33rd European Modeling & Simulation Symposium
18th International Multidisciplinary Modeling & Simulation Multiconference

ISSN 2724-0029 ISBN 978-88-85741-57-7 © 2021 The Authors.
doi: 10.46354/i3m.2021.emss.054

A Hybrid Multi-Criteria Decision Model (HMCDM) based on AHP and TOPSIS analysis to evaluate Maintenance Strategy

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Abstract

The aim of the present paper concerns a Hybrid Multi-Criteria Decision Model (HMCDM) to evaluate Maintenance Strategy. In order to improve production performance, in particular system availability and to reduce cost organization, in particular maintenance cost an integrated MCDM approach is proposed. The aim of the proposed method is to suggest the best maintenance solution for industrial systems. The new hybrid model is able to overcame the shortcomings of literature methods, matching Analytic Hierarchy Process (AHP) with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for the evaluation of maintenance policy. The proposed model has been applied in a real case study in a water bottling company. Different maintenance alternatives were considered and different criteria and sub-criteria were evaluated using Reliability, Availability, Maintainability, Safety (RAMS) and production parameters. The outputs suggested the best maintenance solution for all machines in the analyzed company. The results highlight a Maintenance Cost reduction and a System Availability increase of analyzed water bottling company.

Keywords: Maintenance Strategy Selection, AHP, TOPSIS, Water Bottling Industry, Sensitivity Analysis, RAMS.

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1. Introduction

This paper describes an application of the MCDM for selecting the best maintenance strategy in order to increase availability and reduce maintenance cost. The focus of the present research is a hybrid model for maintenance policy developed and implemented in a case study. The aim is to determine the best maintenance strategies, in order to optimize industrial parameters, e.g. availability, production and costs.

Maintenance design is a crucial issue consisting of several activities in order to achieve levels of availability and to guarantee the production capacity. The availability of a production system depends on performance and connections of the machines. For this reason, an industrial plant can be considered as complex system, whose reliability target depends on the performance of its components.

It is particularly difficult to choose the best mix of maintenance policies when this choice is based on preventive elements. Water Bottling Plant is the case study examined in this paper. This plant will have about 130 machines (depalletizer, labeling machine, inspector machine, compressors, pumps, etc) and the management must decide on the maintenance strategy for the different machines. The maintenance management developed an internal method to solve the maintenance problem for the water bottling plant in the start-up phase. It is based on an upgrade of Failure Mode, Effects, and Criticality Analysis. This internal methodology presents some weakness, i.e.: dependencies among not objective attributes, all maintenance weights are equal to one, the results are not tested, etc. In order to overcome these limitations, the research proposes a combination of AHP and TOPSIS to select suitable maintenance policy for a water bottling plant. In order to obtain final maintenance alternatives ranking a Sensitivity Analysis has been developed. The result is a MCDM integrated approach to evaluate the best maintenance strategy. This paper is organized as follows: in section 2 and section 3 a literature review regarding maintenance strategies and maintenance approaches is performed. In section 4 in described the As-Is of the water bottling company. AHP and TOPSIS are overviewed in section 5 and 6. In section 7 the proposed model is introduced. The proposed method is validated through a case study in section 8. Results are discussed in section 9 and benefits are identified; a conclusion is offered in section 10.

2. Review of maintenance strategies

This section presents a review of maintenance strategies, using MCDM models. In view of the great popularity of this issue and the increasing need for maintenance activities improvement, attention was paid to the maintenance strategies concepts using MCDM models.

AHP has been used as a multi-criteria tool by most of the authors, either independently or in combination with other approaches. Bevilacqua and Braglia [1] used AHP for maintenance selection in an Italian oil refinery. These authors classified over 200 machines in a gas plant into three homogeneous groups and used AHP to analyze alternative maintenance strategies for each group. Bertolini and Bevilacqua [2] proposed a combined goal program and AHP for maintenance selection of centrifugal pumps in the oil industry. They used AHP analysis to provide priority vector of possible maintenance policies for different types of failure.

Ashraf et al. [3] developed an AHP model for maintenance decision-making, based on downtime, spare parts cost and frequency of breakdowns. However, these authors recommend further work on an efficient approach to specify the most appropriate maintenance action to follow based on different rules. Arunraj and Maiti [4] used AHP and GP for maintenance policy selection according to risk of failure and cost of maintenance in a chemical factory.

W.L. Asharaf [5] developed an AHP model for maintenance policy selection using Computerized Maintenance Management System (CMMS). This research observes the CMMS lack of intelligent decision analysis tools and proposes, to overcome this criticality, a model combining AHP and fuzzy logic control to render a decision making grid which has features of fixed rules and flexible strategies. A. HajShirmohammandi and W.C. Wedly [6] used an AHP model for maintenance management for centralization and decentralization. Centralized systems are maintenance systems are managed from a centrally administered location. However, in decentralized systems each production area manages its own maintenance system. Shyjith et al. [7] developed a model using AHP and TOPSIS, for maintenance selection

