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EVALUATION OF TECHNICAL RESILIENCE AND ITS ESTIMATION BY THE LEAST SQUARES METHOD

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Abstract: The resilience of technical systems is an internal characteristic whose values of reliability, maintainability and availability parameters must be estimated in the design process. The difficulty of this approach derives from the fact that the resilience parameters are influenced by the behaviour of the technical system during its operation. For this reason, an analysis of the technical resilience of a technical system in operation is required, the analysis that the present research also makes. The current work aims to provide a tool for analyzing the evolution of technical resilience parameters - reliability, maintainability and availability during the operation of technical systems, useful in the decision-making process of maintenance management. The main purpose of the work is to determine the evolution of the score of the resilience parameter of a technical system in the mechanical field during operation. The parameter, taken from the specialized literature, used for the calculation of resilience is based on the Safety in operation indicators - mean time between failures (MTBF) for system reliability and mean time to repair (MTTR) for maintainability. These two parameters were calculated from the data obtained after the operation of a honing machine, including information about the moments of appearance of the defects, the repair time and the type of defect. The resilience evolution is given by a regression line generated by the least squares method on the measured and calculated data series. The regression analysis proposed in this research follows the evolution of the values of the technical resilience parameter over the time horizon over which the technical system was observed in order to the maintenance management decision process for the analyzed system in accordance with the quality and production policies. The research methodology is specific to a quantitative analysis applied to a technical process, continuing the formulation of the problem, the literature study on the researched topic, the determination and analysis of the series of values for the evaluated parameters, and the generation of conclusions on the analyzed phenomenon. This research's results are compared with those from the specialized literature that evaluates technical resilience through metrics on different mathematical models. Also, the research results are essential due to the comparative analysis of resilience in systems from other technical fields.

Keywords: technical resilience, MTBF, MTTR, Least Squares Method, regression analysis.

1. INTRODUCTION

The The quality of the products was, is and will be an increasing trend that is imposed and demanded by the beneficiaries. Thus, this evolution has a direct projection on the technical flow of production by following the permanent improvement of the values of its performance parameters - reliability, maintainability and availability of technical production systems. The problem of determining the balance between the renewal of morally worn systems VS the extension of their physical duration of operation must be continuously analyzed to ensure the required quality of the products. The optimization of the use of the means of production determines the superior utilization of technical and human resources and the increase of labour productivity, which is reflected in an increase in the quality of the products. Measuring and estimating the quality level of production means is a permanent concern of system engineers. The quality of technical systems is an internal characteristic equivalent, in most cases, to their level of resilience, [1].
Technologists want to know the level of resilience of a technical system right from its design phase. This is extremely difficult to predict due to the impossibility of accurately modelling the real working conditions of a technical system, which equates to a complex multicriteria structure of quantification, numerical analysis and modelling problems defined in this field, [2, 3].
Engineering resilience modelling must be viewed from two perspectives: statistical models based on the analysis of technical dimensions that characterize resilience engineering [3,4] and mathematical modelling based on numerical data from the operation of technical systems, [5].
The ability of a technical system to be resistant to external and internal disturbances is a characteristic that can be

measured by the reliability parameter [6], and the ability to quickly recover in the event of an interruption due to a defect can be measured by the parameter of maintainability, [7].
RAM analysis methodologies (reliability, availability and maintainability analysis) for productive assets were developed by [8].
Resilience quantification is analyzed based on different types of analysis, such as forward propagation, backpropagation, sensitivity analysis and information theory on Bayesian networks [9].
From a statistical point of view, the resilience of a system is correlated with the maintenance functions and the allocation of human and technical resources in order to ensure its operational continuity function [10, 11]. In the specialized literature, there are correlations between the resilience levels of a technical system with the different maintenance strategies applied to it [12], but mathematical modelling of the maintenance strategy-resilience-systemic topology type is impossible to achieve due to the increased variability of the mathematical model.
The metrics used to calculate the resilience characteristic belong to complementary and very diversified fields: probabilistic [12], mathematical [13], Bayesian networks [14], statistical techniques [15], Monte Carlo simulation [5], fuzzy systems - relationships modelled by linguistic expressions and using fuzzy set theory [16]. Such a theory based on fuzzy mathematics constitutes support for the subjective or natural descriptors of the system characteristics and offers a methodology as natural as possible to allow the modelling of resilience from the design process of technical systems, [17].
The present paper proposes an application of a metric for technical resilience based on the least squares method.
The regression rights for modelling the resilience parameter as a function of time provide future information for the analysis of the depreciation of the technical system. The relationship amortization - technical resilience - sustainable operation represents a system whose analysis methodology can also include current research results.

