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PREVENTIVE MAINTENANCE OF TECHNICAL SYSTEMS AS PART OF RISK MANAGEMENT

Abstract: Technical objects used in logistics systems should not only be reliable, but also pose low risk arising from potential failures. Results of damage to or failure of complex objects depend on time of the failure duration and thus on the time of repairs, as well as on reliability structure and reliability characteristics of object elements. The risk connected with complex objects with serial reliability structure, both reparable and unreparable ones, was specified and analysed in the paper. The risk was mitigated by preventive replacements of object elements on the basis of statistical diagnosing. A computer simulation model was used to confirm a feasibility of minimising overall costs of preventive maintenance and failure effects.

Keywords: preventive maintenence, risk management, reliability, logistic systems.

1. Introduction

Functioning of the logistic system consists in using a technical system for carrying out specific tasks, in particular, those associated with supply of goods. Therefore, in a logistic system – as in any other technical system – two aspects of systemic perspective have to be combined.

The first one is the necessity to treat the system as a unit from the moment of designing it until the task implementation. The other one is the necessity to treat the system elements as separate parts operating together to achieve the established goal. It is mainly reflected in the technical sphere of the system, in shaping its reliability.

Functioning of the technical system can be seen in terms of both its failures and their effects. It is expected that the system should not only be reliable, that is characterised by high probability of correct operation, but also permit mitigation of consequences of potential damages and failures.

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It is the risk that is the measure of the failure effects, specified as the product of failure and potential failure effects (Szymanek 2006):

$$r(t) = F(t) \cdot K(t) \tag{1}$$

where:

$F(t)$ – cumulative distribution function of the time of the object correct operation,

$K(t)$ – cost function of the object failure effects.

Thus defined risk is specified for the whole object based on its unreliability and costs of the object potential failure effects. In such a case, any actions intended to mitigate the risk by increasing reliability must of necessity involve the whole object. Considering technical aspect, it is a rarely encountered situation, because actions enhancing the technical object reliability usually apply to its components and the object reliability structure. Preventive renewals of an object involve the whole object and they consist in replacements of the object selected elements. The required level of reliability and the acceptable risk level may be assumed as the criterion of preventive replacement of elements.

2. Risk in operation of complex technical objects

The logistic system, as a technical object, is usually characterised by serial reliability structure. Accordingly, the object failure is caused by a failure of any object component. One can assume that effects of the object failure resulting from nonperformance of the assumed functions do not depend on the kind of faulty element.

However, the given failure duration (and thus time of repair) may depend on which element has failed. If we assume that the cost of the object failure effects depends on its failure(s) duration (and thus the time of repairs), it is important, for estimating the risk occurrence, to take into account the object reliability structure, as well as the reliability characteristics of the object elements. In the case of a particular failure, the cost associated with the faulty element has to be incurred. Only after prolonged operational use of a given object, does the average cost of failure determine the amount of costs to be borne as associated with the failure effects.

In order to estimate the cost of failure consequences based on the costs associated with failures of particular elements it is necessary to specify the share of the failure of particular elements in the overall object failure. For an object with a serial reliability structure the probability of its failure due to the failure of the i-th element thereof may be determined from the following relationship (Ważyńska-Fiok *et al.* 1990):

$$q_i(t) = \int_0^t \lambda_i(x) \cdot R_s(x)\, dx \tag{2}$$

where:

$\lambda_i(x)$ – the i-th element failure intensity function,

$R_s(x)$ – the system reliability function.

Since:

$$\sum_{i=1}^{n} q_i(t) = F_s\left(t\right) = 1 - R_s\left(t\right)$$

then quotient:

$$\frac{q_i\left(t\right)}{F_s\left(t\right)}$$

is the weight specifying the share of the i-th element failure in the overall object failure.

