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Optimum Maintenance Strategy Selection Using a Hybrid Approach Based on Analytical Hierarchy Process and Revised Multi Choice Goal Programming

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KEYWORDS

Revised Multi Choice Goal Programming,
AHP,
Maintenance Strategy Selection,
Reliability Centered Maintenance (RCM).

ABSTRACT

This study aims to select optimal maintenance strategy for components of an electric motor of the National Iranian Oil Refining and Distribution Company. In this regard, a method based on revised multi choice goal programming and analytic hierarchy process (AHP) is presented. Since improving the equipment reliability is an important issue, reliability centered maintenance (RCM) strategies are introduced in this paper. Furthermore, on one hand, we know that maintenance cost consists of a considerable percentage of production cost; on the other hand, the risk of equipment failure is a main factor on personnel's safety. Consequently, the cost and risk factors are selected as important criteria of maintenance strategies.

1. Introduction

Some of the production companies used just corrective maintenances which is applicable only in emergency conditions. Failures might result in high expenditures, due to the delays of production and losses as well as safety danger. It all because they always want to decrease their production cost and one of the main cost items for companies is maintenance cost. Today, this form of intervention is no longer acceptable [1], and it is necessary to choose a suitable maintenance policy in order to prevent the failure and then the selection process of the appropriate maintenance strategy for each of equipment is crucial. A suitable maintenance strategy can decrease the total operating cost and has a significant role in keeping product quality, reliability and safety requirements as well as decreasing the risks. However most of plants contain a wide range of equipment; each has its own reliability. Thus, it is apparent that a proper maintenance program should define different maintenance strategies for different machines so all the equipment will become efficient. For instance, for a standby pump, corrective/time-based maintenance might be more cost-effective than the condition-based/predictive maintenance strategy. As indicated by Mobley [2], 33% of all maintenance costs is wasted as a result of unnecessary or improper maintenance activities. So it is necessary that the managers choose the best maintenance strategy for each equipment.

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The purpose of this paper is to propose the combination of AHP with RMCGP (Revised Multi Choice Goal Programming) to choose the best maintenance strategy for an electric motor in the National Iranian Oil Refining & Distribution Company (NIORDC). Consequently we will consider literature of maintenance strategy selection in Section 2. Then we will give the definition of problem in Section 3. The Section 4 explains the proposed model. Then we will consider a case study in Section 5. Finally, we will present the conclusions.

2. Literature Review

Optimum maintenance strategy selection is obligatory, and many studies has been treated in this area. Almeida and Bohoris [3] discussed a brief review of different decision theory concepts along with their applicability in the choosing of the most appropriate maintenance strategy. Triantaphyllou et al. [4] proposed a method to find the criticality of each criteria dealing with maintenance strategies considering the simplifying of the complex maintenance criteria. Azadivar and Shu [5] presented a new approach to select an appropriate maintenance strategy for each class of systems in a just-in-time environment, exploring 16 characteristic factors that could play a role in maintenance strategy selection. But this method is not applicable to process plants due to the difference between discrete manufacturing plants and process plants. Murthy and Asgharizadeh [6] proposed a methodology based on game theory for selection of maintenance strategy for the companies which outsource the maintenance operations. In the report of Bevilacqua and Braglia [1], the original way for the selection of maintenance strategies in an important Italian oil refinery was given, and the application of the analytic hierarchy process for selecting the best maintenance strategy was described. The criteria they considered seem sufficient, but a crisp decision-making method as the traditional AHP is not suitable because many of the maintenance goals are non-monetary and difficult to be quantified. In another works, Luce [7] and Okumura and Okino [8] proposed the methods to select the most effective maintenance strategy based on different production loss and maintenance costs according to different maintenance strategies. The calculation theories for the related costs presented by them are reasonable. Al-Najjar and Alsyouf [9] used past data and technical analysis of process machines and components to identify the criteria for an multi-criteria decision making (MCDM) problem. They used fuzzy inference system (FIS) to assess the capability of each maintenance approach. Finally, by using simple additive weighting (SAW) method, the efficient maintenance approach was selected. Mechefske and Wang [10] developed a multi-objective model to evaluate and select the most appropriate maintenance strategy. First, they define goals, and then the capability of each strategy for satisfying the given objectives is evaluated with fuzzy expressions. Sharma et al. [11] evaluated the most popular maintenance way utilizing the fuzzy inference theory and MCDM evaluation methodology in fuzzy atmosphere. Ivy and Nembhard [12] integrated statistical quality control (SQC) and partially observable Markov decision processes (POMDPs) for evaluation of maintenance policies under conditions of limited information. Bertolini and Bevilacqua [13] selected a decision support system (DSS) for the inspection staff of oil pipelines based on the decision tree analysis. They proposed a method with respect to some relevant variables such as mechanical failure or system malfunction. Wang, et al., [14] developed an approach for the for maintenance strategy selection problem. Their structure includes only four criteria, i.e., cost, safety, feasibility and added value based on fuzzy analytic hierarchy process. Jafari et al. [15] developed a new approach which can determine the best maintenance strategy by considering the uncertainty and also all the variety in maintenance criteria and their importance. Gaonkar et al. [16] proposed an approach to model the uncertainty in the process of the optimum maintenance strategy selection. Mousavi et al. [17] presented a two-step approach using FA and TOPSIS method to choose the most appropriate maintenance strategy. Saumil et al. [18] proposed a continuous time Markov chain degradation model and a cost model to quantify the effects of maintenance on a multiple machine system. An optimal maintenance policy for a multiple machine system in the absence of resource constraints is obtained, and in the presence of resource constraints, two prioritization methods are proposed to obtain effective maintenance policies for a multiple machine system. Also a case study focusing on a section of an automotive assembly line has been used to illustrate the effectiveness of the proposed method. Vahdani et al. [19] proposed a VIKOR method utilizing interval numbers for numbers for maintenance strategy selection problem while considering monetary and labor acceptance objectives. Van Horenbeek [20] proposed a literature review on maintenance optimization models and developed a general classification structure for maintenance selection model. In their general framework, they consider some technical criteria such as quality, reliability, cost and inventory, as well as the environmental effects. More recently, we can found many related maintenance related researches in literature e.g., [21-23].

