Economic Aspects of Reliability in Mining Processes

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Abstract

In the present article, the issue of reliability of the production process in physical and value terms were discussed. Economic reasons in forming the level of reliability were analyzed. Factors influencing its correct course and multithreading are presented also in relation to the mining process. The main goal of the article was to present the economic aspect of the reliability of production processes, in particular the mining process. In addition, attention was paid to optimizing the level of reliability considering the multi-criteria of this issue. The considerations presented in this work are generalized and their results can also be used in other complex production systems.

Keywords: reliability, production system, economy, optimization

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Economic reasons for shaping the level of reliability

This work considers systems whose goals include production or satisfying needs. The analyzed topic is considered for the underground mine treated as a system composed of a set of subsystems (Tabaszewski, 1999). These, in turn, consist of elements and attributes that form a complex whole linked by functional dependencies and having a specific goal (the coal output). Reliability is a feature of any such system. At the same time, it is the basic factor of usefulness, i.e. the system's ability to satisfy human needs, directly determining the practical possibilities of achieving the objectives of the system. Systems, even the most perfect ones in a functional sense, become useless if the level of their reliability is not satisfying (Migdalski, 1992).

Physical aspect

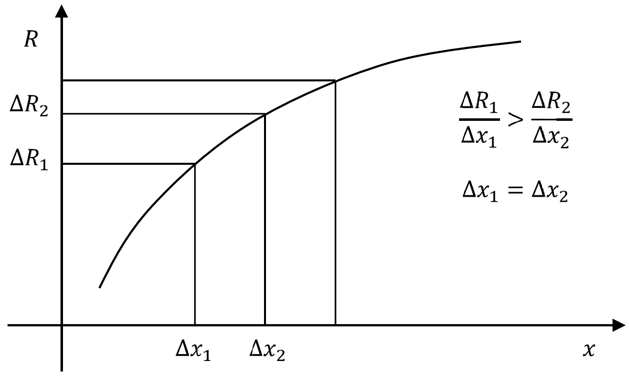
Looking for the premises of rational forming of the level of reliability, it is worth referring to the classic normative models built on the basis of economic theory. For this purpose, some initial assumptions and a terminological convention were adopted. According to them, the set of factors that make up the systems' usability is divided into two separate subsets. The first concerns attributes that determine the scale in which the system's goals can be realized. The combination of the values of these attributes is called system productivity. The second subset deals with all the attributes that determine the level of reliability. The combination of their values was called system reliability.

Because reliability (as well as productivity) depends - obviously - on the size, manner and use of various resources in the design, production and operation of the system, it may be interesting to try to transfer to the area of reliability considerations classic methods of economic analysis of productivity (see e.g. (Jędrzejowicz, 1975). The basis for system productivity analysis is the so-called production function. It is a model for the transformation of resources and resources into a system with specified productivity. The production function describes the relationship between production and inputs of production factors. Most often, the expenditure of living and production assets is taken into account (Begg, 1992).

Similarly, the starting point for the analysis of the reliability of production systems should become the reliability function (Oprychał, 2015). It is a model of transformation of supplies and resources into a system with a defined reliability. It is used to describe the relationship between system reliability and the cost of reliability factors. These factors are the same supplies and resources as production factors. Expenditure of supplies and resources is measured in physical or monetary units as in the case of production functions.

The transformation of resources and supplies is, in the case of both functions described and understood broadly. It covers the processes of consumption and spending of physical resources of various types and properties, human work, various qualifications and, finally, monetary resources. The processes of consuming and spending resources can take place at various stages of system life, from the design and construction phase to the phases of use or renewal.

The type of reliability function can be examined using the concept of marginal reliability R' for X resources. Marginal reliability will be used to describe changes in system reliability when in the course of its design, construction and operation, units of individual resources are added or subtracted. Thus, the marginal



Rys. 1. Wykres funkcji niezawodności w przypadku zmniejszającej się funkcji niezawodności krańcowej. Źródło: (Migdalski, 1992)
Fig. 1. Graph of the reliability function in the case of decreasing marginal reliability function. Source(Migdalski, 1992)

reliability of the j- of the resource is defined at the specified point by the expression:

$$R_j^{'} = \frac{\delta R}{\delta X_j} \tag{1}$$

or, if partial derivatives do not exist, by the following formula:

$$R_j^{'} = \frac{\Delta R}{\Delta X_j} \tag{2}$$

where R is the reliability measured by a physical measure.