On this basis, for unreparable objects that are in operation until the first failure occurrence, the average cost of the object failure can be determined as follows:

$$K_s(t) = \sum_{i=1}^{n} K_i \cdot \frac{q_i(t)}{F_s(t)} \tag{3}$$

where:

- n – number of the object elements,
- K_i – the i-th element failure effects cost,
- $q_i(t)$ – the probability of the object failure due to the failure of the i-th element,
- $F_s(t)$ – cumulative distribution function of the time of the object correct operation.

Using (3) in formula (1), we obtain the formula for risk occurrence concerning the complex object with serial reliability structure:

$$r_s(t) = F_s(t) \cdot \sum_{i=1}^{n} K_i \cdot \frac{q_i(t)}{F_s(t)} = \sum_{i=1}^{n} K_i \cdot q_i(t) \tag{4}$$

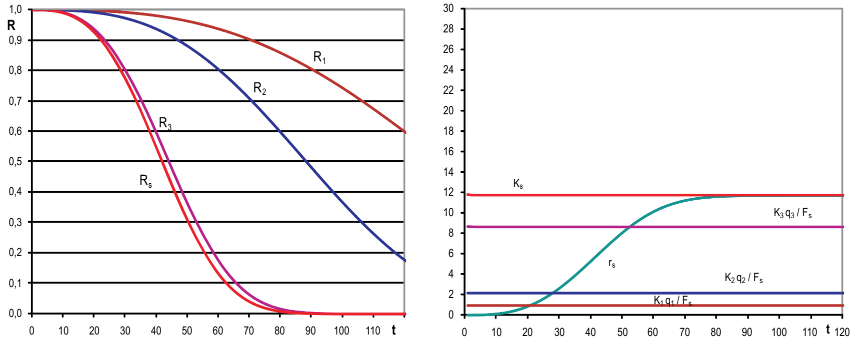
Thus the risk associated with the complex object failure is not a sum of risks caused by failures of particular elements, but it is the resultant of a share of effects of particular kinds of failures. The risk associated with the object failures grows with time from zero to the limit value, being the average cost of the object failure (Fig. 1).

In case of reparable objects in which the faulty elements are replaced with new ones, the average cost of the object failure may be estimated taking into account the number of failures of particular elements and the costs of the failure consequences:

$$K_s = \frac{\sum_{i=1}^{n} K_i \cdot u_i}{\sum_{i=1}^{n} u_i} \tag{5}$$

where:

- K_i – the cost of the object failure consequences due to the failure of the i-th element,
- u_i – the number of the i-th element failures.



(a) (b)

Fig. 1. *Example of a complex object composed of three elements and graph of risk function: (a) reliability function of the object and its elements, (b) risk function and costs of elements failures*

Because the average time between the i-th element consecutive failures may be estimated as:

$$E(T_i) = \frac{T_u}{u_i},$$

where T_u is time of operational use, we obtain:

$$K_s = \frac{\sum_{i=1}^{n} \frac{K_i}{E\left(T_i\right)}}{\sum_{i=1}^{n} \frac{1}{E\left(T_i\right)}} \tag{6}$$

3. Preventive replacements

The reduction of risk occurrence may be achieved by reducing the failure effects cost or increasing the object reliability. An increase in the complex object reliability can be achieved by preventive replacement of its elements. One of the ways consists in periodical statistical diagnosing of the object condition and in its partial renewal by replacement of selected elements. Dynamic determination of a scope of preventive replacements may be based on a statistical assessment of the present status of object elements based on a quantile of time remaining until the object failure (Okulewicz *et al.* 2007).

The statistical diagnosis uses data gathered during normal utilisation of objects. The data concerns failures, repairs and replacements of object elements. Next, the probability distribution function of time or mileage to failure for each of these elements is determined. It can be done either with the use of data collected in the past or by relying upon experts' opinions at the start. On that basis, the set is defined of those elements the replacement of which will effect in a failure probability not exceeding its assumed value in the duration of the scheduled task. The main target is increasing the availability of the equipment by reducing the amount of technical tasks to its minimum, and it reaches this target by substituting the technical inspection with the statistical diagnosis.