2. MATERIALS AND METHODS

Provide Production systems are designed to function and perform the functions for which they were created in an efficient, profitable and sustainable way. The sustainability of technical equipment is given by operational continuity and resistance to internal and external disturbances. Moreover, this technological system's sustainability function is also provided by a third characteristic - the short recovery time after the occurrence of a defect [11].
Reliability is the probability that a piece of equipment will remain operational for a specified time. The metric that most naturally characterizes the reliability of a technical system is the mean time between two failures (MTBF) [18]. On the other hand, maintainability can be calculated by the probability that a system will be repaired within a specific time interval. The most frequently used maintainability metric is the mean time to repair (MTTR) [19]. Both parameters together constitute an Availability indicator (A) according to equation (1):

$$A = \frac{MTBF}{MTBF + MTTR} \tag{1}$$

The technical resilience value is directly proportional to the availability A and inversely proportional to the recovery time t of the availability function after the occurrence of a defect. Thus, the A/t ratio is used to describe the degree of technical resilience [20]. The time value t is logarithmized to use to balance the level of effects between the availability of A and the recovery time t [21]. The value of resilience is considered to be the product A/ln(t) before and after the appearance of external disturbances that lead to the functioning of the technical system [22].
The research methodology includes the following stages: the collection of numerical data from a mechanical honing machine, followed for 18 months, during which the moments of downtime caused by defects, the downtime, and the defect code were extracted. All these time points were reported to a time t_0, the start time of the research.
The technical resilience parameter has a decreasing dynamic depending on the operating time of the technical system; moreover, it depends on the frequency of occurrence of defects and the repair time. After the appearance of a fault and the repair operation to remove its effects, availability, as a function of probabilities, is reduced.
The data were parsed in a numerical system so that all the variables in equation 2 [20] could be calculated.

$$R = \frac{A1}{n * \ln(t_1)} * \sum_{i=1}^{n} \frac{A_2^i * A_3^i}{\ln(t_3^i * t_2^i)} \tag{2}$$

Where: R=Resilience value; A_2^i= availability at the immediate moment of the appearance of the defect; A_3^i= availability at the time of completion of the repair and commissioning of the technical system; t_3^i= the start-up time after repairing the technical system; t_2^i=the moment of appearance of the defect state; A1=availability on the first observation interval; t_1= first observation interval; n= faults number.
The resulting data were grouped by time intervals of different sizes, each containing ten stationary moments of the technical system.
The level curves for the values of the resilience parameter on these time intervals were realized, and the slopes of the regression lines determined by the least squares method were analyzed.
The regression curve for the resilience parameter was determined, and its mathematical expression provides information about the future performance of the analyzed system.

3. RESULTS AND DISCUSSION

Analysis of the evolution of the value of the resilience parameter over time for a technical system, followed for 18 months, during which the following information was collected: fault code - [Job ID], downtime - [Down (HH: MM)], time of occurrence of the defect – [Date: Time Started], time of intervention completion – [Date: Time Completed].
The information was parsed in the following format (all moments of time are reported at time t_0 – the starting moment of the resilience study): no of defects [autonumber], time of good operation [hour: min], time of good operation [min], technical system downtime [min], the sum of good functioning times [min], the sum of idle times [min].
The values of reliability parameters [MTBF], maintainability [MTTR], availability [A] in 2 points on each failure interval ([A2] and [A3]), resilience on each interval [Ri], cumulative resilience [S_R], system resilience [R].
The data were centralized on different time intervals delimited to every ten faults that appeared (table 1). R0 represents the resilience scores over the time interval bounded by defects [1-10], R1 represents the resilience scores over the time interval determined by defects [11-20] and so on.