Based on empirical observations, it is easy to state that in many situations the marginal reliability R_j' decreases when X_j increases. This means that the marginal product of any resource measured in terms of reliability decreases if the quantity of the product used increases, while the number of others does not change.

An example of the case described above can be, among others, a hard coal mine type system and a resource for increasing the qualifications of the crew. As the expenditures for improving the qualifications of the crew with unchanged resources for the production and maintenance of equipment and machines included in the mine equipment are increased, the obtained reliability increases will be smaller and smaller. The reliability function of a similar type is shown in Figure 1.

The specified level of reliability R can be obtained by many alternative combinations of expenditure (consumption) of resources. For example, certain reliability of a longwall system can be guaranteed either through increased investment (use of better materials, more expensive technology, etc.), or through increased operating costs (more frequent repairs, maintenance with better measures, more frequent component replacement, etc.). Each of the possible alternative spending options is, technically effective, as defined by the definition of a reliability function. In other words, in individual variants, only the level of reliability is considered, which was obtained by the best in terms of technical consumption of funds. Figure 2 presents reliability functions R for two reliability factors (e.g. different resources) x_1 and x_2, while Figure 3 presents the projection of reliability isoquants on the plane.

The reliability isoquant, sometimes called the equal reliability curve, presents all quantitative combinations of two reliability factors that give the same reliability (Iwin, Niedzielski, 2002).

All resource combinations on the reliability isoquant are technically efficient. None of these combinations is better than the rest in terms of the result in the physical sense. Choosing the optimal combination of resources is conditioned by two factors::

- relative efficiency in terms of the impact on the reliability of individual resources and / or the way they are used,
- the relative value or cost of individual resources and / or methods of consuming them.

The starting point for determining the optimum in terms of reliability is defining the marginal rate of substitution of reliability factors (resources) in various points of the reliability isoquant:

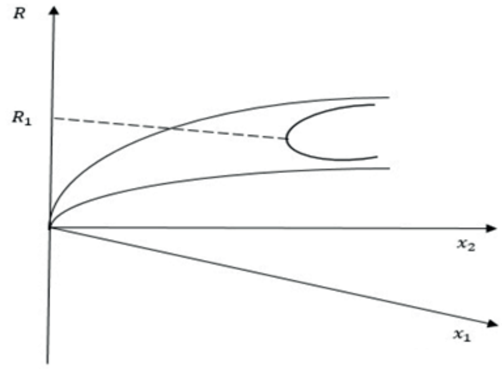
$$X^{'} = \frac{\delta X_i}{\delta X_j} = -\frac{R_j^{'}}{R^{'}} \tag{3}$$

Thus, the marginal rate of substitution of one type of resource to another is equal to the negative inverse of their marginal reliability.

Value aspect

So far, the physical aspects of the production system model have been mainly considered. In order to define the optimum reliability, it is also necessary to consider the value aspect of resource transformation in reliability. Consequently, the following two models are considered:

1) Physical model:
$x=(x_1,\dots,x_n)$ – the amount of money spent;



Rys. 2. Funkcja niezawodności w przestrzeni trójwymiarowej. Źródło: na podstawie (Migdalski, 1992)
Fig. 2. Reliability function in three-dimensional space. Source: based on (Migdalski, 1992)

R – reliability measured by a physical meter;
g – reliability function, *Z=g(x)*.

2) Value model:
h(x) – value of resources spent to ensure reliability;
V(R) – value of reliability;
Z=V(R)- h(x) – value of resources transformation x in reliability R.

The task of optimal selection in the aspect of a certain level of reliability of the R* variant of spending resources is presented below as a problem of maximizing the objective function:

$$Z=V(R)-h(x)\rightarrow max \tag{4}$$

with limits of the type:

$$R'\leq g(x) \tag{5}$$

The formulated task is solvable if and only if the values of reliability and resources can be measured by using the same measure. If not, the task of choosing the optimal variant of spending resources should be solved as one of the following two problems:

- minimizing the value of resources used to achieve the assumed reliability,
- maximizing reliability with data or limited resources.

In the first case, the optimization problem is formulated as follows:

$$K=h(x_1,\dots,x_n)\rightarrow min \tag{6}$$

with the limits:

$$R^*=g(x_1,\dots,x_n) \tag{7}$$

where K is the cost of used resources.