The procedure statistically predicts failures at the part level by calculating the mean residual lifetime to failure (MRL). However, the comparison of MRL with the required work renders about half of the objects requiring servicing before failure, with the other objects failing without any treatment. Thus, it is better to apply the quantile function of residual lifetime instead of the MRL to increase the probability of preventive service. This measure directly relates to predicted work period and the reliability of the system. At any time t, the following conditions have to be met:

$$q_p(t) \geqslant d,$$

where:

d – tasks implementation period,

$q_p(t)$ – quantile of residual lifetime function, order p.

Function $q_p(t)$ shall be defined as follows (Joe *et al.* 1983):

$$q_p(t) = F_t^{-1}(p) = \inf\{x : F_t(x) \geqslant p\}$$
$$1 - F_t(x) = R_t(x) = \frac{R(t+x)}{R(t)}, \qquad x, t \geqslant 0$$

where:

$F_t(x)$ – cumulative distribution function of the residual lifetime,

$R_t(x)$ – conditional reliability function.

In order to use the acceptable risk level as the criterion of element selection for replacement, the quantile order should be assumed as per formula:

$$p = \frac{r_g}{K_s} \tag{7}$$

where:

r_g – acceptable risk level,

K_s – average cost of the object failure (formulas (3) and (6)).

4. Example of risk maintenance

An object consisting of three different elements was considered, whose reliability is described by the Weibull distribution of parameters as in Table 1. The Weibull cumulative distribution function is given by the formula:

$$F(t) = 1 - e^{-\left(\frac{t}{\beta}\right)^{\alpha}},$$

and the expected value of time remaining until the object failure is equal to

$$E(T) = \beta \cdot \Gamma\left(1 + \frac{1}{\alpha}\right),$$

where $\Gamma(x)$ is Gamma function.

Table 1. *Parameters of the object elements*

Element	α	β	Cost of the object failure effects	Cost of preventive replacements
1	3	150	30	6
2	3	100	20	4
3	3	50	10	2

For the assumed data, the average cost of the object failure effects as per formula (6) $Ks = 16.4$. This is the highest risk concerned with that object. In order to decrease the risk level to $r_g = 4$ the preventive replacements should be carried out according to the quantile order $p = 4 / 16.4 = 0.24$.

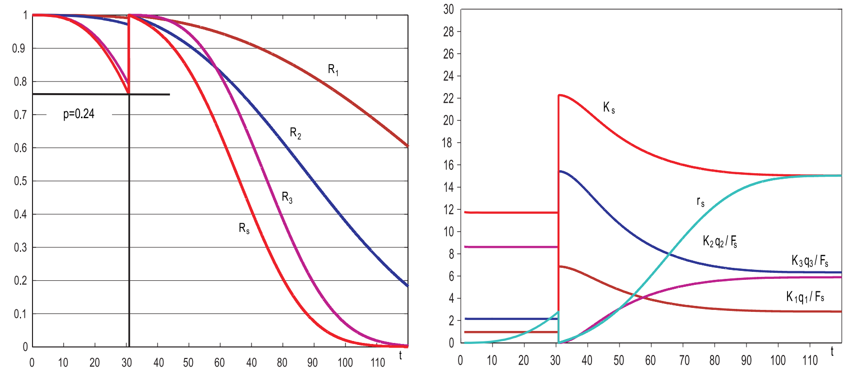


Fig. 2. *Example of effects of carrying out a preventive replacement of element 3 for* $t = 30$, $K_1 = 30$, $K_2 = 20$ *and* $K_3 = 10$: *(a) reliability function of the object and its elements, (b) risk function and costs of elements' failures*

Preventive renewal of one of the elements results in temporary reduction of risk associated with that element failure; also its reliability function increases to 1. Reliability functions of other elements – that have not failed – describe their remaining lifetime and also increase to 1. At the same time, it will cause increases in the shares of the remaining elements in the average cost of failure and – depending on the costs of failure caused by particular elements – the increase or decrease in the average cost of failure. The risk will then be growing with "ageing" of the replaced element, until the new value of the average cost of the object failure is reached in the future (Fig. 2). This growth will be broken by sequential preventive replacement of another object's element. It will also cause a break in the intensity of failure function growth.