Table 1. Resilience values depend on the time

Fault/time	R0	R1	R2	R3	R4	R5
1	0.0274	0.0287	0.0285	0.0281	0.0269	0.026018
2	0.0259	0.0295	0.0283	0.0279	0.0267	0.025995
3	0.0288	0.0299	0.0286	0.0277	0.0266	0.025931
4	0.0282	0.0301	0.0287	0.0274	0.0265	0.025852
5	0.0282	0.0300	0.0289	0.0273	0.0265	0.025833
6	0.0299	0.0298	0.0289	0.0272	0.0263	0.025799
7	0.0295	0.0297	0.0287	0.0271	0.0260	0.025751
8	0.0294	0.0294	0.0284	0.0271	0.0258	0.025735
9	0.0288	0.0288	0.0283	0.0271	0.0259	0.025677
10	0.0294	0.0288	0.0282	0.0269	0.0259	

The graphs of the values of the resilience function as a function of time for every ten defects that appeared in the system after the stabilization period of the technical system operation are presented in Figure 1.
In Table 1, it can be seen that each of the five evaluation intervals of the resilience parameter R1...R5 shows a series of decreasing values. What is very important, besides the idea of reducing resilience over a certain period of time, is also the rate of decrease of this parameter.
The slope of the decrease in resilience over different time intervals related to time t_0 will be graphically analyzed in Figure 1 and Figure 2. The equations of the regression lines that approximate the point level of resilience on each interval are determined by the method of least squares (processing carried out in MS Excel 2021), which minimizes the approximation errors.
A variation of the slopes of the regression curves for the resilience parameter is observed. Thus, the values of the angles of the regression lines are increasingly higher from $-5x10^{-5}$ to $-1x10^{-4}$, which corresponds to a decrease in the resilience parameter of the technical system in the 18-month interval.
Figure 2 shows the evolution of the technical resilience parameter.
Figure 1 does not show the regression curve for technical resilience levels because, over this interval of ten faults, the level of resilience is an increasing one, a fact due to the large intervals between defects and their nature (defects

that involved short downtimes of the technical system). This can also be seen in Figure 2 when the first part of the temporal analysis of resilience shows an increase until the stabilization of the functioning of the technical system.

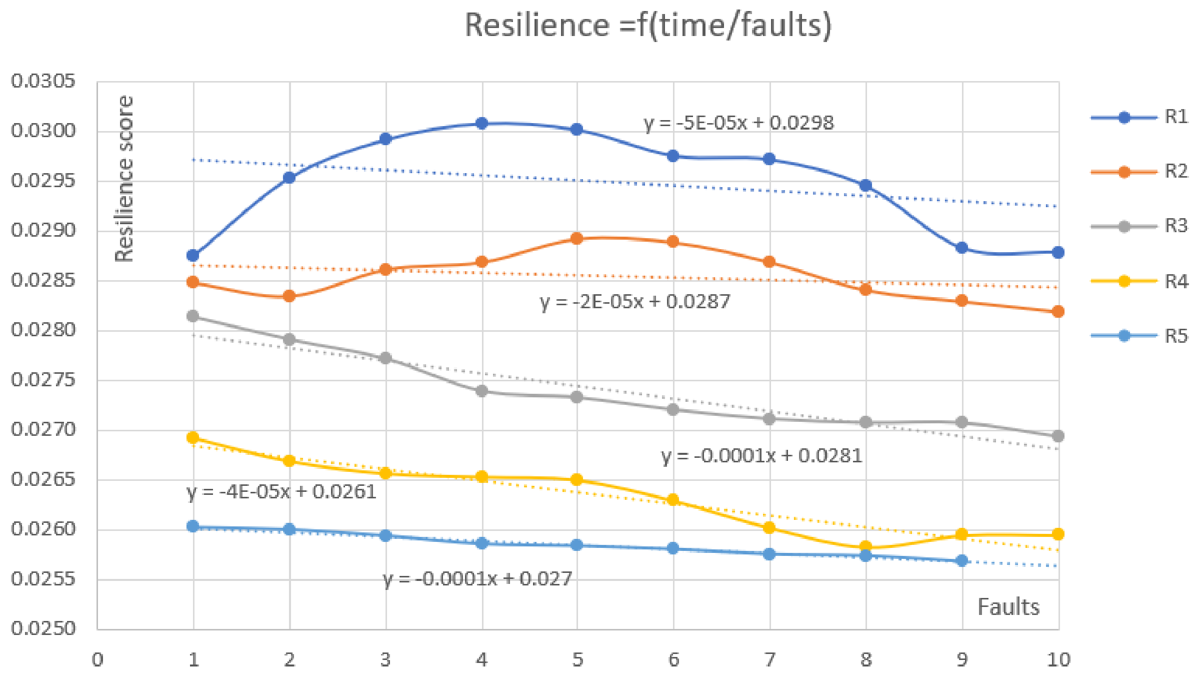

Fig. 1. Technical resilience as a function of time on intervals of 10 defects.

