APPLICATION OF THE MULTICRITERIA DECISION-MAKING FOR SELECTING OPTIMAL MAINTENANCE STRATEGY

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Abstract:
Assessing the best set of maintenance guidelines for various types of failures is often a challenging and complex task. It requires understanding various factors such as safety aspects, environmental issues, energy savings, costs, budget constraints, system reliability, resource utilization, and more. Implementing the correct maintenance process is a critical step in production to increase reliability and improve the effectiveness and quality of the production system. Despite the significant importance of this issue, there are not many studies that analyse and develop procedures for selecting the optimal maintenance strategy. This paper presents the selection of the optimal maintenance strategy using multicriteria decision-making, specifically the Analytic Hierarchy Process (AHP), for a case study involving a company in the automotive industry. The defined alternatives are the four most commonly used machine maintenance strategies in the industry: corrective, preventive, condition-based maintenance, and total productive maintenance. The decision criteria considered in the analysis are: production quality, reliability, costs, and safety, along with their respective sub-criteria.

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1. INTRODUCTION

Maintenance is the process of ensuring the optimal performance of machines and systems. The implementation of a modern maintenance culture and understanding of the maintenance process are unavoidable today. This process requires time and dedication but can yield long-term benefits through increased efficiency, cost reduction, and improved maintenance and equipment performance [1].

Appropriate maintenance management provides greater reliability and uptime for equipment, considerably reducing losses in production processes [2]. The maintenance process is directly influenced by the occurrence of failures, which can vary in intensity and nature. Therefore, managing complex maintenance procedures must be based on the study and analysis of failure occurrences, i.e., the laws of reliability theory [1]. Other important factors must also be considered, primarily maintenance costs, which represent a significant expense in manufacturing companies, accounting for 15-70% of production costs, varying by industry type [3, 4]. Thus, the fundamental function of the maintenance process is to enable the system to operate without failures or with minimal failure probability and associated costs [5].

The assessment and selection of the best maintenance strategy require knowledge of numerous factors, including downtime and severity of failures, spare parts availability and consumption, the share of “critical” parts in machines and systems, repair and part replacement possibilities, average times as performance

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indicators, maintenance costs and safety, quality of production system, reliability theory, etc. [6]. Managing and controlling all these factors constitute the main complexity of successful maintenance management.

The complexity of modeling, analysis, and finding a compromise becomes more challenging as the number of criteria in the model increases. For this reason, most works dealing with such analyses predominantly utilize two or three criteria. Among the most common terms used in these works are "cost" and "reliability" [7].

Wang et al. [4] evaluated different maintenance strategies for various equipment using the fuzzy Analytic Hierarchy Process (AHP) method, proposed as a simple and efficient tool for addressing uncertainty and imprecision in multicriteria decision-making problems.

Melo et al. [8] developed a model for classifying critical factors for improving the production process through Total Productive Maintenance (TPM) analysis in an industrial environment. It is considered that the results of the work in the companies are due to the characteristics of the causes and the perception of the decision makers. In this respect, their approach provides decision-makers with recommendations on critical improvement factors from a TPM perspective.

In his doctoral dissertation, Stanković [9] focused on establishing a risk-based maintenance model to increase the reliability of steam turbines during operation. The model included continuous monitoring of operational and diagnostic parameters and their impact on the reliability of the observed steam turbines.

Muhsen et al. [10] defined a model for selecting the optimal maintenance strategy using the AHP method. Their analysis concluded that there was no dominant solution among the defined alternatives, emphasizing the need to consider multiple variables for long-term research in the field of maintenance.

Nikolić et al. [5] proposed using multicriteria decision-making for selecting the maintenance strategy. Based on the applied VIKOR method, the conclusion was that multicriteria analysis could be successfully applied to solving maintenance strategy selection problems.

Considering the classification of spare parts management as a fundamental area for maintenance management in organizations and for improving internal, technical, and organizational procedures, Ferreira et al. [11] focused on developing a framework for spare parts classification using the AHP method.

Velmurugan et al. [12] noted that the rate of human errors directly affects the efficiency of a production plant by maximizing maintenance costs and machine downtime. Their research aimed to propose an optimal decision support model for maintenance management. They sought to develop a system that, by selecting of the optimal maintenance strategy, would reduce the impact of human errors and thereby improve product quality, worker safety, and machine availability and efficiency in the industry.

Despite the popularity and application of newer maintenance methods such as TPM and RCM and reliability management, conventional maintenance methods often need to be more focused on research. Prabhakar and Dharmaraj [13] provided a comprehensive overview of modern maintenance strategies, emphasizing vast resources for research in the maintenance and reliability of manufacturing facilities.

This paper outlines the decision-making process and the selection of the optimal maintenance strategy from the perspective of defined criteria/ sub-criteria using the AHP method in a company engaged in producing automotive components. The industries most commonly applied maintenance strategies were chosen as alternative solutions. The optimal maintenance strategy should ensure the best decisions on when, where, and which maintenance procedures to implement, considering the required reliability, system availability, and associated costs based on a fundamental understanding of the maintained system's condition.

2. THEORETICAL FOUNDATIONS

2.1 Multicriteria Decision Making

Engineers and other decision-makers often must choose the best solution for products, processes, resources, etc. [14-17]. In such situations, where there are many alternatives and criteria, decision-making becomes highly complex. Multi-criteria decision-making (MCDM) methods need to be applied to address these complex tasks. These methods are based on scientific principles that efficiently determine the best solution [18, 19].

