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Research Article

Evaluation of Maintenance Policies Using Taguchi Loss Functions and Analytical Hierarchy Process

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Abstract

The existence of a company in today's highly automated production environment largely depends on the high availability rates of production machines. High machine availability rates can only be achieved by applying suitable maintenance policies. Determination of a suitable maintenance policy requires the consideration of many factors. In this study, a new methodology integrating Analytical Hierarchy Process (AHP) and Taguchi loss functions was developed for the determination of the most suitable maintenance policy. This methodology represents the first use of Taguchi loss functions for maintenance policy evaluation and the use of these functions ensured the consideration of tangible and intangible maintenance policy evaluation criteria. Applicability and effectiveness of the developed methodology was justified by determining the most suitable maintenance policy for the coating machines of a powder coating factory.

Keywords: Analytical Hierarchy Process, Maintenance Policy, Taguchi Loss Functions.

1. Introduction

Maintenance involves all actions appropriate for retaining an item/part/equipment in, or restoring it to, a given condition [1]. In the past, maintenance was seen as a "necessary evil" [2]. However, in today's highly automated manufacturing environments, higher availability of machines can only be achieved through the effective implementation of appropriate maintenance policies. Hence, maintenance planning is a critical function directly impacting the profitability of a company.

There are three fundamental maintenance policies: breakdown, preventive and predictive. The most commonly used maintenance policy is breakdown maintenance which involves the repair of a machine when the machine breaks down. In preventive maintenance, machines are stopped periodically and maintenance operations are carried out at predefined points on the machine. Predictive maintenance involves the planning of maintenance operations based on the measurements taken from the different parts of a machine.

The success of maintenance activities largely depends on the implementation of the most suitable maintenance policy. There are many factors (training costs, production loss costs, applicability etc.) that have to be considered while determining the most suitable maintenance policy for a machine. The multi-criteria nature of maintenance policy evaluation problem stimulated the use of multi criteria decision making (MCDM) techniques in the literature [3]. The methodology proposed by Arunraj and Maiti [4] integrated AHP and GP (Goal Programming) and considered two criteria: risk of equipment failure and cost of maintenance. Zaim, et al. [5] developed an integrated methodology based on AHP and ANP (Analytical Network Process). The criteria considered include added value, cost, safety and implementation. Emovon, et al. [6] proposed an integrated Delphi-AHP-Promethee methodology. First, Delphi is used to screen the criteria. Then criteria weights are determined using AHP. Finally, Promethee ranks alternative maintenance policies. We refer the interested reader to a recent review paper by Shafiee [3] for a comprehensive overview of MCDM methodologies developed for the evaluation of alternative maintenance policies.

Besides MCDM techniques, various other Industrial Engineering-Operations Research (IE/OR) techniques were employed in maintenance policy evaluation studies. Braglia, et al. [7] used integer programming in order to allocate maintenance budget to four alternative maintenance policies. The methodology developed by Gupta, et al. [8] employed a time-based quality control chart which monitors the failure process of the component or the system under investigation. An appropriate maintenance policy was proposed by analyzing the patterns observed in the control chart. Carazas and Souza [9] used risk analysis methods in order to determine the most suitable maintenance policy for an equipment installed in a thermal plant. The interested reader is referred to a recent review paper by Ding and Kamaruddin [10] for further information on the IE/OR techniques employed in maintenance policy evaluation studies.

In this study, we propose a maintenance policy evaluation methodology based on the integration of AHP and Taguchi loss functions. First, the relative weights of maintenance policy evaluation criteria are determined using AHP. Then, Taguchi loss functions are employed in order to calculate the loss values

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associated with each maintenance policy. Finally, the weighted Taguchi loss value of each policy is calculated by using criteria weights and loss values.

