0.1^2 = 0.99$$

If here, the number of required devices with the probability of no-failure operation $P_g(t_g) = 0.99$, is equal to N_g, the general production of the duplicated devices will be:

$$N_{\Sigma g} = N_g + (1 - P_g(t_g)N_g . \quad (9)$$

Because the number of duplicated devices $(1 - P_g(t_g)N_g$ with the probability of no-failure operation $P_g = P_g(t_g)$ during their use can fail.

Here $(1 - P_g)$ – is the probability of failure of a product when probability of no-failure operation is $P_g = P_g(t_g)$ during the guarantee period of its use $t = t_g$.

One duplicated product represents two identical nonredundant devices, therefore the cost of every duplicated device makes $2C_1$, where C_1 – the cost of one nonredundant device.

Accordingly, taking into account formula (8) the total production costs $N_{\Sigma g}$ of the duplicated products make:

$$C_{\Sigma g} = [N_g + (1 - P_g(t_g)N_g]2C_1 = 2N_g C_1 (2 - P_g) . \quad (10)$$

If our aim is to increase fail-free operation of a product without its duplication, then total expenses C_Σ will make:

$$C_\Sigma = N_1 C_1 [1 + K(a/k)](2 - P_1) , \quad (11)$$

where $K(a/k)$ – factors, characterising the cost of the increase in fail-free operation from the value of probability of no-failure operation P to the value P_1.

Increase in the probability of fail-free operation is equivalent to the decrease in fault intensity:

$$P_1 = e^{-\lambda t} \cdot tr$$

According to Equation (7) the value of the production costs of the product in this case will make:

$$C_{prod} - aP_1^a = aP^{a/k}$$

Using Equations (11) and (12), let us determine the $K(\alpha/k)$ value, in the case of which the number of goods $N_1 = N_g$ and the total costs for the increase in reliability without duplication are equal to the total costs when duplication is used and here the probability of fail-free operation of a device with duplication P_g and a device of enhanced reliability without duplication P_1 are equal. Solving these equations together we will get:

$$K(a/k) = \ln P_1 / \ln P . \quad (12)$$

It coincides with the found dependence $K = \ln P_1 / \ln P$. If the actual probability of fail-free operation of the nonredundant device we used above as an example $P = 0.9$, and the required $P_1 = P_g = 0.99$, than, by inserting these values in (11), we get:

$$K(a/k) = \ln 0.99 / \ln 0.9 \approx 0.1$$

The obtained result means that in the case of AN increase of fail-free operation of a product without backing up, evaluated by means of the value $K(\alpha/k) = 0.1$, the total costs of production and use during the guaranteed period of time t_g of the duplicated products or nonredundant products with the increase of their fail-free operation without duplications are identical, i.e. $C_\Sigma = C_{\Sigma g}$. At $K(\alpha/k) > 0.1$ duplication of a device requires less expenses than the corresponding increase in reliability of a device without duplication in other conditions, described above, i.e. $C_{\Sigma g} < C_\Sigma$. In case of other values of reliability of a product the P and P_1 used in calculation of increase of fail-free operation of a product, and determined by means of (11), will have other values.

For example, at a primary level of reliability (probability of fail-free operation $P = 0.7$) and required level of probability of fail-free operation $P_1=0.9$, the factor determining the increase in cost of a device of enhanced reliability will be:

$$K(a/k) = \ln 0.99 / \ln 0.7 \approx 0.3$$

It means that if the cost of the increase in fail-free operation of a product reached by the enterprise-manufacturer $K(a/k)>0.3$, then manufacturer's total expenses on production and replacement of the faulty devices for new ones in the case of duplication of devices will be less than the total expenses in the case of an increase in fail-free operation of products without their backing up. Indeed, let us suppose that the factor determining the reached cost of increase in fail-free operation of products makes $0.4>0.3$ for the manufacturer, and initial terms remain the same: $P=0.7$, $P_1=0.9$.