Numerous researchers and scientists have developed a variety of MCDM methods, with the most widely used being AHP (*Analytic Hieararchy Process*), TOPSIS (*Technique for Order Preference by Similarity to Ideal Situation*), ELECTRE (*Elimination Et Choix Traduisant la Realite*), PROMETHEE

(*Preference Ranking Organisation Method for Enrichment Evaluations*), etc. These methods can be used to identify: *the most desirable alternative, rank alternatives, select a limited number of alternatives, or simply differentiate acceptable from unacceptable alternatives* [20-22].

The AHP method, as a field of multicriteria decision-making, was developed by *Thomas Saaty* and represents a tool based on mathematical and psychological foundations for analyzing complex decisions [23, 24]. The Analytic Hierarchy Process utilizes a structured hierarchical structure to organize and solve complex decision-making problems. Unlike other methods that assume decision-makers do not make errors, the AHP method acknowledges the occurrence of errors in reasoning, allowing decision-makers to either avoid or confront them. The application of this method involves four basic steps [20, 25]: 1. Identification and formulation of the decision problem - goal functions; 2. Decision model formation - determining the set of alternatives and criteria, as well as collecting relevant data; 3. Application of the MCDM method - determining the weight coefficients of criteria, evaluating alternatives for selected criteria, and assessing alternatives; and 4. Selection of the most acceptable alternative and/or ranking alternatives, followed by sensitivity analysis.

2.2 Maintenance Strategies

The development of maintenance concepts is conditioned by numerous factors: technological requirements, organization, diagnostics, technologies, energy savings, environmental protection, etc.

The original maintenance strategy, “repair after failure”, shortly after industrial expansion, could not meet the increased demands of the global market [9]. The first modern understanding of maintenance as an industrial and scientific discipline was driven by increased product quality requirements, necessitating a reduction in production losses, increased system reliability, and the reduction of machine failures [8]. The emergence of new methodologies such as Total Productive Maintenance (TPM) and Reliability-Centered Maintenance (RCM) provided greater efficiency and reliability of technical systems while keeping them in optimal condition and at minimal costs.

This paper analyzes four maintenance strategies commonly applied in today’s automotive industry: *corrective maintenance, preventive maintenance, condition-based maintenance, and total productive maintenance.*

The application of *corrective maintenance* involves simply acknowledging that damage has occurred and that corrective measures need to be taken on the machine. In maintenance theory, the maintenance process is often modeled as random [1].

Preventive maintenance is based on performing corrective measures on machines at clearly defined intervals. This type of maintenance involves systematic inspection, detection, correction, and prevention of failures before they become actual issues [26, 27].

Condition-based maintenance relies on three basic approaches: protection, monitoring, and diagnostics. It is primarily applied to systems and devices requiring high operational security and reliability [1, 7].

Total Productive Maintenance plays an essential role in Japanese philosophy, representing a concept in the field of maintenance and equipment management aimed at achieving the highest possible level of efficiency and production quality through optimal maintenance and management of production systems [28]. The main goal of TPM is: *zero failures, zero defects, zero accidents* [29].

3. DEFINITION OF THE DECISION MODEL

The first step in solving the problem in the AHP method involves identifying the problem and developing the decision model. The development of the decision model occurs through defining the hierarchical structure, i.e., defining the goal, criteria/sub-criteria, and alternative solutions. Fig. 1 illustrates the hierarchical decision model for selecting the optimal maintenance strategy.

At the top of the hierarchical model, the optimal maintenance strategy is defined as the goal function. The selected basic decision criteria are: *quality of production*, *reliability*, *costs*, and *safety*, with corresponding eighteen sub-criteria. The alternative solutions represent four maintenance strategies: *corrective maintenance* (a_1), *preventive maintenance* (a_2), *condition-based maintenance* (a_3), and *total productive maintenance* (a_4).

A scale of assessment with values ranging from 1 to 9 was used to evaluate criteria/sub-criteria. The assessment scale expresses the value of the criteria through pairwise comparative judgment.