The above task can be described by the following formula:

$$h(x_1,\dots,x_n)-\lambda\left[g(x_1,\dots,x_n)-R^*\right]\rightarrow min \tag{8}$$

where λ is the Lagrange multiplier.

Determining the partial derivatives of the cost function for particular resources and comparing them to zero, we get the dependence:

$$\frac{\delta h}{\delta x_i}-\lambda\frac{\delta g}{\delta x_i}=0 \qquad \text{dla } i=1,2,\dots,n \tag{9}$$

From the above results:

$$\frac{\frac{\delta h}{\delta x_i}}{\frac{\delta g}{\delta x_i}}=\frac{K_i'}{R_i'}=\lambda \qquad \text{dla } i=1,2,\dots,n \tag{10}$$

where K_i' is the marginal cost of the i- of the measure. After transformation, you get:

$$\frac{R_i'}{K_i'}=\frac{R_j'}{K_j'} \qquad \text{for every } i \text{ and } j \tag{11}$$

Equation 11 and limitation 7 are the condition for optimality of the first problem.

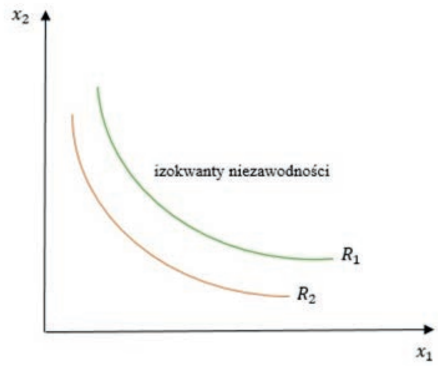
An analogous result gives the solution to the second problem of maximizing reliability for a given level of K_1 consumption.

The Lagrange multiplier in the first case is the inverse of the multiplier for the second case, while the limitation of the second problem takes the form:

$$K_1=h(x_1,\dots,x_n) \tag{12}$$

The marginal cost K_i' should be understood as a valuable measure of the increase in the consumption of the i- of the resource if the level of reliability increased by a unit.

The optimum of the considered problem of reliability is therefore the point at which the ratios of marginal



Rys. 3. Izokwanty niezawodności na dwuwymiarowej płaszczyźnie zasobów. Źródło: na podstawie (Migdalski, 1992)i (Oprychał, 2015)
Fig. 3.Reliability Isoquants on the two-dimensional plane of resources. Source: based on (Migdalski, 1992) and (Oprychał, 2015)

reliability to marginal costs are the same. In this point, the cost isoquant (for the cost of *K*) is tangent to the reliability isoquant (in compare to, Figure 4).

Determining the optimum for various levels of reliability, you can receive the so-called the choice path (Figure 5). It represents a combination of resources with the lowest cost, giving any level of reliability (Migdalski, 1992). Information on the optimum spending (consumption) of resources is not sufficient to determine the optimal level of reliability. On the basis of the previous considerations, it can be stated that the optimal level sought for it lies somewhere on the choice path and on the curve (function) of cost effectiveness. This curve is obtained by successive aggregation in the total cost of the necessary expenses incurred in the next points of the product path (Farrell, 1957). The characteristic course of the cost-effectiveness function is shown in Figure 6.

If the reliability and cost-effectiveness functions include areas restricted by convex curves upwards and if costs and reliability can be measured with one measure, the optimal level of reliability can be determined analytically for different criteria.

For example, if the reliability selection criterion is the total net value of the production system, the goal of optimization is to find the maximum expression:

$$Z=V(R) - h(x)$$

Because reliability *R* is a function of *X* resources and conversely, the cost of resources *h(x)* can be expressed in terms of reliability, so that:

$$Z=V(R) - h(R)$$

The level of reliability *R*, which maximizes the value of the system, is given by a condition:

$$\frac{\delta Z}{\delta R} = 0$$

and from this

$$\frac{\delta V}{\delta R} = \frac{\delta h'}{\delta R}$$

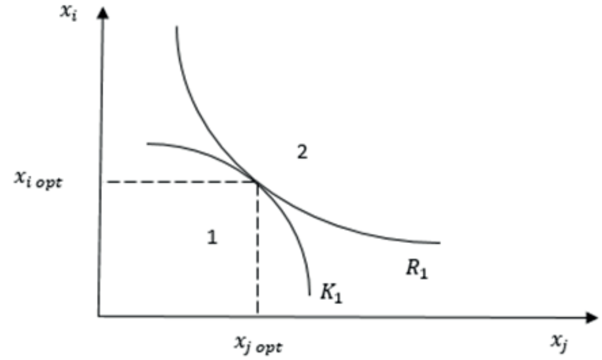
Treating *V* as income, and h as a cost, it can be stated that the optimal level of reliability in the aspect of profit maximization is achieved at the point where the ultimate reliability value ($\delta V/\delta R$) equals marginal costs ($\delta h'/\delta R$).