This way, by controlling the intensity function, the risk will be maintained at the required level (Fig. 3).

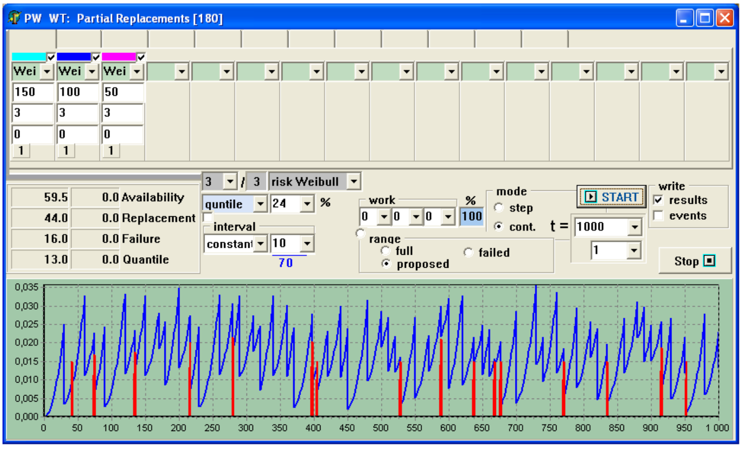


Fig. 3. *Illustration of the failure intensity function graph when using preventive replacements (continues line – intensity function, vertical line – failure occurrence)*

As a result of using the preventive maintenance measures, the object reliability increases, which manifests itself in a reduced number of failures (Tab. 2).

Table 2. *Results of simulation for* $T = 10,000$ *and the period of statistical diagnosing* $d = 10$

		Without preventive replacements	**With preventive replacements** $p = 0.24$
The number of the elements failures:	1	75	48
	2	110	51
	3	223	53
The number of the object failures		408	152
The number of the elements replacements:	1	0	38
	2	0	93
	3	0	350
The total number of the elements replacements		0	481
Aggregate cost of failures		6,680	2,990
Aggregate cost of replacements		0	1,300
Aggregate cost of failures and replacements		6,680	4,290
Average cost of the object failure		16.4	19.7

The costs of failures are here much lower than without applying preventive maintenance measures. Mean failure cost becomes greater than without preventive replacements, because failures of weak elements that are also the cheapest are eliminated.

Selection of the acceptable risk values affects the aggregate costs of failures and preventive replacements (Fig. 4), which thus can be minimised by changing the acceptable risk level.

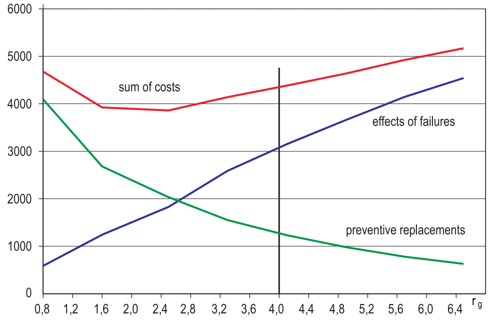


Fig. 4. *Diagram of aggregate costs of failure effects and preventive replacements as a function of acceptable risk level*

5. Conclusions

In the case of reparable objects, the faulty elements are replaced with new ones, instead of replacing the whole objects. This means that the average cost of the object failure should be estimated taking into account probability of failure of particular elements and the costs of its failure consequences. This is because the risk associated with the complex object failure is not a sum of risks caused by failures of particular elements, but it is the resultant of a share of effects of particular kinds of failures. Thus the risk analysis must be carried out with regard to reliability structure of the object.

Given the mutual dependence of risk and reliability, it is possible to decrease aggregate costs of failure consequences by adapting the quantile order to the accepted risk level. On this basis, preventive replacements of object elements could be made. This way the required level of reliability and the acceptable risk level may be used as the dependable criteria of preventive replacement of elements. In practical applications, a risk criterion as well as reliability could be of interest while describing different maintenance strategies.

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