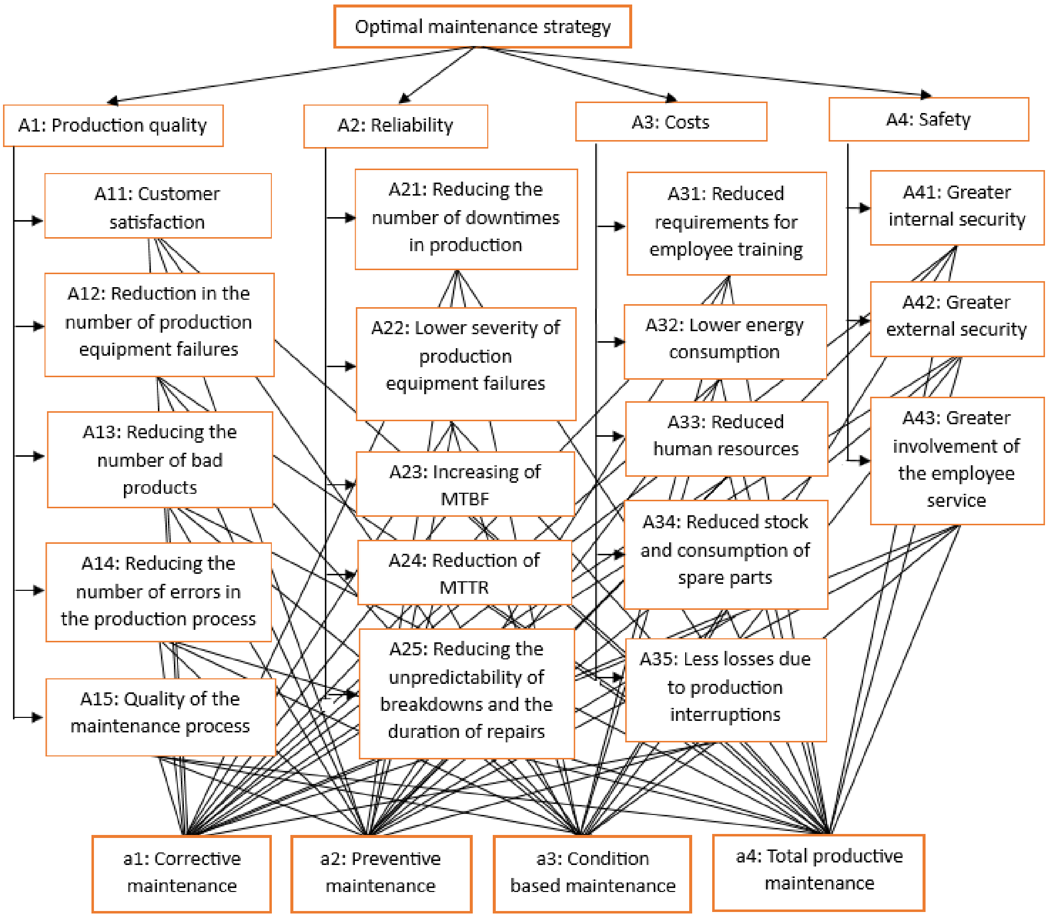

Fig. 1. Hierarchical decision model for selecting optimal maintenance strategy

4. CASE STUDY – SELECTION OF MAINTENANCE STRATEGY USING AHP METHOD

The maintenance process of technical systems is becoming an increasingly relevant topic within business systems, often proposing new maintenance approaches. Additionally, the maintenance process is becoming more directly linked to research, procedures, methods, and practices related to quality management.

In the observed case of choosing the optimal maintenance strategy, an approximate AHP method was used, where decision results could be obtained through simple mathematical operations and specific steps using MS EXCEL software.

Two approaches to analyzing decision solutions were applied:

- In the first, classical approach, comparison matrices were set up, and weight coefficients were determined for criteria and sub-criteria within the defined criteria. The obtained "local" weight coefficients for each sub-criterion were then multiplied by the weight coefficient of the corresponding criterion, resulting in "global" weight coefficients for sub-criteria.
- In the second modified approach, all defined sub-criteria were considered as criteria. Thus, comparison matrices and weight coefficients were determined for eighteen "modified" criteria.

Following this, the importance of alternatives for each criteria/sub-criteria was defined, and a complete synthesis of the problem was then executed.

4.1. Determination of Weight Coefficients for Criteria/Sub-Criteria

Determining the weight coefficients for criteria is used in the multicriteria decision-making process to assign importance to different criteria considered in a specific problem. This step in the decision-making process and solving complex problems can be of great significance due to various criteria of competitive importance in decision-making. The importance of criteria in the analytic hierarchy process is used to decide which criteria/sub-criteria have the greatest impact on final decisions. Criteria with higher importance have a more significant influence on final rankings and alternative selection.

4.1.1 First Solution Approach

The criteria comparison matrix in the decision model is presented in Table 1. A scale of assessment with values from 1 to 9 was used for evaluating criteria/sub-criteria. By applying the appropriate steps of the AHP method, the weight coefficients for criteria were obtained, as shown in the last column (W1 = 0.1507, W2 = 0.2913, W3 = 0.067, W4 = 0.4909), indicating that criterion W4 has the most significant influence, followed by W2, W1, and W3.

Table 1. Comparison matrix and weight coefficients of criteria in the decision-making model

	A_1	A_2	A_3	A_4	W_{Ki}
A_1	1	1/5	1/3	1/7	0.0569
A_2	5	1	3	1/3	0.2633
A_3	3	1/3	1	1/5	0.1219
A_4	7	3	5	1	0.5579

Tables 2, 3, 4 and 5 below show sub-criteria comparison matrices for all four criteria A_1-A_4. In the penultimate columns of these tables, the calculated "local" and the "global" weighting coefficients of the sub-criteria are given in the last columns.

Table 2. Comparison matrix and weight coefficients of the criteria "A_1-production quality"

	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	Local W_{Kij}	Global W_{Kij}
A_{11}	1	2	4	8	6	0.4684	0.0266
A_{12}	1/2	1	2	6	4	0.2681	0.0152
A_{13}	1/4	1/2	1	4	2	0.1436	0.0082
A_{14}	1/8	1/6	1/4	1	1/2	0.0441	0.0025
A_{15}	1/6	1/4	1/2	2	1	0.0759	0.0043

Table 3. Comparison matrix and weight coefficients of the criteria "A_2-reliability"

	A_{21}	A_{22}	A_{23}	A_{24}	A_{25}	Local W_{Kij}	Global W_{Kij}
A_{21}	1	4	2	2	6	0.4060	0.1069
A_{22}	1/4	1	1/2	1/2	2	0.1074	0.0283
A_{23}	1/2	2	1	1	4	0.2148	0.0566
A_{24}	1/2	2	1	1	4	0.2148	0.0566
A_{25}	1/6	1/2	1/4	1/4	1	0.0571	0.0150

Table 4. Comparison matrix and weight coefficients of the criteria "A_3-costs"