3. Problem Definition

National Iranian Oil Refining & Distribution Company (NIORDC) as one of the well-known companies in Iran has a modern industrial plant which all of them need an acceptable level of availability and reliability. This plant has many critical equipment such as compressors, pump, heat exchanger and etc. The manager has to decide on the maintenance approach for different equipment in this organization. In the NIORDC, maintenance strategy has significant effect on the short-term factors such as budget, technological choices, allocation, generational and managerial procedures. Hence application of an efficient maintenance strategy is vital in NIORDC.

As an aid to this issue, some multi-criteria approaches are presented in the literature. This paper presents a multi-attribute decision method based on a combination of revised multi choice goal programming (RMCGP) and Analytic Hierarchy Process (AHP) to choose the suitable maintenance strategy for each equipment. The use of goal programming permits considering multiple criteria to measure multi objectives/goals. In this paper two critical criteria, i.e., cost and risk, are taken into consideration because in this plants the cost of maintenance is too high and there exist toxic components.

3-1. Equipment components

In this paper, we aim to evaluate an electric motor which belongs to the NIORDC. According to ISO 14224, the above-mentioned equipment is a four-sub-unit machine which has many components. Tables 1 and 2 reports the equipment characteristics.

Tab. 1. Equipment Information

Item	Power (KW)	Rpm	Voltage (KV)	Current (Am)
Electro motor	3425	6048	6	365

Tab. 2. Equipment Sub units and components

Sub Units	Electric Motor	Control And Monitoring	Lubrication System	Cooling System
Components	Stator	Control Unit	Lubrication Oil	Air Filter
	Rotor	Monitoring	Oil Filter	Internal Fan
	Radial Bearing	Sensors	Lubrication Oil Pump	External Fan
		Wiring	Lubrication Piping	Heat Exchanger
			Lubrication Valve	Cooling Valve

Stator: The stator is the stationary part of a rotary system found in electric generators, electric motors, sirens, etc. Depending on the configuration of a spinning electromotive device, the stator may either act as the field magnet, interacting with the armature to create motion, or it may act as the armature, receiving its influence from moving field coils on the rotor.

Rotor: The rotor is a moving component of an electromagnetic system in an electric motor, electric generator, or alternator. Its rotation is due to the interaction between the windings and magnetic fields which produces a torque about the rotor's axis.

Radial bearing: A bearing is a machine element that constrains relative motion and reduces friction between moving parts to only the desired motion. The purpose of a radial bearing is to reduce rotational friction and support loads.

Control unit: An electric motor control unit is mounted in an automotive vehicle with a motor that is variable in its rotational speed. A temperature sensing element is arranged to contact a busbar so that relays permit switching operation in response to detection of abnormal heat generation. This controls an electrical power supply to the motor to decrease the rotational speed of the motor without stopping it completely. The rotational speed of the motor returns to a normal speed from the decreased speed by switching operation of the relays with diminishing of the abnormal heat generation.

Monitoring: A process within a distributed system for collecting and storing state data, and also a technique for machinery maintenance and fault diagnosis.

Sensors: Detects a change in a physical stimuli and turns it into a signal which can be measured or recorded.

Wiring: Provides electric circuits for an electric motor and contacts devices to each other.

Lubrication oil: Reduces wear of one or both surfaces in close proximity, and moving relative to each other, by interposing between the surfaces to carry the load between the opposing surfaces.

Oil filter: Designed to remove contaminants from engine oil, transmission oil, lubricating oil, or hydraulic oil. Oil filters are used in many different types of machinery.

Lubrication pump: Transfers lubricant in the piping system by mechanical action.

Air filter: Removes solid particulates such as dust, pollen, mold, and bacteria from the air.

Internal fan: It is an axial fan attached to the rotor of the motor, usually on the opposite end as the output shaft, which spins with the motor and provides increased air flow in the motor internal parts which aids in cooling them.

External fan: Cool air is usually circulated by one or two external fans, it is necessary to continuously transfer the heat to a cooling medium, such as the air.

Heat exchanger: An equipment built for efficient heat transfer from one medium to another.

Lubrication piping: A system of pipes used to convey lubricant from one location to another.