Optimization of the reliability level

While the general model of the relation between resource consumption and the reliability of systems based on the results obtained in economic theory may be useful for theoretical analyzes, its practical value for engineers designing technical systems seems to be very limited. The above results from the focus of assumptions as to the nature of the reliability and resource consumption (ie costs) function. The continuity, convexity, measurability and comparability of these elements of the analysis lead to the idealized model. In exceptional cases, such a model can be used to solve real problems.

The problem of choosing the level of reliability at the design stage of the system, and then the problem of maintaining the system in the state of fitness (the so-called maintenance problem) in the course of its “life” can, however, be considered as problem of spending limited resources to meet certain needs. The search for the optimum in the discussed scope then consists in solving one of the three following variants of the analyzed problem (Migdalski, 1992):

- for a given amount of resources and given technical limitations, the system reliability should be maximized,
- at the required level of system reliability and technical limitations, the use of unnecessary resources should be minimized to obtain and maintain reliability,
- it is essential to obtain a combination of reliability and quantity of resource consumption for its achievement and maintenance, which maximiz-



Rys. 4 Optimum wydatkowania X_i oraz X_j przy niezawodności R. Źródło: na podstawie (Migdalski, 1992)i (Oprychał, 2015)]
Figure 4. Optimum of spending X_i and X_j with reliability R. Source: based on (Migdalski, 1992) and (Oprychał, 2015)]

es the degree of implementation of the system's objectives.

The possibilities of solving each of the presented versions of the problem with the system reliability optimization, are very limited. The more important factors creating these limits are:

Rather nondeterministic character of the relationship between the amounts of expended resources and the reliability of system components. These dependencies are difficult to identify through statistical experiments, for example due to their high costs and the often unique nature of the systems.

The principles of the optimization calculus require taking into account the distribution of expenditure of resources over time, which obviously complicates the calculations and makes it difficult to build a satisfactory (in the sense of accuracy) model of the decision-making problem.

Resources - in presented frame- constitute a concept with a significant degree of aggregation. In fact, resources are not a homogeneous category, and the consumption of various types of resources requires the analysis of the possibility of their eventual substitution. The above is a further complication of the reliability optimization calculus.

In the case of decision problems within the variants (1) and (2) determining the amount of resources at the disposal or, alternatively, determining the required level of reliability requires earlier solution of another decision problem (metaproblem compared to the analyzed). This is not easy in a theoretical or practical sense.

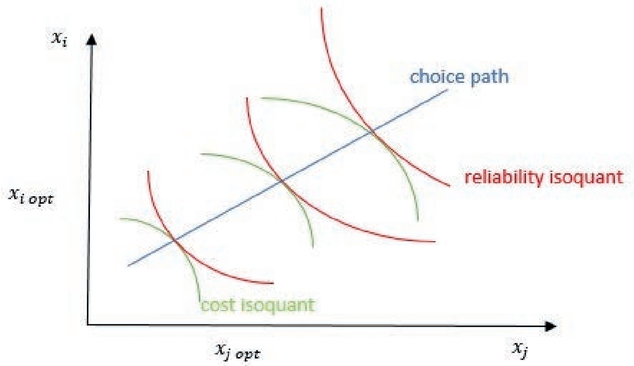
In the case of decision-making problems under option (3), it turns out that the system simultaneously pursues various goals, fulfills many functions and satisfies various social needs. The above leads to the necessity to consider multi-criteria issues in which – as we know – (see e.g. (Tillman at all., 1977)) – finding solutions is subject to further difficulties and limitations.

As a consequence, the real problems of optimizing system reliability belong to the class of uncertain problems, especially complex, dynamic and multi-criteria. Regardless of the above, these are at all economic problems (the method of allocating limited resources) with the limits reflecting technical and organizational conditions and requirements in the scope of functioning, design, production and systems operation.