To the best of authors' knowledge, this methodology is the first application of Taguchi loss functions to maintenance policy evaluation problem. The main advantage provided by Taguchi Loss Functions is their ability of modeling intangible maintenance policy evaluation criteria such as applicability. In Taguchi loss functions, a decision maker can express his/her preferences by defining target values, ranges and specification limits for tangible and intangible criteria. In addition, the use of AHP in weight determination process allows decision makers to make more transparent and consistent comparisons among the evaluation criteria.

The rest of the paper is organized as follows. Section 2 presents the working mechanism of the proposed methodology and provides brief information on the techniques employed in the methodology. A case study involving the application of the proposed methodology to a maintenance policy evaluation problem faced by a powder coating factory is presented in Section 3. Conclusions and future research directions are discussed in Section 4.

2. Proposed Maintenance Policy Evaluation Methodology

The steps of the proposed maintenance policy evaluation methodology are given in Figure 1. First, alternative maintenance policies and maintenance policy evaluation criteria are determined. Then, weights of the criteria are calculated using AHP. Next, loss values of alternative maintenance policies are calculated using Taguchi loss functions. Finally, weighted loss values are calculated and the policy with the lowest weighted loss value is proposed as the most suitable maintenance policy. The following subsections give brief information on AHP and Taguchi loss functions.

2.1. AHP

AHP is an MCDM method developed by Saaty [11]. In AHP, a hierarchical structure is employed in order to define a decision problem. The first level of AHP hierarchy involves the goal of the decision problem. The criteria are placed in the second level and the alternatives are considered in the third level.

Following the construction of the decision hierarchy, AHP follows a two-step solution methodology. In the first step, the pair-wise comparison of the criteria is carried out using the scale given in Table 1. Criteria weights are obtained by applying a suitable method (e.g., Eigen value method) to the pair-wise comparison matrix. The second step involves the pair-wise comparison of decision alternatives for each criterion. The mathematical techniques mentioned in step 1 are employed in order to determine the importance weights of decision alternatives.

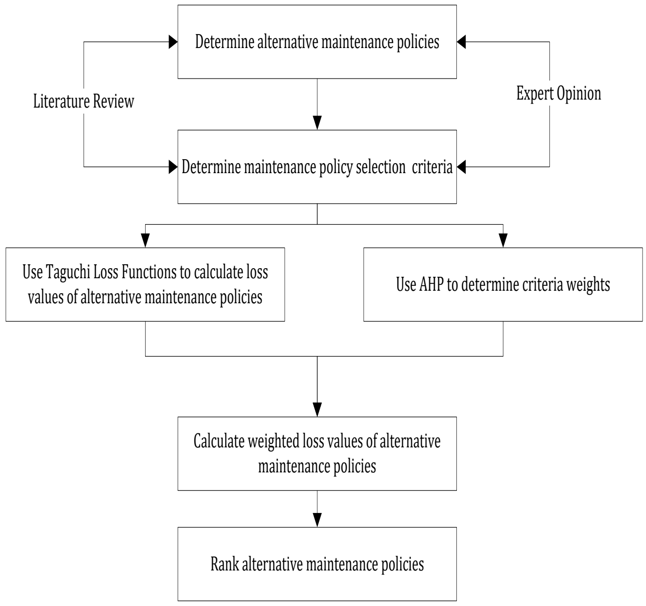

Figure 1: Working mechanism of the proposed methodology

Table 1: Pair-wise comparison scale

Intensity of Importance	Definition
1	Equally important
3	Moderately more important
5	Strongly important
7	Very strongly more important
9	Extremely more important
2,4,6,8	Intermediate judgment values

The consistency level of pair-wise judgments must be checked by calculating a consistency ratio (*CR*) as follows:

$$CR = \frac{(\lambda_{\max} - N)}{(N-1)R} \qquad (1)$$

where $\lambda_{\max}$ is the principal Eigen value of the comparison matrix, *N* is the number of rows (or columns) in the matrix and *R* is the random index value for each *N* value. *R* value is determined using Table 2. The comparison matrix has an acceptable level of consistency if the *CR* value is less than 0.1.