Cooling valve: It is a device in cooling system for controlling the passage of fluid through the piping system, especially an automatic device allowing movement only in one direction.

Lubrication valve: Regulates, directs or controls the flow of the lubricant in a lubrication system.

3-2. Definition of variables and parameters

$W = (W_r, W_c)$

$W_r + W_c = 1$

W_r = Relative Importance of Risk

W_c = Relative Importance of Cost

$S_{c,i}$ = The local priority of the *i*th maintenance strategy with respect to Cost

$S_{r,i}$ = The local priority of the *i*th maintenance strategy with respect to Risk

$S_{ahp,i}$ = The global priority of the *i*th maintenance strategy with respect to Risk and Cost

$$x_i = \begin{cases} 1 \text{ If ith Maintenance Strategy is Selected} \\ 0 \text{ Otherwise} \end{cases}$$

T_C = The additional continuous variable is linked to the local score maximization for the Cost

$T_{C\min}$ = Sum of two higher local scores of costs (lower bound of the cost aspiration levels)

$T_{C\max}$ = Sum of three higher local scores of costs (upper bound of the cost aspiration levels)

T_r = The additional continuous variable linked to the local score maximization for the Risk

$T_{r\min}$ = Sum of two higher local scores of risk (lower bound of the risk aspiration levels)

$T_{r\max}$ = Sum of three higher local scores of risk (upper bound of the risk aspiration levels)

T_{ahp} = The additional continuous variable is linked to the global score maximization for the Risk and Cost

$T_{ahp\min}$ = Sum of two higher global scores of risk and Cost (lower bound of risk and Cost aspiration levels)

$T_{ahp\max}$ = 1 (upper bound of risk and Cost aspiration levels)

Z_1, Z_2, Z_3 = Binary Variables

d_c^+, d_c^- = Positive and negative deviations attached to the $\left|F_c\left(X\right)-T_c\right|$

d_r^+, d_r^- = Positive and negative deviations attached to the $\left|F_r\left(X\right)-T_r\right|$

d_{ahp}^+, d_{ahp}^- = Positive and negative deviations attached to the $\left|F_{ahp}\left(X\right)-T_{ahp}\right|$

e_c^+, e_c^- = Positive and negative deviations attached to the $\left|T_c-T_{c\max}\right|$

e_r^+, e_r^- = Positive and negative deviations attached to the $\left|T_r-T_{r\max}\right|$

e_{ahp}^+, e_{ahp}^- = Positive and negative deviations attached to the $\left|T_{ahp}-T_{ahp\max}\right|$

$$S_{j,i}:\begin{bmatrix} S_{c,1} & S_{c,2} & S_{c,3} & S_{c,4} & S_{c,5} & S_{c,6} \\ S_{r,1} & S_{r,2} & S_{r,3} & S_{r,4} & S_{r,5} & S_{r,6} \end{bmatrix} \quad (1)$$

$$\begin{aligned} &S_{c,1}+S_{c,2}+S_{c,3}+S_{c,4}+S_{c,5}+S_{c,6}=1 \\ &S_{r,1}+S_{r,2}+S_{r,3}+S_{r,4}+S_{r,5}+S_{r,6}=1 \end{aligned} \quad (2)$$

Global scores for maintenance policy is:

$$\mathrm{S}_{\mathrm{ahp},1}=W_r\times S_{r,1}+W_c\times S_{c,1} \quad (3)$$

$$\mathrm{S}_{\mathrm{ahp},2}=W_r\times S_{r,2}+W_c\times S_{c,2} \quad (4)$$

$$\mathrm{S}_{\mathrm{ahp},3}=W_r\times S_{r,3}+W_c\times S_{c,3} \quad (5)$$

$$\mathrm{S}_{\mathrm{ahp},4}=W_r\times S_{r,4}+W_c\times S_{c,4} \quad (6)$$

$$\mathrm{S}_{\mathrm{ahp},5}=W_r\times S_{r,5}+W_c\times S_{c,5} \quad (7)$$

$$\mathrm{S}_{\mathrm{ahp},6}=W_r\times S_{r,6}+W_c\times S_{c,6} \quad (8)$$

4. Proposed Model

The proposed methodology for the problem of maintenance strategy selection is based on a combination of AHP and RMCGP methods. It consists of five basic stages as follows:

Stage 1: Reliability centered maintenance (RCM)
Stage 2: Maintenance Strategies
Stage 3: AHP technique
Stage 4: Multi choice goal programming technique
Stage 5: Revised Multi choice goal programming technique

The schematic diagram of the proposed methodology is shown in Fig. 1. In section 4.1, we define RCM method and then discuss its benefits. After that, we will describe seven questions of this method. In section 4.2, maintenance strategies are selected based on RCM method. In 4.3, The AHP technique will be proposed. Then three benefits of this technique and pair-wise table will be presented. MCGP method will be defined in section 4.4. After that, problem will be formulated according to MCGP. In section 4.5, problem will be formulated by RMCGP method because by using MCGP, the binary variables will get larger and then it would not be easy to understand.