	A_{31}	A_{32}	A_{33}	A_{34}	A_{35}	Local W_{Kij}	Global W_{Kij}
A_{31}	1	4	2	1/4	1/2	0.1436	0.0175
A_{32}	1/4	1	1/2	1/8	1/6	0.0441	0.0054
A_{33}	1/2	2	1	1/6	1/4	0.0759	0.0092
A_{34}	4	8	6	1	2	0.4684	0.0571
A_{35}	2	6	4	1/2	1	0.2681	0.0327

Table 5. Comparison matrix and weight coefficients of the criteria "A_4-safety"

	A_{41}	A_{42}	A_{43}	Local W_{Kij}	Global W_{Kij}
A_{41}	1	2	3	0.5390	0.3007
A_{42}	1/2	1	2	0.2973	0.1658
A_{43}	1/3	1/2	1	0.1638	0.0914

4.1.2 Second Solution Approach

The comparison matrix of sub-criteria ("modified criteria") in the decision-making model is presented in Table 6. By applying the appropriate steps of the AHP method, the weight coefficients of these "modified" criteria were obtained at the output, shown in the last column.

Table 6. Comparison matrix and weight coefficients of "modified" criteria

	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	A_{21}	A_{22}	A_{23}	A_{24}	A_{25}	A_{31}	A_{32}	A_{33}	A_{34}	A_{35}	A_{41}	A_{42}	A_{43}	W_{Kij}
A_{11}	1	1.5	2	3	2.5	1/5,5	1/4,5	1/5	1/5	1/4	1/2,5	1/1,5	2	1/3,5	1/3	1/7	1/6,5	1/6	0.0193
A_{12}	1/1,5	1	1.5	2.5	2	1/6	1/5	1/5,5	1/5,5	1/4,5	1/3	1/2	2.5	1/4	1/3,5	1/7,5	1/7	1/6,5	0.0171
A_{13}	1/2	1/1,5	1	2	1.5	1/6,5	1/5,5	1/3	1/3	1/5	1/3,5	1/2,5	3	1/4,5	1/4	1/8	1/7,5	1/7	0.0165
A_{14}	1/3	1/2,5	1/2	1	1/1,5	1/7,5	1/6,5	1/7	1/7	1/6	1/4,5	1/3,5	1/4	1/5,5	1/5	1/9	1/8,5	1/4	0.0100
A_{15}	1/2,5	1/2	1/1,5	1.5	1	1/7	1/6	1/6,5	1/6,5	1/5,5	1/4	1/3	1/3,5	1/5	1/4,5	1/8,5	1/8	1/7,5	0.0106
A_{21}	5.5	6	6.5	7.5	7	1	2	1.5	1.5	2.5	4	5	4.5	3	3.5	1/2,5	1/2	1/1,5	0.0936
A_{22}	4.5	5	5.5	6.5	6	1/2	1	1.5	1.5	1.5	3	4	3.5	2	2.5	1/3,5	1/3	1/2,5	0.0699
A_{23}	5	5.5	6	7	6.5	1/1,5	1/1,5	1	1	2	3.5	4.5	4	2.5	3	1/3	1/2,5	1/2	0.0745
A_{24}	5	5.5	6	7	6.5	1/1,5	1/1,5	1	1	2	3.5	4.5	4	2.5	3	1/3	1/2,5	1/2	0.0745
A_{25}	4	4.5	5	6	5.5	1/2,5	1/1,5	1/2	1/2	1	2.5	3.5	3	1.5	2	1/4	1/3,5	1/3	0.0531
A_{31}	2.5	3	3.5	4.5	4	1/4	1/3	1/3,5	1/3,5	1/2,5	1	2	1.5	1/2	1/2	1/5,5	1/5	1/4,5	0.0304
A_{32}	1.5	2	2.5	3.5	3	1/5	1/4	1/4,5	1/4,5	1/3,5	1/2	1	1/1,5	1/3	1/2,5	1/6,5	1/6	1/5,5	0.0213
A_{33}	1/2	1/2,5	1/3	4	3.5	1/4,5	1/3,5	1/4	1/4	1/3	1/1,5	1.5	1	1/2,5	1/1,5	1/6	1/5,5	1/5	0.0205
A_{34}	3.5	4	4.5	5.5	5	1/3	1/2	1/2,5	1/2,5	1/1,5	2	3	2.5	1	1.5	1/4,5	1/4	1/3,5	0.0442
A_{35}	3	3.5	4	5	4.5	1/3,5	1/2,5	1/3	1/3	1/2	1.5	2.5	2	1/1,5	1	1/5	1/4,5	1/4	0.0369
A_{41}	7	7.5	8	9	8.5	2.5	3.5	3	3	4	5.5	6.5	6	4.5	5	1	1.5	2	0.1599
A_{42}	6.5	7	7.5	8.5	8	2	3	2.5	2.5	3.5	5	6	5.5	4	4.5	1/1,5	1	1/1,5	0.1290
A_{43}	6	6.5	7	8	7.5	1.5	2.5	2	2	3	4.5	5.5	5	3.5	4	1/2	1.5	1	0.1187

4.2. Determination of Importance of Alternatives for Criteria/Sub-Criteria

The priority value, the importance of alternatives a1-a4, is calculated for each criteria/sub-criteria, using a matrix of comparative values.

In order to more easily define the comparison matrices of alternatives, sub-criteria were qualitatively assessed, shown in Tables 7-10.

In the observed case, the procedure for determining the importance of alternatives for sub-criterion A_{11}-customer satisfaction is presented, Table 11.