Table 2: *R* values

N	3	4	5	6	7	8	9	10
R	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

2.2. Taguchi Loss Functions

In traditional quality control, a product is accepted if it meets pre-defined specification limits. Instead of using rigid specification limits, the loss functions developed by Taguchi [12] employ the "loss" concept. In loss functions, no loss occurs if the value of a performance measure is equal to the target value. However, a loss will occur if the value of the performance measure deviates from the target value. A quadratic function is employed in order to measure the loss [13].

Although there are many loss functions proposed by Taguchi, the following three loss functions are generally preferred in the literature: "target is the best", "lower is better" and "higher is better". The graphs associated with these functions are provided in Figures 2 through 4. Equations 2 through 4 present the loss equations.

"Target is the best" loss function:

$$Loss_x = c(x-t)^2 \quad (2)$$

"Lower is better" loss function:

$$Loss_x = c(x)^2 \quad (3)$$

"Higher is better" loss function:

$$Loss_x = c/(x)^2 \quad (4)$$

where c is the loss coefficient, t is the target value and $Loss_x$ is the loss value associated with a particular value of characteristic x.

2.3. Calculation of Weighted Taguchi Losses

Following the determination of Taguchi losses and criteria weights, the following equation is employed for the calculation of weighted Taguchi losses [14]:

$$WL_j = \sum_{i=1}^{n} w_i \cdot x_{ij} \quad (5)$$

where WL_j is the total weighted Taguchi loss of maintenance policy j for all maintenance policy evaluation criteria, w_i is the weight of criterion i and x_{ij} is the Taguchi loss of maintenance policy j for criterion i.