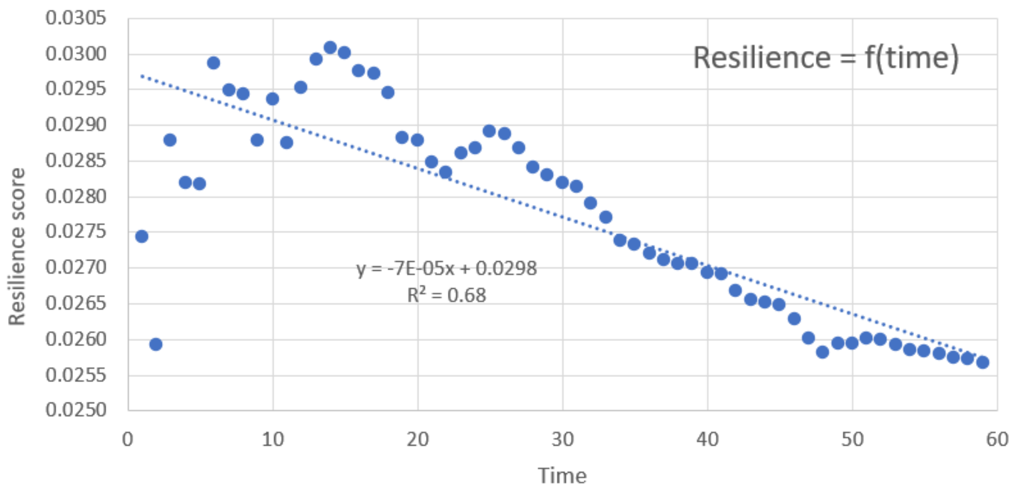

Fig. 2. Technical resilience as a function of time

In Figure 2, an increase in the level of resilience can be observed in the first part of the observation time of the technical system (approximately 10% of the observation time), after it decreases in an approximately linear function.

4. CONCLUSIONS

The analysis of the resilience parameter needs to be done right from the design period of the technical system. This characteristic is closely related to the amortization parameter of the technical system, which must be evaluated as correctly as possible before it is introduced into the production flow. In this sense, estimating the resilience parameter as a function of time is imperatively necessary.
The quantitative analysis carried out by this research leads to conclusions in accordance with the technical achievement, namely that the values of the technical resilience parameter decrease during the operation of the

technical system after a "break-in" period in which it reaches a maximum. The regression curves provided on operating data can provide values of the resilience parameter in the future operation of the technical system so that the system engineer can anticipate the moment when he must make a decision: repair action or change the technical system.
The research methodology proposed by this paper, the techniques used and the innovative approach to the analysis of resilience on time intervals reported at the moment t_0 are useful for simplifying the evaluation of the multivariable system Maintenance - Reliability - Resilience – Economic depreciation. Furthermore, the least squares prediction method is also known for its performance, and the application of resilience points in these instances provides easy-to-interpret information for the future functioning of the technical system.
The current research done on the resilience score of the mechanical system leads to results consistent with the specialized literature – the slopes of the regression curves for the resilience parameter over consecutive time intervals have values that are increasingly higher from $-5x10^{-5}$ to $-1x10^{-4}$, which corresponds to a decrease in the resilience parameter of the technical system in the 18-month period. It should be noted that using this model for the resilience score, based on the availability values of the system depending on the number of defects, initially, the value of the resilience score increases until it stabilizes (normal operating mode) and then decreases on as long as the technical system works.
The research is helpful from the point of view of the proposed practical tool that contains a methodology for assessing the resilience score over time intervals that engineers can use in system maintenance.
The limitations of the research are related to the choice of the reference moment for the calculation of resilience on time intervals because it can be observed that for the chosen system, the first interval shows increasing levels of the resilience parameter (rare defect with small repair intervals). Thus, the slope of the regression curve of the resilience function is different depending on the reference moment t_0 chosen.
If the research methodology - methods, the punctual calculation of the resilience function as a function of time, has a general character, being able to be applied to any technical system, the results obtained are particular for each one.

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