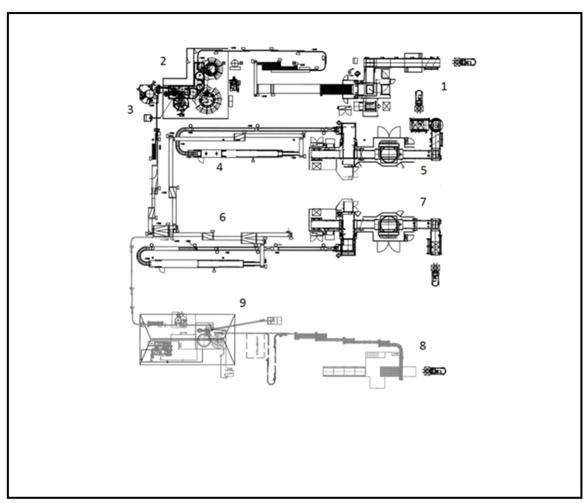

Figure 1. Plant Layout

in textile industry and Zaim et al. [8] proposed the use of AHP and ANP tools to select the most appropriate maintenance strategy for a press industry in Turkey.

The use of GA has been proposed to address the least-cost part replacement problem [9] and Azizollah et al. [10] used the fuzzy Delphi method to select the best maintenance strategy.

Satoshi [11] used simulation approach that enabled robots to undergo preventive maintenance strategy investigated. Hennquin [12] proposed a combination of simulation and fuzzy logic to optimize defective preventive maintenance and remedial steps necessary to be carried out on single pieces of equipment. The reviewed literature shows that AHP has been successfully implemented in maintenance strategy selection. However, no published research matches the influence of RAMS values (i.e MTTF, MTTR, failure modes, failure numbers, detection, etc) with production ones (i.e. flow index, quality product, production cost, production loss, etc) in maintenance strategy selection. Literature methodologies presents some weakness, i.e.: dependencies among not objective attributes, all maintenance weights are equal to one or zero, the help of an Expert Judgement is always present, no link between manintenace and availability, etc. In order to overcome these limitations, the research proposes a combination of AHP and TOPSIS to select suitable maintenance policy. The result is a MCDM integrated approach to evaluate the best maintenance strategy.

3. Maintenance strategies

Five alternative maintenance policies are evaluated in this case, described below.

Corrective Maintenance: Corrective or Failure-based Maintenance (FBM) is unscheduled maintenance or repair to return the machine to a defined state. FBM prescribes activation of maintenance in case of a failure event [13], and no action is taken to detect or to prevent failure [14-15]. FBM is usually the cheapest maintenance strategy.

Preventive Maintenance: Preventive maintenance (or preventative maintenance) is maintenance that is regularly performed on a piece of equipment to lessen the likelihood of it failing [16-17].The main objective of carrying out preventive maintenance (PM) is to reduce frequent and sudden sporadic failures [18-19]. Usually, PM is more expensive than FBM.

Reliability Centered Maintenance: Reliability center maintenance (RCM) is a corporate-level maintenance strategy that is implemented to optimize the maintenance program of a company or facility. RCM was originally designed for the aircraft industry [22-23-24]. RCM costs are similar to an FBM maintenance strategy

Total Productive Maintenance: TPM is an innovative approach that optimizes equipment effectiveness, eliminates breakdowns, and promotes autonomous maintenance by operators. TPM costs are similar to the TQM strategy.

Total Quality Maintenance: Total Quality Maintenance (TQMT) is a model oriented to maintain and continuously improve technical and economic effectiveness of a production process and its elements [20]. TQMT is based on intensive use of real-time data acquisition [21]. Usually TQM is the most expensive maintenance strategy.

4. Maintenance policies in water bottling industry

A water bottling company is considered in order to explore the MCDM to evaluate maintenance strategy. A company with little experience of MCDM methods has been chosen, because as suggested by many authors MCDM practices have been found especially adopted in SME organizations.

The aim of the present activity was to define AS-IS process. For this purpose the lay-out was analyzed. In detail, the layout of plant consists of 9 workstations and 130 machines as shown in Figure 1: Depalletizer (1), One-piece group consisting of rinser / filler / capper (2), Labeling machine (3), Machine Inspector - Bundler 2 (4; 6) and Palletizers 2 (5,7), Depalletizer (8), Machine Inspector (9).
The production process was organized on two lines:

- Line 1. It line fills 1 liter bottles and with a rated speed of 30,000 b/h;
- Line 2. It fills 0.75 liter and 0.5 liter bottles with a rated speed of 15,000 b/h.

The internal methodology developed by the maintenance management to solve the maintenance strategy selection problem for the bottling company plant in the start-up phase is based on "Failure Analysis" which can be considered an upgrade of Failure Mode, Effects, and Criticality Analysis (FMECA) [27, 28, 29]. This analysis takes into account six indexes, described as follows.