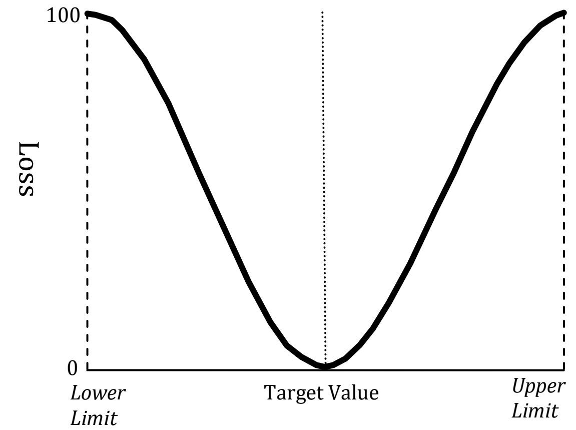

Figure 2: Target is the best loss function

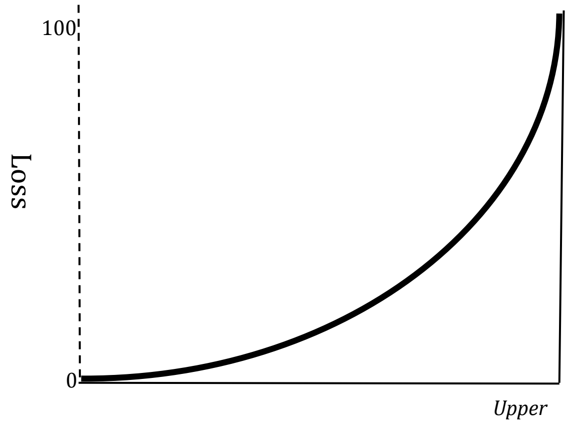

Figure 3: Lower is better loss function

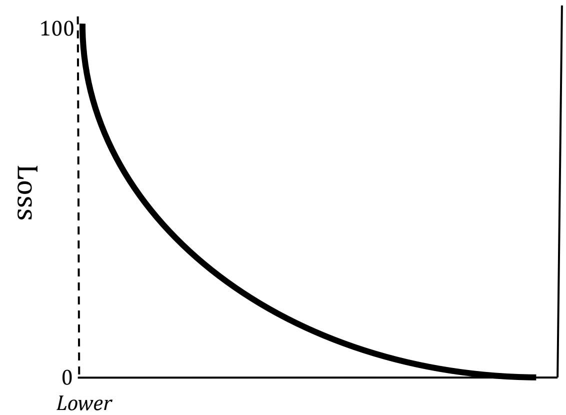

Figure 4: Higher is better loss function

3. Evaluation of Maintenance Policies for a Powder Coating Factory

The proposed methodology was applied to solve the maintenance policy evaluation problem of a powder coating factory located in Manisa. In particular, the most suitable maintenance policy for the powder coating machines of the factory were determined by considering three fundamental maintenance policies, namely breakdown maintenance (*BRM*), preventive maintenance (*PRM*) and predictive maintenance (*PDM*). The maintenance policy evaluation criteria presented in Table 3 were used based on the literature review and the opinions of the experts working in the factory:

Table 3: Maintenance policy evaluation criteria

Criteria	References
Training Costs	[6];[15]
Production Loss Costs	[6];[15];[16];[17]
Applicability	[5];[6];[15]
Safety	[5];[6];[15];[16];[18];[17]
Hardware and Software Costs	[6];[15]
Spare Part Costs	[6];[15]

Training costs (TC) involve all costs associated with the training of maintenance personnel on maintenance procedures, tools, hardware and software. Due to the use of high-technology measurement devices, training costs of *PDM* policy are expected to be higher. *Production Loss Costs (PLC)* is the cost of production losses due to machine breakdowns. In *BRM*, this cost will be higher since this maintenance policy involves the repair of a machine when the machine breakdowns. *Applicability* (*A*) represents the possibility of implementing a maintenance policy. Since the current maintenance policy applied to all coating machines is *BRM*, this policy has the highest applicability. *Safety (S)* is the safety level provided by a maintenance policy. Safety level of *BRM* is expected to be lower since this maintenance policy involves the repair of a machine when a problem occurs. *Hardware and software costs (HSC)* involve the costs associated with the hardware and software required for maintenance activities. This cost will be higher in *PDM* due to hardware and software required for the continuous monitoring of machine condition. *Spare Part Costs (SPC)* involves all costs associated with spare part inventories. *BRM* has generally higher spare part costs. Since there is no planned maintenance activity in this policy, spare part inventory levels cannot be controlled effectively. Instead, spare part inventory levels are kept at maximum in order to deal with any emergent situation which may be the breakdown of several machines at the same time.

3.1. Determination of Criteria Weights Using AHP

The criteria weights were determined using AHP. The pair-wise comparison matrix of maintenance policy evaluation criteria given in Table 4 was obtained based on the opinions of the experts working in the factory. The criteria weights presented in Table 5 were obtained by employing the Eigen value method. It must be noted that *CR* value associated with the pair-wise comparison matrix is 0.02. There is no inconsistency associated with the pair-wise comparisons since the *CR* value is less than 0.1.

Table 4: Pair-wise comparison matrix of evaluation criteria

	TC	PLC	A	S	HSC	SPC
TC	1	1/2	1/4	1/3	2	3
PLC	2	1	1/3	1/2	3	4
A	4	3	1	2	5	6
S	3	2	1/2	1	4	5
HSC	1/2	1/3	1/5	1/4	1	2
SPC	1/3	1/4	1/6	1/5	1/2	1

Table 5: Criteria weights

Criteria	Weight
TC	0.101
PLC	0.160
A	0.382
S	0.250
HSC	0.064
SPC	0.043

3.2. Calculation of Loss Values of Maintenance Policies Using Taguchi Loss Functions

"Lower is better" Taguchi loss function was used for cost-related criteria (viz., *TC*, *PLC*, *HSC* and *SPC*). The other two criteria (viz., *A* and *S*) were modeled using "Higher is Better" Taguchi loss function. Target values, ranges and specification limits were determined for each criterion based on the opinions of the experts working in the factory (See Table 6).

