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Selection of Maintenance Strategy Using Hybrid AHP-VIKOR Approach for a Smart Manufacturing Application in Industry 4.0

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Abstract
In Industry 4.0, choosing the right maintenance strategy is important for improving machine performance, reducing downtime, and ensuring smooth operation in smart manufacturing systems. This study aims to find the most suitable maintenance strategy for a customized machine-making company by using a combination of AHP and VIKOR methods. In this study, four types of maintenance strategies are considered: breakdown maintenance, time-based maintenance, condition-based maintenance, and predictive maintenance. First, the AHP method is used to decide the importance of different factors such as cost, reliability, system availability, and efficiency. Then, the VIKOR method is used to compare these strategies and rank them based on their performance. The results show that condition-based maintenance is the best option among all the strategies, as it gives a good balance between cost, performance, and reliability. This shows that modern maintenance methods are more effective for smart manufacturing systems. This study provides a clear and simple approach that can help managers and decision-makers choose the right maintenance strategy in Industry 4.0 environments.

Keywords:
Industry 4.0, smart manufacturing, maintenance, Analytic Hierarchy Process (AHP), VlseKriterijumskaOptimizacijaKompromisnoResenje(VIKOR).

1 Introduction

According to reference [1], the present world is influenced by the Fourth Industrial Revolution. It includes technologies like Big Data, Cloud Computing, Advanced Robotics, Internet of Things, and Digital Twins, which are together known as "Industry 4.0." The aim is to improve production so that better quality products can be produced in less time and at lower cost. One important concept under this is "smart manufacturing," which uses data-based methods to deal with these issues.

As stated in reference [2], in recent years, more focus is being given to "smart manufacturing" by researchers and industry experts. It is a system that can adjust in real time according to changing customer needs with the help of advanced technologies. However, such systems need regular maintenance. According to reference [3], even in advanced factories, maintenance is still an important and difficult activity and it is not fully automated.

In today's competitive industrial world, maintenance is very important. Machines need regular servicing to avoid downtime and loss of productivity. When machines break down, it leads to delays, loss of reputation, and financial loss. Maintenance requires proper planning, budgeting, and management. While making a plan, a suitable maintenance strategy should be selected according to the company's goals and daily operations. A good maintenance plan is useful for all types of industries. Different maintenance strategies are available, and each has its own advantages and disadvantages. Machine performance depends on the maintenance method used. These methods may vary from machine to machine based on safety, cost, and user satisfaction. It is also necessary to manage the factors affecting machine performance. If an unsuitable maintenance method is used, it increases the maintenance cost [4].

Considering the above facts, the present research work deals with the selection of a maintenance strategy for a manufacturing firm. For this purpose, multiple-criteria decision making (MCDM), also known as MCDA, is used. It is a method in which different alternatives are compared on the basis of various criteria using scoring and weighting. It is suitable when many alternatives are available and different criteria are to be considered. It also helps in balancing positive and negative aspects [5]. In this method, alternatives are compared based on different criteria to achieve the objective. In the present study, VIKOR method is used for evaluation of alternatives, and AHP is used as a prioritization technique for evaluation of criteria.

1.1 Objectives of Research

The following are the objectives of the present research work:
(a) Identification of a set of evaluation criteria for evaluation;
(b) Evaluation of different alternatives; and
(c) Identification of optimum maintenance strategy for the firm.

2. Literature Review

The present section tells about the research contributions made by different researchers in the field of maintenance strategies and concludes with gaps in the research.

2.1 Research contributions in the field of Maintenance Strategies

The present section is based on the contribution of different researchers in the field of industry 4.0, smart manufacturing, and maintenance strategy selection, presented as follows:

Global interest in the Fourth Industrial Revolution has been growing steadily over the last several years, as reported by reference [6]. According to reference [7], "Industry 4.0" leads to shorter production cycles, higher product quality, and enhanced organizational efficacy. The scope of Industry 4.0 is vast, including not just manufacturing but also efficiency, data management, customer relationships, and business competitiveness. At the same time, it's clear that Industry 4.0 has emerged as a central topic in the study of management and business economics, with several articles published on a wide range of related topics [8].