As follows from (9), the relative total costs of the enterprise in the case of duplication of the product are equal to:

$$C_{\Sigma g} / C = 2(2 - P_g) = 2(2 - 0.91) = 2.18$$

It is easy to show that if primary reliability is equal to 0.7, P_g will be

$$P_g = 1 - [1 - P]^2 = 1 - 0.3^2 = 0.91$$

In the case of an increase in fail-free operation of the product without duplication, from expression (5) we get:

$$C_{\Sigma g} / C = (1 + 0.4(\ln 0.7 / \ln 0.9))(2 - 0.91) = 2.589$$

As a result

$$\Delta C_{\Sigma} = C_{\Sigma} - C_{\Sigma g} = 2.589 - 0.409C .$$

Taking into account that the total cost of the initially manufactured products $C=N_1C_1$, where N_1 – number of manufactured products, and C_1 – cost of one product.

Thus, the economic efficiency of the duplication of a product depends on the actual safety level of the product, the required reliability level P_1, as well as the cost of the increase in fail-free operation of the product, evaluated by means of α/k value in case backing up is not made.

Thus, the higher the cost of the increase in fail-free operation of the product without its duplication, the higher the probability that duplication of the product will require lower costs regarding the production and warranty service from the consumer compared to the increase in fail-free operation of the product without duplication.

Duplication of products at low values of cost for an increase in fail-free operation is economically inefficient, except for the cases when duplication is obligatory for an enterprise-manufacturer according to the specifications of the produced device.

The results stated above on the comparative analysis of the cost of production and warranty service of the backed up and non-redundant devices of innovative products, allow justification of the necessary amount of money for the financing of an innovative project by an investor.

The approach applied to the analysis of these requirements allows certain methods for a decrease in the expended monetary means regarding the duplication of products to be offered, if the strategy of duplication is accepted. If a non-redundant device offers the probability of fail-free operation P, and the required probability is equal to P_1, then in a number of cases it is possible to do as follows.

If products of two quality classes are manufactured, one of them with a probability of fail-free operation P, and the other one with a probability $P_2<P$. If $P_2<P$, the cost of the second-class quality product will be lower according to the presented in equations. In the case of duplication of these two devices, the resulting probability of fail-free operation will be:

$$P_g = 1 - (1 - P)(1 - P_2) . \quad (14)$$

From the presented dependence it is evident, that if $P_2<P$, and the production costs of such a product are lower, then later during decision-making it is necessary to discuss requirements applied to level of reliability.

If applying the requirement $P_g=P_1$ of the required probability of fail-free operation, using (9) we get:

$$P_g = (P_1 - P) / (1 - P) . \quad (15)$$

For example we will perform the calculation of the required reliability of the cheaper device P_2, if the reliability of the first-class quality product $P = 0.95$, and the required probability of fail-free operation of the duplicated product $P_1 = 0.99$. Using the given numbers in (8) we get $P_2 = 0.8$.

Obviously the product with lower reliability will have a lower price and will allow requirements for investments to be reduced without a decrease in the requirements for the reliability of the produced innovative product.

The only inconvenience in this case is that two assembly lines may be required for the first- and second-class quality products, but due to the obvious economic efficiency of it, such an approach has a right to exist.

Modern technological processes allow this problem to be solved. It is far from certain that for the production of products of a different quality class two different production lines will be required. Such a requirement is only possible in the case if they are absolutely technologically different, or if the identical number of such products must be manufactured at the same time. If there are no such requirements, the organisation of production can be performed consistently using one and the same production line.

5 Conclusions

Thus, it is determined that the higher the cost for an increase in fail-free operation of the product without its duplication, the higher the probability that duplication of the product will require lower total costs regarding the production and warranty service of the products compared to the increase in fail-free operation of the product without duplication. The higher the cost for an increase in fail-free operation of the product without its duplication, the higher the probability that the total costs consumer will be lower than the costs for duplication of the products.

Economic efficiency of duplication of a product at low values of cost for an increase in fail-free operation is only possible in the case of a comparatively high level of fail-free operation of the nonredundant product.

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