(C_1) Flow Index = $\frac{F_i}{F_{tot}}$ (1)

is the technical indicator is intended as a measure of the importance of the unit or the machine to the production process. where: F_i = flow of materials in the machine i-th F_{tot} = flow of materials in the system

(C_2) Time Index = $\frac{\sum_{j=1}^{n} T_{ij}}{\sum_{j=1}^{n}(\sum_{i=1}^{n} TC_i)}$ (2)

is the ratio between the working time of the machine for a unit of product and the cycle time of the product where: $\sum_{j=1}^{n} T_{ij}$ = working time of the machine i-th for a unit of all processing products $\sum_{j=1}^{n}(\sum_{i=1}^{n} TC_i)$ = takt time of the product

(C_3) Maintenance Index = $\frac{Tm_i}{Tm_{tot}}$ (3)

is the ratio between the average number of hours spent in maintenance in the i-th station (Tmi) and the average number of hours of maintenance time, calculated for the unit with the highest maintenance time (Tmmax).

(C_4) Cost Index = $\frac{Cm_i}{Cm_{tot}}$ (4)

is the ratio between the annual cost of maintenance for the i-th unit (Cmi) and total cost of maintenance of the system (Cmtot) in a year.

(C_5) Failure Mode Index = $\frac{Fm_i}{Fm_{tot}}$ (5)

is the ratio between the failure modes occurring in the i-th machine (Fmi) and all the different failure modes (Fmtot) of the plant (in a year).

(C_6) Failure Number Index = $\frac{Fn_i}{Fn_{tot}}$ (6)

is the ratio between the failure numbers occurring in the i-th machine (Fni) and all failure numbers (Fntot) of the plant (in a year).

The six indexes take positive values between 0 and 1. The indexes taken into consideration are linked together in the following Global Maintenance Index (GMI):

$$GMI = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \quad (7)$$

The GMI index has been used to classify about 130 machines in the plant into different groups corresponding to four different maintenance strategies, as shown in Table 1.

Table 1. GMI Maintenance Policy Selection

Criticality Index	Maintenance Policy	Cluster	Machines
>4	Total Quality Maintenance	Group 1	85
3-3.9	Total Productive Maintenance	Group 2	25
2-2.9	Preventive Maintenance	Group 3	17
<2	Corrective Maintenance	Group 4	3

The main features of the four groups are the following:

Group 1: a failure of group 1 machines could have serious consequences in terms of workers' safety and environmental damages (internal and external). In this case, savings in maintenance investments are not advisable.

Group 2: The damages resulting from a failure can be serious but, in general, they do not affect the external environment.

Group 3: The damages derived from a failure can affect the production but not the workers safety and environment

Group 4: The failures are not relevant. The cheapest corrective maintenance is, therefore, the best choice.

Eq (7) is a weighted sum model (WSM) [30,31]. WSM is the best-known and simplest multi-criteria decision analysis Multi-Criteria Decision Making method (MCDM) [32] to evaluate a number of alternatives in terms of a number of decision criteria, where AiWSM is:

$$A_i^{WSM} = \sum_{j=1}^{n} w_j a_{ij} \quad (8)$$

In the above case, there are some weakness:

- dependencies among the seven attributes should be carefully analyzed and discussed;
- all weights are equal to 1 and are not justified in a satisfying manner;
- no sensibility analyses have been conducted to test the robustness of the results.

The GMI results partly satisfy the maintenance staff. This situation has been used as the starting point for development of an AHP approach to improve or confirm the GMI outputs, linking the bottling company maintenance indexes with other reliability/safety ones.

5. AHP and TOPSIS method

The AHP method was developed first by Saaty [34]. It is a powerful and flexible multi-criteria decision-making tool. The top level of the hierarchy is the main goal of the decision problem. The lower levels are the tangible and/or intangible criteria and sub-criteria that contribute to the goal. The bottom level is formed by the alternatives to evaluate in terms of the criteria. The modeling process can be divided into different phases for the ease of understanding which are described as follows:

Establishment of a Hierarchy Structure: define the decision criteria in the form of a tree of objectives.

Establishment of Comparative Judgments: a set of comparison matrices of all elements in a level of the hierarchy with respect to an element of the immediately higher level are constructed. The meaning of each scale measurement is explained in Table 2.

Table 2. Semantics Scale of Saaty

Intensity of importance aij	Definition
1	Equal Importance
3	Moderate importance
5	Strong importance
7	Very strong or demonstrated importance
9	Extreme importance
2,4,6,8	For compromise between the above values

For a general AHP application we can consider that A1, A2,...,Am denote the set of elements, while aij represents a quantified judgment on a pair of Ai, Aj. Through the 9-value scale for pairwise comparisons, these yields an [m x m] matrix where aij > 0 (i, j = 1, 2,..,m), aii = 1 (i = 1, 2,...,m), and aij = 1/aji (1; 2;...,m). A is a positive reciprocal matrix. The result of the comparison is the so-called dominance coefficient aij that represents the relative importance of the component on row (i) over the component on column (j), i.e., aij=wi/wj. The pairwise comparisons can be represented in the form of a matrix. The score of 1 represents equal

importance of two components and 9 represents extreme importance of the component i over the component j.
In matrix A, the problem becomes one of assigning to the m elements A1, A2,...,Am a set of numerical weights w1, w2,...,wm that reflects the recorded judgments. If A is a consistency matrix, the relations between weights wi, wj and judgments aij are simply given by aij = wi/wj (for i,j = 1, 2, ..., m). The measurement of consistency can be evaluated by means of the inconsistency ratio CR. This is imperative aspect of the AHP technique. Briefly, before determining an inconsistency measurement, it is necessary to introduce the consistency index CI of an n £ n matrix defined by the ratio: $CI = \frac{\lambda_{\max} - n}{n-1}$

(9)
where λmax is the maximum Eigen value of the matrix. Then the consistency ratio is calculated using the formula:

CR =CI/RI (10)
where RI is a known random consistency index obtained from a large number of simulations runs and varied depending upon the order of the matrix. Table 3 shows the value of the random consistency index (RI) for matrices of order 1 to 10.