According to reference [9], the concept of "smart manufacturing" was first developed in the United States and has since spread throughout the world. Smart manufacturing, as described by reference [10], dates back to the second part of the twentieth century. According to reference [11], IoT is a manufacturing technology that increases efficiency and quality. With the use of IoT, a smart factory may be built out of sensors, actuators, and other components. One of the primary goals of manufacturing process management is the minimization of industrial waste and the enhancement of goods. In a larger sense, "smart manufacturing" might be defined as the use of interconnected, networked, and data-rich equipment to carry out predetermined, repetitive activities.

Initial studies on smart manufacturing, as reported by reference [12], concentrated on the many technologies already in use in the industrial sector. New studies in this field, however, go far further by covering such topics as strategy, design, production, human resources, and more. Through the use of tools like simulation and big data, smart manufacturing can carry out duties like global monitoring and performance optimization. Management and other production factors including efficiency, quality, delivery, and flexibility based on current technology are key to achieving sustainable development in smart manufacturing, as stated by reference [13].

Using cost, safety, value-added services, and equipment and technology as factors, reference [4] explores the issue of choosing the best maintenance plan. Reference [14] study work seeks to identify the most effective approaches to servicing vital centrifugal pumps in an oil refinery. They claim that the model can factor in the maintenance strategy for each potential failure mode of the pump. References [15] and [14], both investigate how to choose between preventative, condition-based, corrective, and opportunistic maintenance for a given plant, with the former focusing on the occurrence, severity, and detectability of maintenance problems.

2.2 Gaps in the Research

During the review, most studies focus on the selection of maintenance strategies. Also, very little research is available on the use of combined MCDM techniques in decision-making problems.

3 Solution Methodology

The Analytic Hierarchy Process (AHP) was developed by Thomas L. Saaty in the 1970s. It is a method used for solving difficult decision-making problems in a simple and systematic way. It is based on mathematics and human thinking. AHP does not give a direct decision, but helps in selecting the best option. It is useful for understanding the problem clearly, dividing it into parts, and comparing different alternatives. Because of this, it is used in government, business, industry, healthcare, and education [16].

In AHP, the problem is arranged in the form of a hierarchy. The main objective is at the top, criteria and sub-criteria are in the middle, and alternatives are at the bottom. A hierarchy means arranging things in different levels, where lower elements are connected to higher ones. Each element is called a node, and their relation is called parent and child (fig 1). After preparing the hierarchy, priorities are decided by taking opinions from people and doing simple calculations. This helps in selecting the most suitable option among the available alternatives [17].

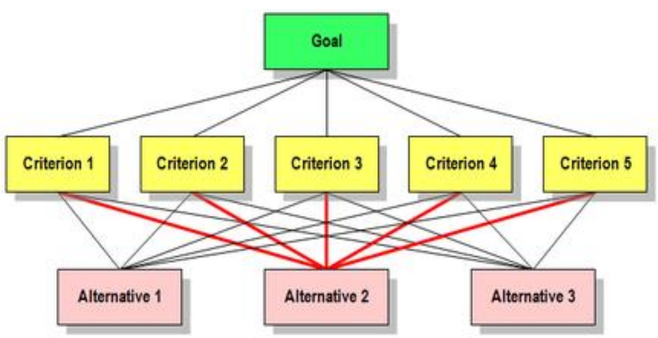

Fig. 1. General AHP Hierarchy Structure [17].

3.2 VlseKriterijumskaOptimizacija I KompromisnoResenje (VIKOR)

VlseKriterijumskaOptimizacija I KompromisnoResenje, which translates to "multi-criteria optimization and compromise solution" in Serbian, is the acronym for VIKOR. Opricovic created it back in 1998. The focus of this strategy is on evaluating and choosing the best option out of many that have competing criteria. In addition, it facilitates the final choice by helping decision-makers locate the optimal compromise option [18].