Table 7. Alternatives comparison matrix for sub-criteria of A_1-production quality

	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}
a_1	1	3	3	3	1
a_2	3	7	5	5	5
a_3	5	7	5	5	7
a_4	7	7	5	5	7

Table 8. Alternatives comparison matrix for sub-criteria of A_2-reliability

	A_{21}	A_{22}	A_{23}	A_{24}	A_{25}
a_1	3	1	1	1	1
a_2	3	7	7	7	7
a_3	5	5	7	7	7
a_4	7	7	7	7	7

Table 9. Alternatives comparison matrix for sub-criteria of A_3-costs

	A_{31}	A_{32}	A_{33}	A_{34}	A_{35}
a_1	1	3	1	1	1
a_2	3	3	1	1	1
a_3	5	5	5	5	7
a_4	5	7	7	7	7

Table 10. Alternatives comparison matrix for sub-criteria of A_4-safety

	A_{41}	A_{42}	A_{43}
a_1	1	1	1
a_2	5	5	5
a_3	5	5	5
a_4	7	7	7

Table 11. Importance of alternatives for the sub-criteria “customer satisfaction”

	a_1	a_2	a_3	a_4	W_A
a_1	1	1/3	1/5	1/7	0.0569
a_2	3	1	1/3	1/5	0.1219
a_3	5	3	1	1/3	0.2633
a_4	7	5	3	1	0.5579

At the output, it was found that alternative a4 has the greatest influence on this sub-criterion. In the same way, the importance of the alternatives for all eighteen sub-criteria was determined.

4.3. Determination of Importance of Alternatives in the Model

The total importance values for each alternative are calculated using the importance of criteria and evaluating alternatives according to the criteria. These values represent the results of the AHP method and are used to rank the alternatives.

After calculating the sums of the scores for each criterion/sub-criterion and each alternative, the next step was to multiply the given sums with the corresponding importance of criteria/sub-criteria.

The final score is obtained by summing the total values for each alternative and is used to rank alternatives. The alternative with the highest total value has the highest priority and is considered the best concerning the defined criteria.

Given that the AHP method is designed to support complex decision-making processes rather than make decisions for someone else, it is crucial to understand and interpret the results to reach appropriate conclusions and decisions.

4.3.1 Final Results for the First Approach

Tables 12-15 show the results obtained for the significance and ranking of alternatives for the first mentioned approach in solving the problem. The following columns are listed: alternative, weight coefficients of criteria/sub-criteria, weight coefficients of alternatives, product of weight coefficients, significance of alternative, and rank of alternative.

Table 12. Results for significance of alternative a_1

Alt.	W_K	W_A	W_K*W_A	Sig.	Rank
a_1	0.0266	0.0569	0.0015	0.0738	**4**
	0.0152	0.0758	0.0012		
	0.0082	0.1000	0.0008		
	0.0025	0.1000	0.0003		
	0.0043	0.0408	0.0002		
	0.1069	0.0967	0.0103		
	0.0283	0.0483	0.0014		
	0.0566	0.0455	0.0026		
	0.0566	0.0455	0.0026		
	0.0150	0.0483	0.0007		
	0.0175	0.0687	0.0012		
	0.0054	0.0967	0.0005		
	0.0092	0.0691	0.0006		
	0.0571	0.0691	0.0039		
	0.0327	0.0625	0.0020		
	0.3007	0.0789	0.0237		
	0.1658	0.0789	0.0131		
	0.0914	0.0789	0.0072		

Table 13. Results for significance of alternative a_2

Alt.	W_K	W_A	W_K*W_A	Sig.	Rank
a_2	0.0266	0.1219	0.0032	0.1986	**3**
	0.0152	0.3746	0.0057		
	0.0082	0.3000	0.0025		
	0.0025	0.3000	0.0008		
	0.0043	0.2767	0.0012		
	0.1069	0.0967	0.0103		
	0.0283	0.3936	0.0111		
	0.0566	0.3182	0.0180		
	0.0566	0.3182	0.0180		
	0.0150	0.3936	0.0059		
	0.0175	0.1535	0.0027		
	0.0054	0.0967	0.0005		
	0.0092	0.0691	0.0006		
	0.0571	0.0691	0.0039		
	0.0327	0.0625	0.0020		
	0.3007	0.2009	0.0604		
	0.1658	0.2009	0.0333		
	0.0914	0.2009	0.0184		

Table 14. Results for significance of alternative a_3

Alt.	W_K	W_A	W_K*W_A	Sig.	Rank
a_3	0.0266	0.2633	0.0070	0.2379	**2**
	0.0152	0.1749	0.0027		
	0.0082	0.3000	0.0025		
	0.0025	0.3000	0.0008		
	0.0043	0.3412	0.0015		
	0.1069	0.2516	0.0269		
	0.0283	0.1645	0.0047		
	0.0566	0.3182	0.0180		
	0.0566	0.3182	0.0180		
	0.0150	0.1645	0.0025		
	0.0175	0.3889	0.0068		
	0.0054	0.2516	0.0014		
	0.0092	0.2869	0.0027		
	0.0571	0.2869	0.0164		
	0.0327	0.4375	0.0143		
	0.3007	0.2009	0.0604		
	0.1658	0.2009	0.0333		
	0.0914	0.2009	0.0184		

Table 15. Results for significance of alternative a_4

Alt.	W_K	W_A	W_K*W_A	Sig.	Rank
a_4	0.0266	0.5579	0.0149	0.4896	**1**
	0.0152	0.3746	0.0057		
	0.0082	0.3000	0.0025		
	0.0025	0.3000	0.0008		
	0.0043	0.3412	0.0015		
	0.1069	0.5549	0.0593		
	0.0283	0.3936	0.0111		
	0.0566	0.3182	0.0180		
	0.0566	0.3182	0.0180		
	0.0150	0.3936	0.0059		
	0.0175	0.3889	0.0068		
	0.0054	0.5549	0.0030		
	0.0092	0.5749	0.0053		
	0.0571	0.5749	0.0328		
	0.0327	0.4375	0.0143		
	0.3007	0.5193	0.1562		
	0.1658	0.5193	0.0861		
	0.0914	0.5193	0.0475		

4.3.2 Final Results for the Second Approach

Tables 16-19 show the results obtained for the significance and ranking of alternatives for the second mentioned approach in solving the problem.