Table 3. RI Values for Different Matrix Orders

n	1	2	3	4	5	6	7	8	9	
RI	0	0	0.58	0.90	1.12	1.24.	1.32	1.41	1.45	

TOPSIS is based on a simple and intuitive concept [35], which is based on choosing the best alternative having the shortest distance from the ideal solution and the farthest distance from the negative ideal solution. The procedure of the TOPSIS is described below.
Determination of the Ideal and Negative Ideal Solutions: the ideal solution (A+) is defined as the best performance score result and negative ideal solution (A-) is determined as the worst performance score result among all alternatives on a criterion:

$$A_J^+ = \{(Max h_{ij}\, j \in J), (Min h_{ij}\, j \in J), i = 1,2.....n\}... \quad (11)$$

$$A_J^- = \{(Min h_{ij}\, j \in J), (Max h_{ij}\, j \in J), i = 1,2.....n\}... \quad (12)$$

Separation of Each Alternative for the Ideal and Negative Ideal Solution: the distance between the two solutions for each alternative are given as:

$$D_i^+ = \sqrt{(\sum_{i=1}^{m}(h_{ij} - h_j^+)^2}\; i = 1,2.....n \quad (13) \quad D_i^- = \sqrt{(\sum_{i=1}^{m}(h_{ij} - h_j^-)^2}\; i = 1,2.....n$$

(14)
where Di+ ,Di- represent the distance between the performance scores of alternatives with respect to all criteria and all ideal and negative ideal solutions respectively.

Calculation of relative closeness to the ideal solution: (15)

$$R_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

where Ri denotes the final performance score in TOPSIS method.

6. HMCDM model for maintenance

An Hybrid Multi-Criteria Decision Model (HMCDM) is proposed to evaluate the best selection of a maintenance policy in order to improve the plant availability, to reduce the number of failures and cost maintenance. The new hybrid model is able to match Analytic Hierarchy Process (AHP) with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for the evaluation of maintenance policy.
The AHP hierarchy developed in this paper is a four-level tree:
Level 1: top level represents the maintenance selection;
Level 2: criteria for maintenance policy selection;
Level 3: sub-criteria;
Level 4: alternatives maintenance strategies
Therefore, the following steps are proposed:
Step 1: Objective or goal definition.
Step 2: RAMS and Production criteria (Ci where i=1...n) and sub-criteria (SCij j=1...m) identification for the goal.
Step 3: Alternative maintenance strategies definition (Ai where i=1....z)
Step 4: Hierarchy framework definition. The definition of the hierarchy scheme should be developed using a brainstorming process. with all the people involved in maintenance problems.
Step 5: Empirical information and data collection (reliability, safety, cost, failure, etc).
Step 6: Pair-wise comparisons for each level of matrix (Cij)=[wij/wji] and matrix (SCij)=[wij/wji], where wij represents a quantified judgment on a pair of criteria/sub-criteria, wij > 0 (i, j = 1, 2,..., m), wij/wij =1 (i = 1, 2,..., m) and wij = 1/ wji (1, 2, ..., m). All AHP matrixes are positive and reciprocal.
Step 7: Consistency test applying eq. (10).
Step 8: Global weights of each criteria and sub-criteria calculation according to Saaty's Scale as follows:

	C_1	C_2	C_3		C_n	Weights
C_1	$\frac{1}{\sum_{i=1}^{n}\frac{w_i}{w_1}}$	$\frac{(w_1/w_2)}{\sum_{i=1}^{n}\frac{w_i}{w_2}}$	$\frac{(w_1/w_3)}{\sum_{i=1}^{n}\frac{w_i}{w_3}}$		$\frac{(w_1/w_n)}{\sum_{i=1}^{n}\frac{w_i}{w_3}}$	$z_1 = \frac{\sum_{i=1}^{n}\frac{(w_1/w_n)}{\sum_{i=1}^{n}\frac{w_i}{w_1}}}{n}$
C_2	$\frac{(w_2/w_1)}{\sum_{i=1}^{n}\frac{w_i}{w_1}}$	$\frac{1}{\sum_{i=1}^{n}\frac{w_i}{w_2}}$	...		...	$z_2 = \frac{\sum_{i=1}^{n}\frac{(w_2/w_j)}{\sum_{i=1}^{n}\frac{w_i}{w_1}}}{n}$
C_3	$\frac{(w_3/w_1)}{\sum_{i=1}^{n}\frac{w_i}{w_1}}$	...	...		...	
....	...	...	...		...	...