VIKOR method is based on Lp–metric used in compromise programming. This metric is used to find a solution which is nearest to the ideal solution. Its mathematical form is given in reference [19].VIKOR is a Multi-Criteria Decision

Making (MCDM) method based on the outranking principle. It is used for finding compromise ranking list, best compromise solution, and weight stability intervals.

$$L_{p.j} = \left\{ \sum_{i=1}^{n} \left[w_i \left(f_i^* - f_{ij} \right) / \left(f_i^* - f_i^- \right) \right]^p \right\}^{1/p} \quad (1)$$

$$1 \le p \le \infty, \qquad j = 1, 2, 3, \ldots\ldots\ldots\ldots J \quad (2)$$

3.2.1 General Procedure of VIKOR

The following steps are involved in the VIKOR method:

Step 1: Representation of normalized decision matrix

The normalized decision matrix can be expressed as

$$\mathbf{F} = \left[\mathbf{f}_{ij} \right]_{m \times n} \quad (3)$$

Here**,**

$$f_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^{2}}}, i = 1, 2, \ldots\ldots\ldots\ldots m; \quad (4)$$

and,$X_{ij}$is the performance ofalternative $A_i$concerning the j^{th} criterion.

Step 2: Obtain the maximum criterion function f_j^* and the minimum criterion function f_j^-, where j = 1. . . . . . m.

Maximum Criterion Functions

$$f_j^* = \max_i f_{ij} = \max\left[\left(f_{ij} \right) \backslash i = 1, 2, 3, \ldots\ldots n \right] \quad (5)$$

Minimum Criteria Functions

$$f_j^- = \min_i f_{ij} = \min\left[\left(f_{ij} \right) \backslash i = 1, 2, 3, \ldots\ldots n \right] \quad (6)$$

Step 3: Calculation of utility measure and regret measure

The utility measure and the regret measure for each alternative are given as

Utility Measure

$$S_i = \sum_{j=1}^{n} w_j \frac{\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)} \tag{7}$$

Regret Measure

$$R_i = \max_j \left[w_j \right] \frac{\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)} \tag{8}$$

Step 4: Computation of VIKOR Index

The VIKOR index can be expressed as follows:

$$Q_i = \nu \left[\frac{S_i - S^*}{S^- - S^*} \right] + \left(1 - \nu\right) \left[\frac{R_i - R^*}{R^- - R^*} \right] \tag{9}$$

Q_i represents the VIKOR index value of i^{th}alternative .i=1,2,………n.

$$S^* = \min_i S_i = \min\left[(S_i)/i = 1,2,3,.......n\right] \tag{10}$$

$$S^- = \max_i S_i = \max\left[S_i/i = 1,2,3,.......n\right] \tag{11}$$

$$R^* = \min_i R_i = \min\left[R_i/i = 1,2,3,.......n\right] \tag{12}$$

$$R^- = \max_i R_i = \max\left[R_i/i = 1,2,3,.......n\right] \tag{13}$$

where v is the weight for the maximum value of group utility and 1-v is the weight of the individual regret. v is generally set to 0.5.

4 Case Study

In the present research work, investigations about the selection of appropriate maintenance strategies for the firm dealing with smart manufacturing practices are targeted with the help of multi-criteria decision-making techniques. For this purpose, first of all, an MCDM model formulation was made, and then its solution was derived, the details of which are presented in upcoming sections.

4.1 Problem Formulation

The research was accomplished in a customized machine manufacturing firm. The firm produces customized machines and lab equipment of prime quality. Due to the versatile nature of items it produces via smart manufacturing practices, the management of the firm wanted to choose a successful maintenance strategy, due to which present research work came into the picture. The first step in the implementation of research tools to the case problem was the problem formulation, for which the help of industry personnel as well as academicians was taken, due to which a list of criteria was obtained, the details of which are as follows (table 1).