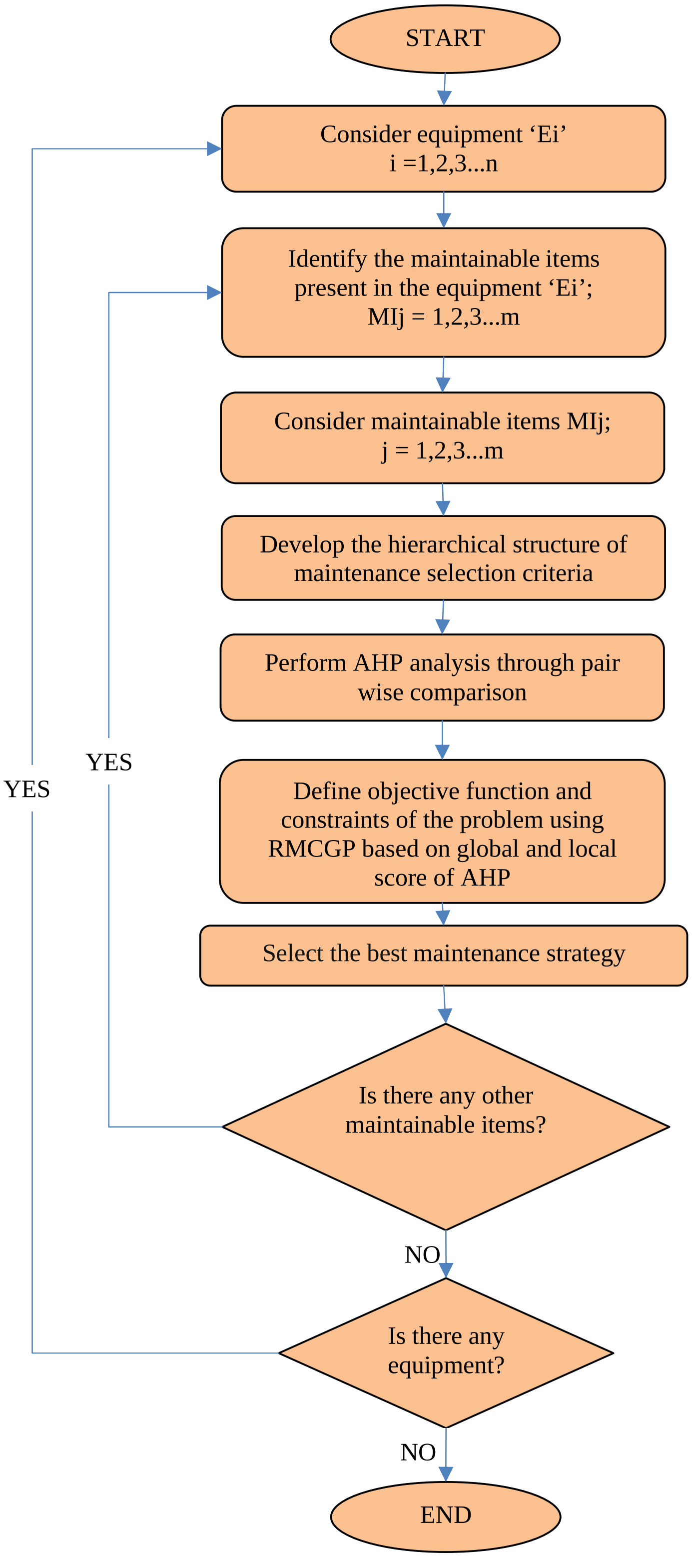

Fig. 1. Methodology for maintenance strategy selection

The decision hierarchy diagram is established by using identified evaluation criteria (Fig. 2). There are three levels in the decision hierarchy. These levels are as followings: goal level, criteria level and alternative level.

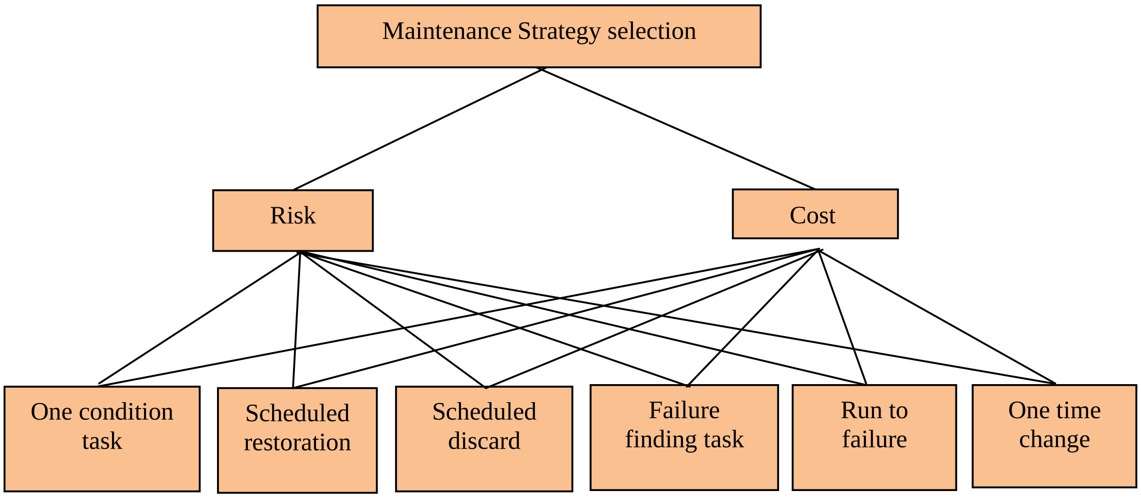

Fig. 2. Hierarchy structure for maintenance strategy selection

4-1. Reliability centered maintenance (RCM)