C_n	$\frac{(w_n / w_1)}{\sum_{i=1}^{n} \frac{w_i}{w_1}}$	...	...	$\frac{1}{\sum_{i=1}^{n} \frac{w_i}{w_n}}$	$z_n = \frac{\sum_{i=1}^{n} \frac{(w_i / w_j)}{\sum_{i=1}^{n} \frac{w_i}{w_1}}}{n}$
					$\sum_{i=1}^{n} z_i =$

Where $\sum_{i=1}^{n} z_{i1} = 1$ and unit with zi1max it will be the criteria with a higher value of performance. Then the global weights of each criteria and sub-criteria are calculated as follows:

SC_{i1}	$z_i \cdot d_{i1}$
SC_{i2}	$z_i \cdot d_{i2}$
SC_{i3}	$z_i \cdot d_{i3}$
SC_{i4}	$z_i \cdot d_i$
SC_{ij}	$z_i \cdot d_{ij}$
SC_{ij+1}	$z_i \cdot d_{ij+1}$
SC_{im}	$z_i \cdot d_{im}$

Where dij is the local weight of j-subcriteria of i-criteria and $\sum_{i=1}^{m} d_{i1} = 1$ and unit with di1max will be the subcriteria with a higher value of performance. The Global and local Matrix (Table 4) is:

Table 4. Global and Local Matrix

Hierarchy Level	Criteria/Sub-Criteria	Local Weights	Global Weights
Level 2	C_1	z_1	z_1
	C_2	z_2	z_2
	C_i	z_i	z_i
	C_{i+1}	z_{i+1}	z_{i+1}
	C_n	z_n	z_n
Level 3	SC_{11}	d_{11}	$z_1 \cdot d_{i1}$
	SC_{12}	d_{12}	$z_1 \cdot d_{i2}$
	SC_{1h}	d_{1h}	$z_2 \cdot d_{1h}$
	SC_{i1}	d_{i1}	$z_j \cdot d_{i1}$
	SC_{i2}	d_{i2}	$z_j \cdot d_{i2}$
	SC_{if}	d_{if}	$z_n \cdot d_{if}$
	SC_{n1}	d_{n1}	$z_n \cdot d_{n1}$
	SC_{n2}	d_{n2}	$z_n \cdot d_{n2}$
	SC_{ng}	d_{ng}	$z_n \cdot d_{ng}$

Step 9: definition of Aj for j=1 ... .n (for each single goal) and pairwise comparison through Saaty's scale for each criterion Ci for the determination of the related weights. Subsequently, the weights wij of the corresponding alternatives Aj for the considered Ci can be evaluated. Then, the final score WAj(Ci) of each Aj, equal to the sum of the corresponding weights for each Ci is calculated. The weight of an alternative related to a particular criterion, is given by the product of the relative weight of the criterion i and the total weight of the alternative j related to the considered criterion i:

$$WA_j(C_i) = \sum_{i=1}^{z} z_i \times d_i \times w_{ij} \quad (16)$$

The score of each alternative is a measure of the estimated advantages deriving from its adoption.

Applying eq (11), the results are summarized in an Alternative Weight Matrix (table 5).

where wij are weights of ith-alternative for jth-subcriteria, and $\sum_{i=1}^{z} \sum_{j=1}^{m} w_{ij} = m$ (17)

The value WAi is the global priorities for each alternative and

$$\sum_{i=1}^{z} WA_i = 1 \quad (18)$$

Step 10: TOPSIS application to verify AHP outputs.

Step 11: Sensitivity analysis to improve the effectiveness of the AHP methodology.

Step 12: Final ranking of proposed alternatives.

Table 5. *Alternative Weight Matrix*

	SubCr. Weight	A_1	Weight x A_1	A_2	A_z	Weight x A_z
C_1						
SC_{11}	$z_1 \cdot d_{i1}$	w_{11}	$z_1 \cdot d_{i1} w_{11}$	w_{21}	w_{z1}	$z_1 \cdot d_{i1} w_{z1}$
SC_{12}	$z_1 \cdot d_{i2}$	w_{12}	$z_1 \cdot d_{i2} w_{12}$	w_{22}	w_{z2}	$z_1 \cdot d_{i2} w_{z2}$
......	......	.....	....	.....	....	....
SC_{1h}	$z_1 \cdot d_{1h}$	w_{1h}	$z_1 \cdot d_{1h} w_{1h}$	w_{2h}	w_{zh}	$z_1 \cdot d_{1h} w_{zh}$
C_j						
SC_{i1}	$z_j \cdot d_{i1}$	.....	....	.....	.....	....
SC_{i2}	$z_j \cdot d_{i2}$	.....	....	.....	.....	....
......	......	.....	....	.....	.....	....
SC_{if}	$z_n \cdot d_{if}$	w_{1f}	$z_n \cdot d_{if} w_{1f}$	w_{2f}	w_{zf}	$z_n \cdot d_{if} w_{zf}$
C_n						
SC_{n1}	$z_n \cdot d_{n1}$	.....	....	.....	.....	....
SC_{n2}	$z_n \cdot d_{n2}$	.....	....	.....	.....	....
......	......	.....	....	.....	.....	....
SC_{ng}	$z_n \cdot d_{ng}$	w_{1g}	$z_n \cdot d_{ng} w_{1g}$	w_{2g}	w_{zg}	$z_n \cdot d_{ng} w_{zg}$
$\sum_{i=1}^{z}$			$\sum_{i=1}^{z} z_n d_{ng} w_{1g} = WA_1$			$\sum_{i=1}^{z} z_n d_{ng} w_{zg} = WA_z$

7. Case study: maintenance selection policy in a water bottling company

The proposed methodology has been applied to identify the best maintenance selection for each machine of a water bottling plant.