Table 1. List of Criteria for Model Formulation

S.No	Criteria	Sub Criteria
1.	Safety	Personal safety
2.		Facility safety
3.		Environmental safety
4.	Cost	Hardware cost
5.		Software cost
6.		Personal training cost
7.	Added value	Spare part inventories
8.		Production loss
9.		Fault identification
10.	Feasibility	Acceptance by labor
11.		Technique reliability

Regarding alternatives, again with the help of industry personnel and academicians was taken and maintenance types, *breakdown maintenance, time-based maintenance, condition-based maintenance, and predictive maintenance* were chosen as alternatives. Based on available criteria and alternatives, an MCDM model was developed, the details of which are as presented as follows (fig 2).

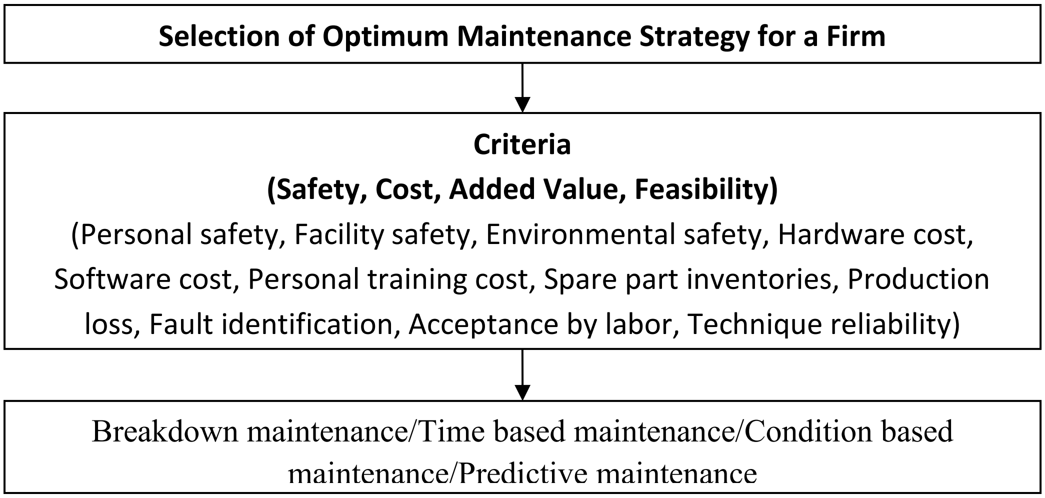

Fig. 2. Model Formulation for Research Problem

4.2 Solution of the Model

To solve the model, *two* well-known multi-criteria decision-*making* techniques *Analytical Hierarchy Process (AHP)* and *VlseKriterijumskaOptimizacija I KompromisnoResenje (VIKOR)* were used. Details of the procedure adopted for the solution of the model are as follows:

a) First of all, the weights of the criteria were identified with the help of AHP. For this purpose, A systematically designed questionnaire for the identification of weights of criteria was circulated among the industry personnel. The scale used in the questionnaire was a pairwise comparison scale. The responses were, then, fed to AHP-CGI software available at http://www.isc.senshu-u.ac.jp/~thc0456/EAHP/AHPweb.html. Following are the details of responses as well as weights of criteria as well as sub-criteria (table 2-11).

Table 2. Pairwise comparison matrix for Criteria

From/to	Safety	Cost	Added value	Feasibility
Safety	1	5	6	7
Cost	1/5	1	4	4
Added value	1/6	¼	1	1
Feasibility	1/7	1/4	1	1

Table 3. Weights of Criteria

S.No	Criteria	Weights
1.	Safety	0.638
2.	Cost	0.2917
3.	Added value	0.07282

4.	Feasibility	0.0691
	CR = CI/RI = 0.06	

Table 4. Pairwise comparison matrix for sub-criteria under Criteria 'Safety'

From/to	Personal safety	Facility safety	Environmental safety
Personal safety	1	7	3
Facility safety	1/7	1	1/4
Environmental safety	/3	4	1

Table 5. Weights of Sub-Criteria under Criteria 'Safety'

S.No	Criteria	Weights	
		Local Priorities	Global Priorities
1.	Personal safety	0.658	0.419804
2.	Facility safety	0.0786	0.050147
3.	Environmental safety	0.2627	0.167603
	CR = CI/RI = 0.027		