RCM is characterized by recognizing failure modes, prioritizing functions, and selecting efficient maintenance. It is a technique which is used to develop cost-effective maintenance plans and criteria in order to achieve, restore or maintain the operational capability of equipments. Reducing the maintenance cost by focusing on the most important functions of the system is the main objective of RCM. RCM was developed in 1970s by the Air Transport Association (ATA), the Aerospace Manufacturers' Associates (AMA), and the US Federal Aviation Administration (FAA). It has its origins in the findings of the Maintenance Steering Groups (MSG) that were formed in the aviation industry to develop a maintenance program for the Boeing 747 and Lockheed L1011. United Airlines were one of the biggest company that implemented this method. The MSG used a logic tree for decision making. In 1975, the US Department of Defense directed the MSG concept to be called ‘‘reliability-centered maintenance’’ and to be applicable to all major military systems. RCM has gained considerable recognition in the armed navies.

Some common definitions of RCM are as follows:

- ‘‘RCM is a systematic method to keep a balance between preventive and corrective maintenance. This method chooses the right preventive maintenance activities for the right component at the right time to reach the most cost-efficient solution’’.
- ‘‘RCM is a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context’’.
- ‘‘RCM employs a system perspective in its analyses of system functions, failures of the unction's, and prevention of these failures’’.

Moreover, RCM benefits are as follows:

- It usually leads to a maintenance program which focuses preventive maintenance on specific failure modes which are likely to happen.
- Any organization can benefit from RCM if its breakdowns account for more than 20–25% of the total maintenance work load.
- RCM can reduce the amount of routine maintenance work by 40–70%, if it is correctly applied.

In addition, RCM benefits can be traced back to two broad categories: risk reductions and cost savings. The RCM methodology is completely described in the following four features.

- Preserve functions
- Identify failure modes that can defeat the functions
- Priorities function need (via the failure modes)
- Select only applicable and effective tasks

Based on SAE1011, an RCM analysis basically provides answers to the following questions:

- What are the functions and associated performance standards of the equipment in its present operating context (functions)?
- In what ways can it fail to full fill its functions (functional failures)?
- What is the cause of each functional failure (failure modes)?

- What happens when each failure occurs (failure effects)?
- In what way does each failure matter (failure consequences)?
- What can be done to prevent each failure (proactive tasks and task intervals)?
- What should be done if a suitable preventive task cannot be found (default actions)?

4-2. Maintenance strategies

Six alternative maintenance strategies are considered in this paper. These strategies are based on RCM and selected from SAE1011.

1. on condition tasks

✓ Condition based Maintenance (CBM)
✓ Predictive Maintenance (PDM)

Any on-condition task which also called predictive or condition-based or condition monitoring task is used to detect a potential failure. Most failure modes do not occur absolutely instantly. In such cases, it is often possible to detect before reaching the failed state. This evidence of imminent failure is known as a potential failure. If this condition can be detected, it may be possible to take action to prevent the item from failing completely and avoid the consequences of the failure mode.

2. scheduled discard tasks

There shall be a clearly defined age at which there would be an increase in the probability of the occurrence of the failure mode. A scheduled discard task discards an item before the defined age, regardless of its condition at the time.

3. scheduled restoration tasks

There shall be a clearly defined age at which there would be an increase in the probability of the occurrence of the failure mode. A scheduled restoration task restores the capability of an item before the defined age, regardless of its condition at the time.

4. failure finding tasks

Failure finding tasks do not apply to evident failure modes but used to determine if a specific hidden failure has occurred. These tasks shall be physically possible to do the task at the specified intervals.

5. one time changes

✓ Proactive Maintenance
✓ Redesign Maintenance

Any task which has to be taken to change the physical configuration of an asset or system such as redesign or modification. It is necessary to change the method used by an operator or maintainer to perform a specific task and change the operating context of the system or change the capability of an operator or maintainer.

6. run to failure

✓ Corrective Maintenance (CM)
✓ Emergency Maintenance (EM)
✓ Shut down Maintenance (SDM)
✓ Failure Maintenance (FLM)
✓ Fault Maintenance (FTM)

A Maintenance strategy that permits specific failure mode happens without any attempt to anticipate or avoid it. It is considered as a feasible strategy in the cases where profit margins are large [11]. However, this type of maintenance strategies will result in serious damage to personnel, environment and equipment.

4-3. Analytical hierarchy process

According to mathematics and psychology, AHP was developed by Thomas L. Saaty (1970) and has been studied and refined afterwards. It is used across the globe in a range of decision situations. In the AHP, the decision-making problem is structured hierarchically at different levels with each level consisting of a finite number of elements (Khajeh, 2010). It is a powerful and flexible MCDM tool for complex issues where both qualitative and quantitative aspects need to be taken into consideration. But this method has some limitations. The conventional AHP is not able to reflect the human thinking style. For instance, while doing pair-wise comparisons, it is challenging for maintenance staff to precisely quantify the statements such as what is the relative importance of risk in terms of cost in this study.