Step 1: The objective of the study is to evaluate and select the most appropriate maintenance policy.

Step 2: Starting from indexes in section 4, in this study reliability measures, production measures, safety measures and maintainability measures were applied as criteria. The criteria and sub-criteria have been defined, following suggestions from the maintenance and production staff of the water bottling plant. The selected RAMS and Production criteria and sub-criteria (table 6) are the following:

Table 6. Maintenance Criteria/Sub-criteria

Criteria	Description	Sub-Criteria	Description
C_1	Reliability		
		SC_{11}	Mean Time to Failure
		SC_{12}	Failure Modes
		SC_{13}	Failure Numbers
C_2	Maintainability		
		SC_{21}	Mean Time to Repair
		SC_{22}	Detection
		SC_{23}	Maintenance Cost
C_3	Safety		
		SC_{31}	People Damage
		SC_{32}	Plant Damage
		SC_{33}	Environmental Damage

C_4	Production		
		SC_{41}	Production Loss
		SC_{42}	Production Quality
		SC_{43}	Production Cost

Table 6 also indicates whether the sub criterion should be maximized or minimized. Thus the number of criteria i=4 and the number of subcriteria is m=3+3+3+3=12.

Step 3: Different maintenance strategies, and strategies have been identified as possible alternatives (table 7).

Table 7. Alternatives Maintenance Policies

Alternatives	**Description**
A_1	Total Quality Maintenance (TQM)
A_2	Total Productive Maintenance (TPM)
A_3	Preventive Maintenance (PM)
A_4	Reliability Centered Maintenance (RCM)
A_5	Corrective Maintenance (FBM)

Step 4: Criteria and sub-criteria were included in a hierarchy structure. According to these reports, more than 4 criteria and 12 sub-criteria have initially been considered. In order to reduce the complexity and the costs of the analysis, the less meaningful parameters were removed, since an increasing number of parameters does not means a higher analysis accuracy.

Step 5: The next phase is measurement and data collection, which involves a team of evaluators. In this study, a group of 8 evaluators were chosen for evaluating the selected criteria and sub criteria. Three evaluators were chosen from academia and five from industry.

Step 6: Evaluators were asked to carefully compare criteria of each hierarchy level by assigning relative scales according to the objective of the proposed model. Thanks to Saaty's Scale a pair-wise comparison for each machine has been performed. The following matrix gives an example of pair-wise comparison of a depalletizer machine:

	C1	C2	C3	C4
C1	1	5	4	$\frac{1}{2}$
C2	$\frac{1}{5}$	1	$\frac{1}{3}$	$\frac{1}{5}$
C3	$\frac{1}{4}$	3	1	$\frac{1}{4}$
C4	2	5	4	1
$\sum_{i=1}^{n} \frac{w_i}{w_j}$	$\frac{69}{20}$	14	$\frac{28}{3}$	$\frac{39}{20}$

Step 7: In this step the consistency of each pair of criteria is examined. Applying Eq. (10), the consistency ratio (CR) is used to check if a criterion can be used for decision-making. In the example the CR is less than 10 percent.

Step 8: Subsequently, criteria weights are evaluated (zi). Depalletizer machine weights are:

	C1	C2	C3	C4	Weights
C1	$\frac{20}{69}$	$\frac{5}{14}$	$\frac{3}{7}$	$\frac{10}{39}$	z1=0.333
C2	$\frac{4}{69}$	$\frac{1}{14}$	$\frac{1}{28}$	$\frac{4}{39}$	z2=0.067
C3	$\frac{5}{69}$	$\frac{3}{14}$	$\frac{3}{28}$	$\frac{5}{39}$	z3=0.130
C4	$\frac{40}{69}$	$\frac{5}{14}$	$\frac{3}{7}$	$\frac{20}{39}$	z4=0.470

The Global and Local Matrix is showed in Table 8.

Table 8. Global and Local Matrix for Depalletizer Machine

Hierarchy Level	**Criteria/Sub-Criteria**	**Local Weights**	**Global Weights**
Level 2	C_1	0.333	0.333
	C_2	0.067	0.067
	C_3	0.130	0.130
	C_4	0.470	0.470
Level 3	SC_{11}	0.320	0.107
	SC_{12}	0.450	0.150
	SC_{13}	0.230	0.077
	SC_{21}	0.480	0.032
	SC_{22}	0.450	0.030
	SC_{23}	0.070	0.005
	SC_{31}	0.480	0.062
	SC_{32}	0.450	0.059
	SC_{33}	0.070	0.009
	SC_{41}	0.250	0.118
	SC_{42}	0.260	0.122
	SC_{43}	0.490	0.230

Step 9: In order to obtain an alternative matrix, all alternative weights wij are multiplied by the global weights of the single sub-criteria. Applying Eq. (16-17-18), the Alternative Matrix for the Depalletizer machine is showed in table 9.