Table 6. Pairwise comparison matrix for sub-criteria under Criteria 'Cost'

From/to	Hardware cost	Software cost	Personal training cost
Hardware cost	1	1/4	1/5
Software cost	4	1	1/3
Personal training cost	5	3	1

Table 7. Weights of Sub-Criteria under Criteria 'Cost'

S.No	Criteria	Weights	
		Local Priorities	Local Priorities
1.	Hardware cost	0.0936	0.027303
2.	Software cost	0.279	0.081384
3.	Personal training cost	0.626	0.182604
	CR = CI/RI = 0.0724		

Table 8. Pairwise comparison matrix for sub-criteria under Criteria 'Added Value'

From/to	Spare part inventories	Production loss	Fault identification
Spare part inventories	1	1	1/2
Production loss	1	1	1
Fault identification	2	1	1

Table 9. Weights of Sub Criteria under Criteria 'Added Value'

S.No	Criteria	Weights	
		Local Priorities	Local Priorities
1.	Spare part inventories	0.2599	0.018926
2.	Production loss	0.327	0.023812
3.	Fault identification	0.4125	0.030038
	CR = CI/RI = 0.044		

Table 10. Pairwise comparison matrix for sub-criteria under Criteria 'Feasibility'

From/to	Acceptance by labor	Technique reliability
Acceptance by labor	1	1
Technique reliability	1	1

Table 11. Weights of Sub-Criteria under Criteria 'Feasibility'

S.No	Criteria	Weights	
		Local Priorities	Local Priorities
1.	Acceptance by labor	0.5	0.03455
2.	Technique reliability	0.5	0.03455
	CR = CI/RI = 0		

b) In the next step scores of different alternatives were investigated with the help of the VIKOR process. Following are the details of the results obtained during VIKOR calculations (table 12-15).

Table 12. Values of X_{ij}

S.No	Alternative	Personal safety	Facilities safety	Environmental safety	Hardware cost	Software cost	Personnel training cost	Spare part inventories	Production loss	Fault identification	Acceptance by labor	Technique reliability

1.	Breakdown maintenance	5	5	1	1	1	1	2	5	5	5	2
2.	Time-based maintenance	2	1	1	1	1	1	1	1	1	1	4
3.	Condition-based maintenance	3	2	2	5	5	2	1	1	2	3	5
4.	Predictive maintenance	1	1	2	1	5	2	2	1	1	1	3

Table 13. Values of f_{it}

S.No	Alternative	Personal safety	Facilities safety	Environmental safety	Hardware cost	Software cost	Personnel training cost	Spare part inventories	Production loss	Fault identification	Acceptance by labor	Technique reliability
1.	Breakdown maintenance	0.801	0.898	0.316	0.189	0.139	0.316	0.632	0.945	0.898	0.833	0.272
2.	Time-based maintenance	0.320	0.180	0.316	0.189	0.139	0.316	0.316	0.189	0.180	0.167	0.544
3.	Condition-based maintenance	0.480	0.359	0.632	0.945	0.693	0.632	0.316	0.189	0.359	0.500	0.680
4.	Predictive maintenance	0.160	0.180	0.632	0.189	0.693	0.632	0.632	0.189	0.180	0.167	0.408

Table 14. Values of fmax, fmin and fmax-fmin

S.No	Criteria

	Parameter	Personal safety	Facilities safety	Environmental safety	Hardware cost	Software cost	Personnel training cost	Spare part inventories	Production loss	Fault identification	Acceptance by labor	Technique reliability
1.	**fmax**	0.801	0.898	0.632	0.189	0.139	0.316	0.316	0.189	0.898	0.833	0.680
2.	**fmin**	0.160	0.180	0.316	0.945	0.693	0.632	0.632	0.945	0.180	0.167	0.272
3.	**fmax-fmin**	0.641	0.718	0.316	0.756	0.555	0.316	0.316	0.756	0.718	0.667	0.408

Table 15. Values of Si, Ri, and Qi

S.No	Alternative	Si	Ri	Qi
1.	Breakdown maintenance	4.535412	2.752339	0.528186
2.	Time-based maintenance	1.898814	0.786083	0.5
3.	Condition-based maintenance	4.69292	1.441501	0.166667
4.	Predictive maintenance	2.912935	0.972285	0.365874

5 Results and Discussion

The present section tells about the results obtained and discussions made about the research work, the details of which are presented in upcoming sections.