AHP has three main levels. First level is goal (in this case is selecting the best maintenance strategy for each component of electric motor). Next level is consisted of criteria and finally the alternatives are being evaluated.

The AHP consists of three main operations, including hierarchy construction, priority analysis, and consistency verification. First of all, the decision makers are required to break down complex multiple criteria decision issues into its detailed parts of which every possible attributes are sorted into multiple hierarchical levels. After that, the decision makers have to compare each cluster in the same level in a pairwise fashion based on their own experience and knowledge. The one of main steps of AHP is to organize problem hierarchically as the first step, the issue is structured as a family tree in this step. The mentioned pair-wise comparisons are based on a standardized evaluation schemes which is displayed in Table 3.

Tab. 3. Pair-wise comparison scheme for data collection

Value of rating judgments	Verbal judgments
Aij = 1	The two parameters are equally important
Aij = 3	Parameter *i* is weakly more important than parameter *j*
Aij = 5	Parameter *i* is strongly more important than parameter *j*
Aij = 7	Parameter *i* is very strongly more important than parameter *j*
Aij = 9	Parameter *i* is absolutely more important than parameter *j*
Aij =2,4,6,8	Interval values between two adjacent choices

Moreover, calculation of local priorities from judgment matrices which include several methods for deriving local priorities from judgment matrices have been developed. In addition, consistency check should be implemented for each judgment matrix.

Finally, alternatives ranking, is done to obtain global priorities by aggregating all local priorities with the application of a simple weighted sum. Then the final ranking of the alternatives are determined on the basis of these global priorities.

This model has three benefits [4]:

1. The only known MCDM model which is able to measure the consistency in the decision makers' judgments is the AHP.
2. The AHP model is able to help the decision makers to organize the critical aspects of a problem into a hierarchical structure similar to a family tree which helps to deal with the decision process easily.
3. The decision makers often prefer the pair-wise comparisons in the AHP which allow them to derive scores of options and weights of criteria from comparison matrices rather than quantify weights/scores directly.

4-4. Multi choice goal programming

Chang [24] argued that due to uncertainty/imprecision, the DMs may prefer to set multiple aspiration levels for every objective. Multi-choice goal programming (MCGP) method allows decision makers (DMs) to set multiple aspiration levels for their problems. In such a condition, "the more/higher is better" and "the less/lower is better" in the aspiration levels are addressed. The conflicts of resources and the incompleteness of available information make it almost impossible for DMs to build a reliable mathematical model for representation of their preferences. And DMs would like to minimize the deviations between the achievements of goals and their aspiration levels.

In the following, the problem is formulated based on MCGP model.

$$Min\ Z = \sum_{i=1}^{n}\left[W_i\left(d_i^+ + d_i^-\right) + \varphi_i\left(e_i^+ + e_i^-\right)\right] \qquad (9)$$

$$s.t. \qquad (10)$$

$$f_i\left(X\right) - d_i^+ + d_i^- = y_i \qquad (11)$$

$$y_i - e_i^+ + e_i^- = g_{i,\min} \qquad (12)$$

$$g_{i,\min} \le y_i \le g_{i,\max} \qquad (13)$$

$$d_i^+, d_i^-, e_i^+, e_i^- \ge 0 \quad i = 1, 2, ..., \mathrm{n} \qquad (14)$$

$\mathrm{X} \in \mathrm{F}$ (F is a feasible set, X is unrestricted in sign) for minimization of y_i.

4-5. Revised multi choice goal programming

Chang [24] discussed that the multiplicative terms of binary variables that are used to express multiple aspiration levels increase the complexity of the model. The formulation with the multiplicative terms of binary variables is difficult to implement especially when the problem size gets large and it is not easily understood by industrial participants. In fact, the new approach is a linear form of MCGP which can easily be solved by common linear programming packages, not requiring the use of integer programming packages. According to the mentioned issues, Chang [24] proposed a revised MCGP approach. Thus, the problem is being formulated based on RMCGP and. By using GAMS software the solution can be achieved.

The model in this paper is formulated by RMCGP as follows:

$$Min\ Z = d_c^+ + d_c^- + d_r^+ + d_r^- + d_{ahp}^+ + d_{ahp}^- + e_c^+ + e_c^- + e_r^+ + e_r^- + e_{ahp}^+ + e_{ahp}^- \qquad (15)$$

s.t. (16)

$$S_{c,1} \times X_1 + S_{c,2} \times X_2 + S_{c,3} \times X_3 + S_{c,4} \times X_4 + S_{c,5} \times X_5 + S_{c,6} \times X_6 - d_c^+ + d_c^- = y_c \quad (17)$$

$$y_c - e_c^+ + e_c^- = T_{c,\max} \quad (18)$$

$$T_{c,\min} \le y_c \le T_{c,\max} \quad (19)$$

$$S_{r,1} \times X_1 + S_{r,2} \times X_2 + S_{r,3} \times X_3 + S_{r,4} \times X_4 + S_{r,5} \times X_5 + S_{r,6} \times X_6 - d_r^+ + d_r^- = y_r \quad (20)$$