For the considered machine the most expensive maintenance policy (TQM) is highly preferable to other strategies (A1=0,401) because depalletizer machines are very important for the production process. In fact, C4 production criteria (z4= 0.470) and SC43 ($z4 \cdot d43$= 0,230) production cost sub-criteria are the highest weight values.

The following table (table 10) shows the final ranking vector for five machines that represent an example for each alternative.

Table 9 – Alternative Matrix for the Depalletizer machine

Criteria	SubCriteria Weights		A_1	Weights x A_1	A_2	Weights x A_2	A_3	Weights x A_3	A_4	Weights x A_4	A_5	Weights x A_5
C_1	SC_{11}	0.320	0.450	0.048	0.230	0.025	0.190	0.020	0.120	0.013	0.010	0.001
	SC_{12}	0.450	0.354	0.053	0.345	0.052	0.150	0.022	0.110	0.016	0.041	0.006
	SC_{13}	0.230	0.235	0.018	0.450	0.034	0.260	0.020	0.020	0.002	0.035	0.003
C_2	SC_{21}	0.480	0.450	0.014	0.230	0.007	0.190	0.006	0.120	0.004	0.010	0.000
	SC_{22}	0.450	0.560	0.017	0.210	0.006	0.120	0.004	0.100	0.003	0.010	0.000
	SC_{23}	0.070	0.230	0.001	0.420	0.002	0.310	0.001	0.010	0.000	0.030	0.000
C_3	SC_{31}	0.480	0.354	0.022	0.345	0.022	0.150	0.009	0.110	0.007	0.041	0.003
	SC_{32}	0.450	0.430	0.025	0.330	0.019	0.150	0.009	0.010	0.001	0.080	0.005
	SC_{33}	0.070	0.235	0.002	0.450	0.004	0.260	0.002	0.020	0.000	0.035	0.000
C_4	SC_{41}	0.250	0.354	0.042	0.345	0.041	0.150	0.018	0.110	0.013	0.041	0.005
	SC_{42}	0.260	0.430	0.053	0.220	0.027	0.150	0.018	0.150	0.018	0.050	0.006
	SC_{43}	0.490	0.460	0.106	0.210	0.048	0.120	0.028	0.100	0.023	0.110	0.025
	$\sum_{i=1}^{z}$			0.401		0.287		0.158		0.100		0.054

Table 10. Final Ranking Alternatives

Machine	TQM	TPM	PM	RCM	FBM
Depalletizer	0.401	0.287	0.158	0.100	0.054
Compressor	0.141	0.489	0.214	0.130	0.026
Pump	0.170	0.305	0.435	0.080	0.010
Inspector Machine	0.150	0.110	0.180	0.510	0.050
Palletizer	0.165	0.213	0.166	0.115	0.341

Applying the AHP methodology for all machines in the water bottling plant the **results are given in Table 11:**

Table 11. AHP Maintenance Policy selection

Maintenance Policy	Cluster	Machines (GMI)	Machines (AHP)	Δ machines
TQM	Group 1	85	70	-15
TPM	Group 2	25	21	-4
PM	Group 3	17	16	-1
RCM	Group 4	0	13	+13
FBM	Group 5	3	10	+7

As shown, the AHP methodology results generally confirm the GMI. The difference between AHP and GMI refers to 20 machines. AHP suggests adopting economic maintenance (RCM and FBM) for these machines. The obtained results have been considered scientifically and economically robust for the maintenance plant staff. In any case, AHP results are considered as an initial best solution for maintenance design during the start-up phase of the water bottling plant.

Step 10: By applying Eq. (11-12-13-14-15), the computed distance between ideal solution and negative ideal solution for each maintenance policy of depalletizer machine and the relative closeness are showed in table 12:

Table 12. TOPSIS Results of Depalletizer Machine

	TQM	TPM	PM	RCM	FBM
D+	0.017	0.069	0.102	0.117	0.129
D-	0.129	0.083	0.038	0.022	0.005
R	0.886	0.547	0.273	0.160	0.036

AHP outputs of ring frame are validated: TQM alternative is the best maintenance solution for TOPSIS analysis too. AHP outputs are equal to TOPSIS analysis for 123 machines of water bottling plant.

Step 11: In order to validate the best maintenance strategies coming from AHP-TOPSIS methodology, a sensitivity analysis has been developed. The aim of sensitivity analysis is to explore how these changes can affect the priorities of the selected alternatives. According Expert Judgment of water bottling company, the analysis concerns the priorities of the four criteria (Ci) in the AHP model and criteria weights have been increased by approximately 30 percent one by one (consequently the other three criteria were decreased by approximately 10 percent), determining four different scenarios. Sensitivity Analysis has been developed for the depalletizer machine. The TQM strategy remains the best solution for the depalletizer machine in the four scenarios. Only when the priority of C1 or C3 increases to 80%, does the alternative final ranking change. The same sensitivity situation is almost the same for machines of Group 1.