Table 16. Results for significance of alternative a_1

Alt.	W_K	W_A	W_K*W_A	Sig.	Rank
a_1	0.0193	0.0569	0.0011	0.0703	**4**
	0.0171	0.0758	0.0013		
	0.0165	0.1000	0.0017		
	0.0100	0.1000	0.0010		
	0.0106	0.0408	0.0004		
	0.0936	0.0967	0.0090		
	0.0699	0.0483	0.0034		
	0.0745	0.0455	0.0034		
	0.0745	0.0455	0.0034		
	0.0531	0.0483	0.0026		
	0.0304	0.0687	0.0021		
	0.0213	0.0967	0.0021		
	0.0205	0.0691	0.0014		
	0.0442	0.0691	0.0031		
	0.0369	0.0625	0.0023		
	0.1599	0.0789	0.0126		
	0.1290	0.0789	0.0102		
	0.1187	0.0789	0.0094		

Table 17. Results for significance of alternative a_2

Alt.	W_K	W_A	W_K*W_A	Sig.	Rank
a_2	0.0193	0.1219	0.0024	0.2199	**3**
	0.0171	0.3746	0.0064		
	0.0165	0.3000	0.0050		
	0.0100	0.3000	0.0030		
	0.0106	0.2767	0.0029		
	0.0936	0.0967	0.0090		
	0.0699	0.3936	0.0275		
	0.0745	0.3182	0.0237		
	0.0745	0.3182	0.0237		
	0.0531	0.3936	0.0209		
	0.0304	0.1535	0.0047		
	0.0213	0.0967	0.0021		
	0.0205	0.0691	0.0014		
	0.0442	0.0691	0.0031		
	0.0369	0.0625	0.0023		
	0.1599	0.2009	0.0321		
	0.1290	0.2009	0.0259		
	0.1187	0.2009	0.0238		

Table 18. Results for significance of alternative a_3

Alt.	W_K	W_A	W_K*W_A	Sig.	Rank
a_3	0.0193	0.2633	0.0051	0.2446	**2**
	0.0171	0.1749	0.0030		
	0.0165	0.3000	0.0050		
	0.0100	0.3000	0.0030		
	0.0106	0.3412	0.0036		
	0.0936	0.2516	0.0235		
	0.0699	0.1645	0.0115		
	0.0745	0.3182	0.0237		
	0.0745	0.3182	0.0237		
	0.0531	0.1645	0.0087		
	0.0304	0.3889	0.0118		
	0.0213	0.2516	0.0054		
	0.0205	0.2869	0.0059		
	0.0442	0.2869	0.0127		
	0.0369	0.4375	0.0161		
	0.1599	0.2009	0.0321		
	0.1290	0.2009	0.0259		
	0.1187	0.2009	0.0238		

Table 19. Results for significance of alternative a_4

Alt.	W_K	W_A	W_K*W_A	Sig.	Rank
a_4	0.0193	0.5579	0.0108	0.4652	1
	0.0171	0.3746	0.0064		
	0.0165	0.3000	0.0050		
	0.0100	0.3000	0.0030		
	0.0106	0.3412	0.0036		
	0.0936	0.5549	0.0519		
	0.0699	0.3936	0.0275		
	0.0745	0.3182	0.0237		
	0.0745	0.3182	0.0237		
	0.0531	0.3936	0.0209		
	0.0304	0.3889	0.0118		
	0.0213	0.5549	0.0118		
	0.0205	0.5749	0.0118		
	0.0442	0.5749	0.0254		
	0.0369	0.4375	0.0161		
	0.1599	0.5193	0.0830		
	0.1290	0.5193	0.0670		
	0.1187	0.5193	0.0617		

5. RESULTS AND DISCUSSION

After the analysis, results that assessed the importance of four defined maintenance strategies based on all set criteria and sub-criteria were obtained.

According to the results obtained for the first approach, alternative 4 has the highest total value of *0.4896*. Therefore, it is considered the best for the defined conditions. On the other hand, as expected, the worst results were obtained for corrective maintenance, *0.0738*. Preventive maintenance and condition-based maintenance are ranked between corrective maintenance and TPM with total values of *0.1986* and *0.2379,* respectively, Fig. 2.

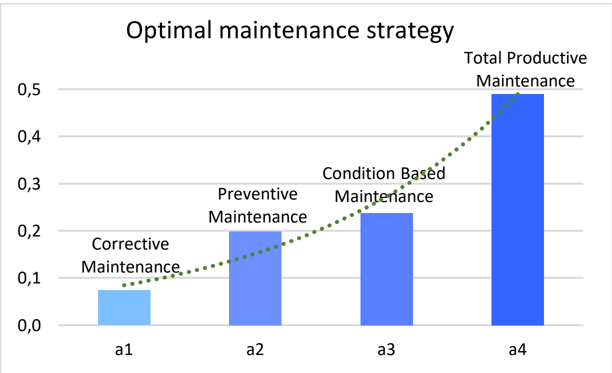

Fig. 2. Rank of alternatives – maintenance strategies for first approach

According to the results obtained for the second approach, alternative 4 again has the highest overall value. For this approach, similar results were obtained as for the first approach, with slight differences in overall values of approximately 0.02 or less, Fig. 3.