$$y_r - e_r^+ + e_r^- = T_{r,\max} \quad (21)$$

$$T_{r,\min} \le y_r \le T_{r,\max} \quad (22)$$

$$S_{ahp,1} \times X_1 + S_{ahp,2} \times X_2 + S_{ahp,3} \times X_3 + S_{ahp,4} \times X_4 + S_{ahp,5} \times X_5 + S_{ahp,6} \times X_6 - d_{ahp}^+ + d_{ahp}^- = y_{ahp} \quad (23)$$

$$y_{ahp} - e_{ahp}^+ + e_{ahp}^- = 1 \quad (24)$$

$$T_{ahp,\min} \le y_{ahp} \le 1 \quad (25)$$

$$d_c^+, d_c^-, e_c^+, e_c^-, d_r^+, d_r^-, e_r^+, e_r^-, d_{ahp}^+, d_{ahp}^-, e_{ahp}^+, e_{ahp}^- \ge 0 \quad (26)$$

5. Case Study

In this section, a numerical example is used to explain how the maintenance strategy selection decisions are made using the proposed model. This study is applied to an electric motor in the paper industry located in NIOPDC. After the construction of the hierarchy diagram of the problem to determine their relative weights, the AHP methodology requires pair-wise comparison of the criteria. In the pair-wise comparison process, by using Saaty's nine-point scale we are able to compare each criterion with others. In this step, three sets of pair-wise comparisons are performed: (1) pair-wise comparison between risk and cost for each component, (2) pair-wise comparisons among maintenance strategies based on cost criterion for each component and (3) pair-wise comparisons among maintenance strategies based on risk criterion for each component. For example, the obtained results from three mentioned sets of pair-wise comparison for stator are shown in detail in Tables 4-6, respectively. In addition, the results for the other components are summarized in Tables 7-9. After that, global scores of maintenance strategies for each component are calculated and are given in Table 10. Finally, the most suitable maintenance strategy for each component is obtained by using the revised multi-choice goal programming. The obtained results are shown in Table 11.

Tab. 4. Comparison matrix for maintenance selection criteria for stator

Criteria	Risk	Cost	Priority weights (normalized)
Risk	1	5	W_c= 0.83
Cost	0.2	1	W_r= 0.17

Tab. 5. Priority weights for maintenance strategies based on risk contribution for stator

Maintenance strategies	On condition tasks	Scheduled restoration	Scheduled discard	Failure finding	Run to failure	One time changes	Priority weights (normalized)
On condition tasks	1	5	6	7	9	9	0.53
Scheduled restoration	0.2	1	2	3	5	5	0.19
Scheduled discard	0.17	0.5	1	2	4	4	0.13
Failure finding	0.14	0.3	0.5	1	2	2	0.07

Maintenance strategies	On condition tasks	Scheduled restoration	Scheduled discard	Failure finding	Run to failure	One time changes	Priority weights (normalized)
Run to failure	0.1	0.2	0.25	0.5	1	1	0.04
One time changes	0.1	0.2	0.25	0.5	1	1	0.04

Tab. 6. Priority weights for maintenance strategies based on cost contribution for stator

Maintenance strategies	On condition tasks	Scheduled restoration	Scheduled discard	Failure finding	Run to failure	One time changes	Priority weights (normalized)
On condition tasks	1	4	2	0.25	0.2	0.2	0.09
Scheduled restoration	0.25	1	0.5	0.33	0.14	0.14	0.04
Scheduled discard	0.5	2	1	0.5	0.2	0.2	0.07
Failure finding	4	3	2	1	0.5	0.5	0.17
Run to failure	5	7	5	2	1	1	0.32
One time changes	5	7	5	2	1	1	0.32

Tab. 7. Weights of the criteria for each component

Component	W_c	W_r
Stator	0.83	0.17
Rotor	0.80	0.20
Radial Bearing	0.67	0.33
Control Unit	0.20	0.80
Monitoring	0.20	0.80
Sensors	0.20	0.80
Wiring	0.14	0.86
Lubrication Oil	0.30	0.67
Oil Filter	0.30	0.67
Lubrication Oil Pump	0.13	0.88
Lubrication Piping	0.30	0.67
Air Filter	0.30	0.67
Lubrication Valve	0.30	0.67
Internal Fan	0.75	0.25
External Fan	0.30	0.67
Heat Exchanger	0.30	0.67
Cooling Valve	0.30	0.67

Tab. 8. Local scores based on risk of the component

maintenance component	On condition tasks	Scheduled restoration	Scheduled discard	Failure finding	Run to failure	One time changes
Stator	0.53	0.19	0.13	0.07	0.04	0.04
Rotor	0.53	0.19	0.13	0.07	0.04	0.04
Radial Bearing	0.46	0.17	0.23	0.07	0.03	0.03
Control Unit	0.34	0.13	0.11	0.37	0.03	0.03
Monitoring	0.30	0.12	0.15	0.35	0.05	0.05
Sensors	0.34	0.13	0.11	0.37	0.03	0.03
Wiring	0.47	0.19	0.12	0.16	0.03	0.03
Lubrication Oil	0.39	0.17	0.25	0.13	0.03	0.03
Oil Filter	0.39	0.17	0.25	0.13	0.03	0.03
Lubrication Oil Pump	0.45	0.20	0.21	0.07	0.03	0.03
Lubrication Piping	0.42	0.23	0.15	0.13	0.03	0.03

maintenance component	On condition tasks	Scheduled restoration	Scheduled discard	Failure finding	Run to failure	One time changes
Air Filter	0.37	0.17	0.28	0.10	0.04	0.04
Lubrication Valve	0.43	0.18	0.18	0.14	0.04	0.04
Internal Fan	0.47	0.24	0.18	0.05	0.03	0.03
External Fan	0.45	0.23	0.19	0.06	0.04	0.04
Heat Exchanger	0.42	0.23	0.15	0.13	0.03	0.03
Cooling Valve	0.43	0.18	0.18	0.14	0.04	0.04