5.1 Results

Table 16 shows the details of rankings obtained by different maintenance alternatives.

Table 16. Rankings of Alternatives

S.No	Alternative	Qi	Ranking
1.	Breakdown maintenance	0.528186	4
2.	Time-based maintenance	0.5	3
3.	Condition-based maintenance	0.166667	1
4.	Predictive maintenance	0.365874	2

5.2 Discussion

Results of the research work show the suitability of condition-based maintenance for the firm, as it earns the rank 1. For rank 2, alternative predictive maintenance seems to be appropriate. Similarly, alternative time-based maintenance and breakdown maintenance earn ranks 3 and 4, respectively.

Condition maintenance needs an in-depth analysis of the tools and equipment and repair activities as the fault is investigated. For this purpose, a regular watch on the tools and equipment is needed. These activities need additional monitoring devices as well as skilled manpower, which gets added to the total cost of resources. On investigating the reasons behind the suitability of condition-based maintenance for the firm, the following points came into the picture.

- Type of machinery;
- High cost of machinery;
- Complexity of mechanisms used in machinery;
- High number of fragile parts in machinery;
- The high worth of orders; and
- Closer delivery dates.

Considering above mentioned facts, a condition-based maintenance strategy seems to be appropriate for the targeted firm.

For rank 2, alternative predictive maintenance appears. While dealing with this approach, prediction regarding the condition of the machine that needs maintenance is used as a basis for maintaining the system. Considering this type of maintenance, the following in-capabilities in the system were observed.

- Semi-skilled or unskilled workers;
- Less efficient monitoring sensors;
- Lack of awareness of predictive; and
- High cost of predicting maintenance equipment as compared to condition-based maintenance equipment.

For rank 3, alternative time-based maintenance appeared. While dealing with time-based maintenance, periodic checks of machines are needed. After discussions, with the employees of the firm, the following points, regarding the unsuitability of time-based maintenance, were recognized.

- Complexity of designs of machines;
- Uneven failure of tools and equipment due to uneven job designs; and
- Different demands for different types of products.

For rank 4, alternative breakdown maintenance appears which is undesired by responses due to the following reasons.

- Huge disturbances in delivery timings;
- Uneven nature of maintenance timings;
- Increase in in-process inventories; and
- Inappropriate quality of products.

Considering the above discussion, one can analyze the reasons behind the selection of condition-based maintenance by the firm's personnel.

6 Conclusion, Limitations, and Future Scope of the Research

The present section is devoted to the conclusion of the research work, its limitations, and future scope, details of which are presented in upcoming sections.

6.1 Conclusion

The present research work is done to select a maintenance strategy for a customized machine-making firm. In this study, four maintenance strategies are compared on the basis of eleven criteria taken from literature and expert opinion. AHP-VIKOR method is used for analysis. The results show that condition-based maintenance is ranked first, predictive maintenance second, time-based maintenance third, and breakdown maintenance fourth.

From these results, condition-based maintenance is the best option for the firm. Predictive maintenance is the second option. Time-based maintenance is less suitable. Breakdown maintenance is the least suitable for the firm.

6.2 Limitations and Future Scope of the Research

The present research work is limited to a selected set of criteria. Because of this, all factors are not covered. The study is also limited to a few approaches used to solve the problem. Other methods are not considered, which may affect the results. So, the study remains limited to the selected criteria and approaches only.

The future scope of the research is wide. More studies can be done by including more criteria to get better results. Different methods can also be used to solve the problem. Further work in this area can give better understanding and improved results in future.

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