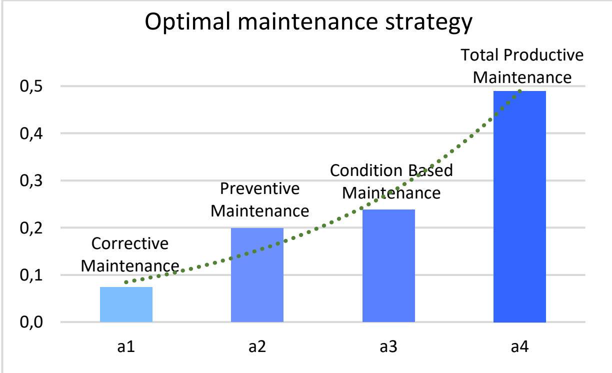

Fig. 3. Rank of alternatives – maintenance strategies for the second approach

In practice, there are a large number of factors that influence the choice of an adequate maintenance strategy. When making a decision, it is impossible to consider all influential factors. However, the more significant the number of factors included in the analysis, the better the final decision will contribute to achieving the set goals.

Finally, we specifically state that there is a possibility of further improving the model, changing criteria/sub-criteria, alternatives, sensitivity analysis, etc. to adapt to specific situations and problems in machine maintenance processes.

6. CONCLUSION

The development of a maintenance culture in organizations and the manufacturing industry has a significant impact on the efficiency and success of production. Maintenance activities are vital for manufacturing companies due to economic and operational requirements, which is why maintenance is one of the key optimization problems in the industry. However, making decisions and choosing the optimal procedure, strategy, or approach to solving a problem is often a complex problem due to many conflicting criteria among the available alternatives.

Reliability of machines and systems is a parameter that must be satisfied in every maintenance process to ensure a smooth production flow. Costs are also important maintenance parameters that must be monitored and optimized. It is necessary to find the optimum balance between maintenance costs and the reliability and effectiveness of the machines. Safety in the maintenance process is a criterion that is usually put first. Also, nowadays, the maintenance process of machines is more and more directly connected with the quality of production.

This paper defined a decision-making model for choosing the optimal maintenance strategy in a company from the automotive sector among the four most commonly applied strategies: corrective maintenance, preventive maintenance, condition-based maintenance and total productive maintenance, according to four defined criteria: production quality, reliability, costs and security, along with their respective sub-criteria.

With the applied AHP analysis, the TPM approach stood out as convincingly the best for application in maintenance processes in the automotive industry. Some of the direct benefits of TPM are a significant reduction in production costs, reduction in customer complaints, reduction in work accidents, less environmental pollution, increase in equipment reliability and effectiveness, etc. Indirect advantages include increasing employee confidence, standardizing and organizing the workspace, teamwork, exchanging acquired knowledge and experiences, etc. Productive maintenance not only prevents malfunctions and losses but also encourages efficient use of resources and the participation of all workers in raising production to a higher level.

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REFERENCES

[1] T. Nakagawa, Maintenance Theory of Reliability. *Springer*, London, 2005. https://doi.org/10.1007/1-84628-221-7

[2] E. Ruschel, E.A.P. Santos, E. de F.R. Loures, Industrial maintenance decision-making: A systematic literature review. *Journal of Manufacturing Systems, Society of Manufacturing Engineers,* 45, 2017: 180-194. https://doi.org/10.1016/j.jmsy.2017.09.003

[3] M. Bevilacqua, M. Braglia, The analytic hierarchy process applied to maintenance strategy selection. *Reliability Engineering and System Safety,* 70(1), 2000: 71-83. https://doi.org/10.1016/S0951-8320(00)00047-8

[4] L. Wang, J. Chu, J. Wu, Selection of optimum maintenance strategies based on a fuzzy analytic hierarchy process. *International Journal of Production Economics,* 107(1), 2007: 151-163. https://doi.org/10.1016/j.ijpe.2006.08.005

[5] M. Nikolić, Lj. Radovanović, E. Desnica, J. Pekez, The application of VIKOR method for selection of maintenance strategies. *Technical Diagnostics*, 9(4), 2010: 25-32.

[6] I. Gertsbakh, Reliability theory with applications to preventive maintenance. *Springer*, Berlin, 2000. https://doi.org/10.1007/978-3-662-04236-6

[7] A.T. de, Almeide, R.J.P. Ferreira, C.A.V. Cavalcante, A review of the use of multicriteria and multi-objective models in maintenance and reliability. *IMA Journal of Management Mathematics*, 26(3), 2015: 249-271. https://doi.org/10.1093/imaman/dpv010

[8] F.J.C. de, Melo, J.V. Sousa, J.T. de, Aquino, T. de B. Jerônimo, Using AHP to improve manufacturing processes in TPM on industrial and port complex. *American Psychological Association (APA),* 19(3), 2021: 523-549. https://doi.org/10.5585/exactaep.2021.16693

[9] N. Stanković, Risk-based maintenance models and their impact on steam turbine reliability, (Ph.D. Thesis). *Technical faculty "Mihajlo Pupin", University of Novi Sad*, Zrenjanin, Serbia, 2018.