Tab. 9. Local scores based on cost of the component

maintenance component	On condition tasks	Scheduled restoration	Scheduled discard	Failure finding	Run to failure	One time changes
Stator	0.09	0.04	0.07	0.17	0.32	0.32
Rotor	0.09	0.04	0.07	0.17	0.32	0.32
Radial Bearing	0.09	0.04	0.06	0.17	0.32	0.32
Control Unit	0.13	0.06	0.07	0.09	0.33	0.33
Monitoring	0.11	0.06	0.07	0.09	0.34	0.34
Sensors	0.16	0.08	0.10	0.06	0.30	0.30
Wiring	0.13	0.06	0.07	0.09	0.33	0.33
Lubrication Oil	0.13	0.06	0.04	0.16	0.31	0.31
Oil Filter	0.13	0.06	0.04	0.16	0.31	0.31
Lubrication Oil Pump	0.13	0.06	0.04	0.16	0.31	0.31
Lubrication Piping	0.12	0.04	0.06	0.17	0.30	0.30
Air Filter	0.13	0.06	0.04	0.16	0.31	0.31
Lubrication Valve	0.12	0.04	0.06	0.17	0.30	0.30
Internal Fan	0.09	0.04	0.07	0.17	0.32	0.32
External Fan	0.10	0.05	0.07	0.17	0.31	0.31
Heat Exchanger	0.12	0.04	0.06	0.17	0.30	0.30
Cooling Valve	0.12	0.04	0.06	0.17	0.30	0.30

Tab. 10. Global scores of maintenance strategies for each component

maintenance component	On condition tasks	Scheduled restoration	Scheduled discard	Failure finding	Run to failure	One time changes
Stator	0.46	0.16	0.12	0.09	0.09	0.09
Rotor	0.44	0.16	0.12	0.09	0.1	0.1
Radial Bearing	0.34	0.13	0.18	0.1	0.13	0.13
Control Unit	0.18	0.07	0.08	0.14	0.27	0.27
Monitoring	0.14	0.07	0.09	0.14	0.28	0.28
Sensors	0.2	0.09	0.1	0.12	0.25	0.25
Wiring	0.18	0.08	0.08	0.1	0.28	0.28
Lubrication Oil	0.22	0.09	0.11	0.15	0.21	0.21
Oil Filter	0.22	0.09	0.11	0.15	0.21	0.21
Lubrication Oil Pump	0.17	0.07	0.06	0.15	0.27	0.27
Lubrication Piping	0.22	0.1	0.09	0.16	0.21	0.21
Air Filter	0.21	0.09	0.12	0.14	0.22	0.22
Lubrication Valve	0.23	0.09	0.1	0.16	0.21	0.21
Internal Fan	0.37	0.19	0.15	0.08	0.11	0.11
External Fan	0.21	0.11	0.11	0.13	0.22	0.22
Heat Exchanger	0.22	0.1	0.09	0.16	0.21	0.21

Cooling Valve	0.23	0.09	0.1	0.16	0.21	0.21

Tab. 11. Final ranking of maintenance strategies using AHP and RMCGP

Component	Best Maintenance Strategies
Stator	Scheduled Restoration
Rotor	Scheduled Restoration
Radial Bearing	Scheduled Restoration
Control Unit	Scheduled Restoration
Monitoring	Failure-Finding Task
Sensors	Scheduled Restoration
Wiring	Scheduled Restoration
Lubrication Oil	Scheduled Restoration
Oil Filter	Scheduled Restoration
Lubrication Oil Pump	Scheduled Restoration
Lubrication Piping	Scheduled Restoration
Air Filter	Scheduled Restoration
Lubrication Valve	Scheduled Restoration
Internal Fan	Scheduled Restoration
External Fan	Scheduled Restoration
Heat Exchanger	Scheduled Restoration

6. Conclusion

This study aims to choose best strategy of maintenance based on risk and cost criteria for electric motor's components in National Iranian Oil Products Distribution Company. The selection strategy is designed based on SAE JA1012 and SAE JA1011 that are main references of RCM. The sensitive and important electric motor's components include 17 parts based on ISO 14224. This is a reference standard for oil, gas and petrochemical data gathering. Then optimization approach by combining AHP and RMCGP has been offered. In this approach, AHP is used to determine weight for criteria based on pair-wise comparisons. Then, for each goal function (risk and cost), acceptance level is determined by decision maker and RMCGP is used to minimize deference from acceptance level. Result shown that Scheduled Restoration is the most suitable maintenance strategy for most of components.

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