Criteria values for each maintenance policy are provided in Table 7. The values of cost-related criteria are determined based on a scale of 1-10, 10 being the highest cost. The values of two other criteria were expressed in percentages.

Table 6: Target values, ranges and limits for the criteria

Criteria	Target Value	Range	Specification Limit
TC	Lowest	1-6	6 or higher
PLC	Lowest	1-3	3 or higher
A	100%	40%-100%	40% or lower
S	100%	70%-100%	70% or lower
HSC	Lowest	1-5	5 or higher
SPC	Lowest	1-4	4 or higher

Table 7: Criteria values for each maintenance policy

Policy	TC	PLC	A	S	HSC	SPC
BRM	4	9	100%	20%	3	6
PRM	6	6	80%	70%	4	4
PDM	8	3	50%	90%	8	2

Prior to the calculation of Taguchi loss values, loss coefficients must be determined. Specification limits given in Table 6 are used while calculating the loss coefficients. The calculation steps can be expressed for the criterion "Applicability (*A*)"as follows. According to Table 6, when the applicability of a maintenance policy is 40%, the loss will be 100% or 1. Based on this information, the loss coefficient can be obtained using Equation 4 as follows:

$$1 = k / (0.4)^2 \Rightarrow k = 0.16$$

The loss coefficients for *TC*, *PLC*, *S*, *HSC* and *SPC* are 0.027778, 0.111111, 0.49, 0.04 and 0.0625, respectively. Taguchi losses of alternative maintenance policies calculated using equations 3 and 4 are presented in Table 8.

Table 8: Taguchi losses of alternative maintenance policies

Policy	TC	PLC	A	S	HSC	SPC
BRM	0.44	9	0	12.25	0.36	2.25
PRM	1	4	0.25	1	0.64	1
PDM	1.78	1	0.64	0.61	2.56	0.25

3.3. Calculation of Weighted Taguchi Loss Value for Each Maintenance Policy

Weighted Taguchi loss values of alternative maintenance policies were calculated using Equation 5 (see Table 9). For instance, the weighted Taguchi loss value of preventive maintenance policy was calculated as follows:

$$WL_{PRM} = 0.101 \cdot 1 + 0.160 \cdot 4 + 0.382 \cdot 0.25 + 0.250 \cdot 1 + 0.064 \cdot 0.64 + 0.043 \cdot 1$$

$$WL_{PRM} = 1.17046$$

According to Table 9, the maintenance policy with the lowest weighted Taguchi loss value is *PDM* policy. Hence, this policy is proposed as the most suitable maintenance policy. If the company has financial difficulties in providing necessary education and equipment for *PDM*, *PRM* with the second lowest weighted Taguchi loss value can be implemented. The implementation of *PRM* policy will be less costly due to its lower training and software-hardware costs. The firm currently implements *BRM* policy for the coating machines. However, this policy has a very high weighted loss value and it may create safety problems like explosions or fires. That is why the company should certainly avoid implementing this maintenance policy.

Table 9: Weighted Taguchi losses of maintenance policies

Policy	Weighted Taguchi Loss
BRM	4.66673
PRM	1.17046
PDM	0.91135

It must be noted that, the integrated maintenance policy evaluation approaches discussed in the introduction section can be applied for the maintenance policy evaluation problem considered in this study. This will provide a comparison of different integrated approaches with the proposed approach, in terms of criteria weights and final evaluation results.

4. Conclusions and Future Research Directions

Higher availability of production machines can only be achieved with the implementation of a suitable maintenance policy. The determination of the most suitable maintenance policy requires the simultaneous consideration of many tangible and intangible factors. In this study, a maintenance policy evaluation methodology integrating AHP and Taguchi Loss Functions was developed. The proposed methodology was used to determine the most suitable maintenance policy for the coating machines of a powder coating company.

The proposed methodology can be applied to the maintenance policy evaluation problems faced by companies operating in other sectors. Different maintenance policy evaluation criteria and different alternative maintenance policies such as condition based maintenance can also be considered in future studies.

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