For several machines of Group 2 the final solution is less stable. For 5 machines of Group 2 the final ranking changes to the TQM strategy, but this is not an important problem because the TQM cost and TPM cost are very similar.

For machines of Group 3 and Group 4 the final solution is quite robust (for 3 machines of Group 3 and 5 machines of Group 4 the alternative changes). For 10 machines of Group 5 the final solution is not stable: for 7 machines it changes to the RCM strategy and for 3 machines it changes to the PM strategy.

Step 12: In the case of significant variations in terms of alternative priority (more than 30 percent) coming out from step 11, the maintenance policies are changed according to sensitivity analysis results. Finally, the final maintenance solutions are summarized in table 13:

Table 13. Final Maintenance Solution

Maintenance Policy	Cluster	Machines (AHP-TOPSIS)	Machines (Sensitivity)
TQM	Group 1	70	78
TPM	Group 2	21	24
PM	Group 3	16	10
RCM	Group 4	13	12
FBM	Group 5	10	6

8. Results and discussion

The results obtained through the proposed method show a reduction in the number of machines in Clusters 1-2-3-5 and an increase in Cluster 4 (+12 machines), based on the RCM maintenance solution. This choice was not taken into consideration by the company management as it was considered similar to the FBM solution, in terms of costs and performance. As described in Section 3, the RBM solution allows an increase in availability (reducing plant downtime due to unexpected failures) with a slightly higher cost than the FBM solution (failure maintenance). The solution obtained in Table 14 was implemented in the Water Bottling Plant at the beginning of 2019.
The outputs of the analyzed clusters were:
- Total Maintenance Cost for the j-th cluster (Ctotj) where j=1...5; and
- Average availability for the j-th cluster (Amj) where j=1...5;
where:

$$Ctot_j = C_j \cdot n_j \quad (16)$$

Cj: Average maintenance cost for machines of j-th cluster
nj: number of machines of j-th cluster

$$Am_j = \frac{\sum_{i=1}^{n} A(t)_i}{n} \quad (17)$$

$$A(t)_i = \frac{\sum MTTF}{\sum MTTF + \sum MTTR} \quad (18)$$

availability of i-th machine
The outputs are summarized in Table 15:

Table 15 – Maintenance Outputs 2019

Maintenance Policy	Cluster	Ci	Sol. 2019	$Ctot_{cluster}$ 2019	$Am_{cluster}$ 2019
TQM	Group 1	€ 16000	78	€ 1248000	0.865
TPM	Group 2	€ 12000	24	€ 288000	0.925
PM	Group 3	€ 6000	10	€ 60000	0.845
RCM	Group 4	€ 4500	12	€ 54000	0.890
FBM	Group 5	€ 4000	6	€ 24000	0.799
				€ 1674000	$A(t)_s$=0.859

Where $A(t)_s = \frac{\sum_{j=1}^{5} Am_j \cdot n_j}{150}$ is the average weighted availability of the system considering, for the benefit of safety, a series configuration of the machines belonging to the 5 clusters.
The 2019 results were compared with those obtained in 2018 by the company applying the GMI methodology.
The proposed methodology has allowed an estimated saving of about € 100000, equal to 5.70% of the maintenance budget. These results were obtained through the redistribution of the machines in the five maintenance clusters through the use of decision making techniques,
This involved:
- 10% reduction in costs in 1-2-3 clusters;
- 40% reduction in costs in cluster 3;
- 50% reduction in costs in cluster 5;
- approximately 2.30% increase in the average weighted availability of the plant which, considering a production year equal to 365 days, is equivalent to a productivity increase of 9 days (approximately 2 working weeks in a year).

9. Conclusion

During the start-up phase, maintenance strategy selection is very difficult due to low data collections. In order to overcome these difficulties and give decision support to management staff an AHP-TOPSIS model is proposed and developed to select the best maintenance strategies. The proposed approach has been implemented and tested in a water bottling industry.
Five maintenance alternatives were considered: FBM, RCM, PM, TPM and TQM and four RAMS and Production Criteria were used: reliability, maintainability, safety and production. The combined AHP-TOPSIS model was applied in two subsequent steps: the first part of the analysis provided the ranking of the five maintenance alternatives. Considering the subjective evaluation of AHP weights, in the second part of the analysis a TOPSIS methodology is developed to revise AHP outputs. To ensure a stable and robust final solution, a sensitivity analysis was performed. Thanks to the sensitivity analysis, AHP-TOPSIS outputs were revised in order to improve manufacturing performance.
Thanks to the generality of RAMS and Production features, the proposed technique can be used by all types of company to select maintenance strategies with higher impact on maintenance and production performances.
The comparison with internal method GMI shows that:
System availability was increased during the 2019 (+2.30%)
Maintenance costs were reduced during 2019 (-5.70%)

Production days were increased during 2019 (+9 days);
The results highlight how the proposed method is both accurate and realistic.
Future research developments will be directed toward:
- testing the method on other production systems;
- identification of new criteria and sub-criteria that better characterize the machines (failure times, inspection times, series/parallel systems, etc.).

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