[10] A.A. Muhsen, G.M. Szymanski, T.A. Mankhi, B. Attiya, Selecting the most efficient maintenance approach using AHP multiple criteria decision making at Haditha hydropower plant. *Zeszyty naukowe politechniki poznańskiej*, 78, 2018: 113-136. https://doi.org/10.21008/j.0239-9415.2018.078.09

[11] L.M.D.F. Ferreira, I. Maganha, V.S.M. Magalhães, M. Almeida, A multicriteria Decision Framework for the Management of Maintenance Spares – A Case Study. *IFAC PapersOnLine*, 51(11), 2018: 531-537. https://doi.org/10.1016/j.ifacol.2018.08.373

[12] K. Velmurugan, S. Saravanasankar, P. Venkumar, R. Sudhakarapandian, G.D. Bona, Hybrid fuzzy AHP-TOPSIS framework on human error factor analysis: Implications to developing optimal maintenance maintenance management system in the SMEs. *Sustainable Futures*, 4, 2022: 100087.

https://doi.org/10.1016/j.sftr.2022.100087
[13] D. Prabhakar, A. Dharmaraj, Modern Plant Maintenance and Reliability Management Methods – A Review. *International Journal of Mechanical and Production Engineering Research and Development,* 8(3), 2018: 791-802. https://doi.org/10.24247/ijmperdjun201883
[14] D. Lukic, M. Milosevic, A. Antic, S. Borojevic, M. Ficko, Multi-criteria selection of manufacturing processes in the conceptual process planning. *Advances in Production Engineering & Management,* 12(2), 2017: 151-162. https://doi.org/10.14743/apem2017.2.247
[15] A. Aytekin, Energy, Environment, and Sustainability: A Multi-criteria Evaluation of Countries. *Strategic Planning for Energy and the Environment*, 41(3), 2022: 281-316. https://doi.org/10.13052/spee1048-5236.4133
[16] G. Marinković, T. Ninkov, M Trifković, Ž. Nestorović, G. Pejičić, On the land consolidation projects and cadastral municipalities ranking. *Tehnički vjesnik*, 23(4), 2016: 1147-1153. https://doi.org/10.17559/TV-20140316225250
[17] M. Madić, G. Petrović, D. Petković, J. Antucheviciene, D. Marinković, Application of a Robust Decision-Making Rule for Comprehensive Assessment of Laser Cutting Conditions and Performance. *Machines*, 10(2), 2022: 153. https://doi.org/10.3390/machines10020153
[18] M. Köksalan, J. Wallenius, S. Zionts, Multiple Criteria Decision Making: From Early History to the 21st Century. *World Scientific Publishing*, Singapore. 2011. https://doi.org/10.1142/8042
[19] A. Ishizaka, P. Nemery, Multi-Criteria Decision Analysis: Methods and Software. *John Wiley & Sons*, Hoboken, 2013. http://dx.doi.org/10.1002/9781118644898
[20] D. Lukic, R. Cep, J. Vukman, A. Antic, M. Djurdjev, M. Milosevic, Multi-Criteria Selection of the Optimal Parameters for High-Speed Machining of Aluminum Alloy Al7075 Thin-Walled Parts. *Metals*, 10(12), 2020: 1570. https://doi.org/10.3390/met10121570
[21] E.C. Özcan, S. Ünlüsoy, T. Eren, A combined goal programming – AHP approach supported with TOPSIS for maintenance strategy selection in hydroelectric power plants. *Renewable and Sustainable Energy Reviews*, 78, 2017: 1410-1423. https://doi.org/10.1016/j.rser.2017.04.039
[22] I. Vinogradova, Multi-attribute decision-making methods as a part of mathematical optimization. *Mathematics*, 7(10), 2019: 915. https://doi.org/10.3390/math7100915
[23] T.L. Saaty, The Analytic Hierarchy Process: planning, priority setting, resource allocation. *McGraw-Hill*, New York, USA, 1980.
[24] M. Bertolini, M. Bevilacqua, A combined goal programming - AHP approach to maintenance selection problem. *Reliability Engineering and System Safety*, 91(7), 2006: 839-848. https://doi.org/10.1016/j.ress.2005.08.006
[25] G.-H. Tzeng, J.-J. Huang, Multiple Attribute Decision Making: Methods and Applications. *Chapman and Hall/CRC,* New York, USA, 2011. https://doi.org/10.1201/b11032
[26] C.A.B. Costa, M.C. Carnero, M.D. Oliveira, A multi-criteria model for auditing a Predictive Maintenance Programme. *European Journal of Operational Research*, 217(2), 2012: 381-393. https://doi.org/10.1016/j.ejor.2011.09.019
[27] M. Milošević, D. Lukić, G. Ostojić, M. Lazarević, A. Antić, Application of cloud-based machine learning in cutting tool condition monitoring. *Journal of Production Engineering*, 25(1), 2022: 20-24.
[28] Z.T. Xiang, C.J. Feng, Implementing total productive maintenance in a manufacturing small or medium-sized enterprise. *Journal of Industrial Engineering and Management*, 14(2), 2021: 152-175. https://doi.org/10.3926/jiem.3286
[29] M. Kannan, S. Singh, R.R. Prasad, Synthetic methods to obtain calcia-stabilized zirconia powders: a review. In: G. Manik, S. Kalia, S.K. Sahoo, T.K. Sharma, O.P. Verma, (eds). Advances in mechanical engineering: Lecture notes in mechanical engineering. *Springer,* Singapore, 2021: 405-416. https://doi.org/10.1007/978-981-16-0942-8_39