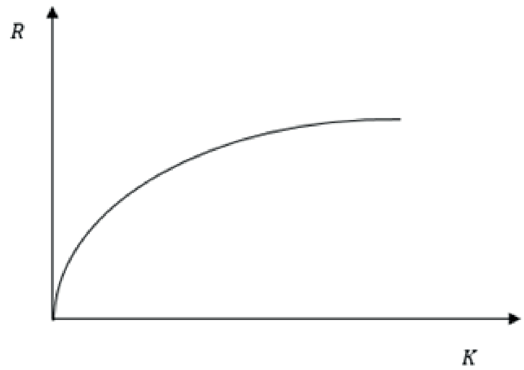
A number of models for optimizing system reliability have already been published (for example: (Farrell, 1957), (Oprychał, 2015), (Tillman at all, 1977), (Tao, Tam, 2012)). They are based on significant simplifications of reality. They mainly take into account only selected aspects and factors of significant real problems. The models in question differ in the way they treat time, the nature of goal functions and limitations, and techniques for obtaining solutions.

When considering the temporal structure, models of synthesis of static structures of reliability and models of reliability optimization in the course of the whole life of the system can be distinguished. The latter have dynamic nature, taking into account the expenditure of resources to maintain system traffic. Another criterion for classifying models of the type discussed is the scope of decision variables representing possible strategies for shaping and maintaining reliability. In the simplest models, the tool for shaping reliability is only the choice of the degree of redundancy of individual elements or system modules. More complex models allow selection of both the level of redundancy and the reliability of system components. Finally, the last group of models assumes the joint optimization of the choice of elements reliability, the method of reserving and selection of service and renewal strategies.

Regardless of the complexity of the model, methods of solving it, time structure or range of decision variables, it is not difficult to distinguish a certain set of basic information, without knowledge, which would be difficult to consider any approach to optimization of systems reliability. This collection includes, in particular, the following types of information:



Rys. .5 Ścieżka wyboru wariantów wydatkowania zasobów X_i oraz X_j dla różnych poziomów niezawodności
Fig. 5. The choice path of spending variants of resources X_i and X_j for different levels of reliability



Rys. 6. Funkcja efektywności kosztów
Fig.6. Cost-effectiveness function

- knowledge of the system's reliability structure or, alternatively, knowledge of the structure of the event tree binding elementary events with the final event;
- knowledge of the reliability of elements as a function of resource expenditure or, alternatively, knowledge of the probability of elementary events occurring as a function of many resources;
- knowledge of the impact of possible service strategies and renewals on their reliability.

Summary

Assuming that the designer or user has both a model of reliability of elements in the function of resource deployment and a model of reliability of the entire system, the problem of seeking its economically justified reliability requires overcoming another barrier - a computational barrier.

Calculation difficulties related to reliability optimization are related to the fact that in the case of a finite set of possible spending strategies for shaping the level of reliability, the appropriate decision problem is usually in the NP class - complete (i.e. computationally difficult) and can be effectively solved only with approximate methods. In a situation in which a set of possible strategies is uncountable, analytical solutions have been obtained only for the simplest models.

Attempts to optimize the reliability of systems are based on the above results from the conscious acceptance of many simplifications and inaccuracies. The determination of the extent to which they distort the sense of the solutions obtained is an indispensable element of a correct economic analysis of the rational level of reliability.

The reliability of such a complex system as a hard coal mine, is a multi-criteria problem and not easy to analyze. The decision maker must simultaneously optimize the values of various system attributes. For example, the quality of the production system, which is undoubtedly the mining process, must be related to its reliability, costs of traffic maintenance and security. Presented considerations treat the subject in general and can also be used in other systems.

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Ekonomiczne aspekty niezawodności procesów wydobywczych

W artykule omówiono zagadnienie niezawodności w procesie produkcyjnym w ujęciu fizycznym i wartościowym. Przeanalizowano przesłanki ekonomiczne kształtowania poziomu niezawodności. Przedstawiono czynniki wpływające na jego prawidłowy przebieg oraz wielowątkowość zagadnienia także w odniesieniu do procesu wydobywczego. Głównym celem artykułu było przybliżenie aspektu ekonomicznego niezawodności procesów produkcyjnych, a w szczególności procesu wydobywczego. Ponadto zwrócono uwagę na optymalizację poziomu niezawodności rozważając wielokryterialność tego zagadnienia. Przedstawione w pracy rozważania są uogólnione, a ich wyniki mogą być wykorzystane także w innych, złożonych systemach produkcyjnych.

Słowa kluczowe: niezawodność, system produkcyjny, ekonomia, optymalizacja