A risk evaluation framework for the best maintenance strategy: the case of a marine salt manufacture firm

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Abstract. This paper intends to contribute with a multi-criteria decision-making (MCDM) framework to support risk evaluation for maintenance activities carried out on critical systems in industry. We propose to first select the best maintenance strategy tailored to companies' requirements and systems' features, and second to perform a risk prioritisation aimed at highlighting priorities of intervention. The Analytic Network Process (ANP) is suggested to select the maintenance policy representing the best trade-off considering the complex and varied interdependencies among a diversity of clustered elements characterising the system. Then, the main risks related to the interventions associated to the selected maintenance policy are ranked using the ELimination Et Choix Traduisant la REalité III (ELECTRE III) method, using the same criteria weighted by the previous ANP application. This hybrid MCDM framework is applied to a core subsystem of a real-world marine salt manufacture firm.

Keywords: Maintenance policy selection, risk evaluation, ANP, ELECTRE III

1. Introduction and research objectives

The standard BS EN 13306:2010 defines maintenance as the combination of technical and organisational activities aimed at guaranteeing systems' functioning during their whole life cycle, in terms of retaining them in (or restoring them to) a state in which they can perform their required tasks. The importance companies attribute to the maintenance function has been increasing since the beginning of the industrial era, having nowadays achieved the connotation of key factor in improving productivity by reducing the breakdown risk at a reasonable cost.

Effectiveness of industrial production, especially in the case of continuous production systems (Özcan et al., 2019), directly depends on maintaining expensive and technically complex capital goods in a functioning state. This is the reason why several companies decide to allocate huge budgets on maintenance management, sometimes reaching a 70% of the total production cost (Ilangkumaran and Kumanan, 2012). Undeniably, maintenance should not be considered a mere cost-centred activity (Sharma et al., 2011). On the contrary, using a wider perspective, it is a profit-generating function that should be considered with foremost priority by companies willing to achieve high levels of asset performance (Fouladgar et al., 2012). Given this evidence, companies have attempted to enhance maintenance efficacy through various strategies and, in this context, being able to select the most suitable strategy is crucial for obtaining successful outcomes. It has been reported as ineffective maintenance strategies may result in serious losses for companies (Wollenhaupt, 2016), amounting to 20% of reduction of their direct production capacity. In the report published by IndustryWeek and Emerson (2017), the estimation of these losses is around $50 billion per year. Furthermore, implementing improper maintenance strategies is responsible of circa 80% downtime increase (Özcan el al., 2017). In contrast, selecting an effective maintenance strategy leads to a consequent cost saving estimated up to 28% of the total cost reduction (Karabağ el al., 2020).

As stressed by Badía et al. (2020), designing effective maintenance policies is important to extend the useful life of industrial systems and to simoultaneously reduce costs derived from early and unnecessary equipment replacements. Making decisions about maintenance strategies cannot be separated from undertaking proper actions of risk management aimed at evaluating and reducing to an acceptable level (Leoni et al., 2019) the possible risks related to the execution of maintenance interventions associated to a given strategy. Assessing the main risks involved when leading maintenance operations plays a fundamental part in enhancing conditions of safety and security at work, what is compulsory according to the standards of reference. Given the multiple aspects relevant to this topic, the present paper proposes a novel general framework to be adapted and customised by companies according to the needs of their industrial reality under analysis. Specific objectives of the paper are:

a) selecting a maintenance strategy as the best trade-off according to criteria and subcriteria considered important by the existing independent literature;
b) analysing risks potentially affecting maintenance interventions associated to the chosen strategy, and rank them according to the established set of criteria.

The final ranking of risks will offer a structured input to plan and implement measures aimed at optimising the process of maintenance management. The proposed hybrid framework will be implemented in an Italian marine salt manufacture firm, the final risk prioritisation referring to maintenance interventions belonging to the chosen strategy for a critical subsystem.

2. Literature review

The existing literatures group maintenance strategies into the following main categories.

1. Reactive (or corrective) maintenance. This maintenance policy assumes that interventions are accomplished after failure occurrence, to restore an item into a functioning state (BS EN 13306:2010). As affirmed by such authors as Ben-Daya et al. (2016) and Golbasi and Turan (2020), corrective maintenance can be further distinguished into immediate and deferred corrective maintenance, depending on the readiness in carrying out interventions upon failures. In the first case, maintenance interventions are executed immediately after those failures directly influencing production and/or core services by the deputed maintenance crew which is immediately available in site. In the second case, interventions are not immediately carried out after fault detection but delayed in time according to rules established by the management. This case regards those maintenance activities that are not so urgent or require longer execution times (due, for instance, to their sudden or complex nature or to the need of involving an external maintenance crew).
2. Preventive maintenance. Interventions belonging to this category are based on such criteria as time, age, usage or condition information (De Jonge and Scarf, 2020) and take place prior to the occurrence of failures with the aim of keeping equipment in specified conditions through organized check-up, detection and prevention of potential failure (Tatari and Skibniewski, 2006). Such authors as Christer and Lee (2000) also refer to this strategy with the definition of "time-based maintenance", which can be further grouped into:
   2.1. Maintenance scheduled at planned intervals. Interventions are carried out according to an established schedule, as in the case of age-based and clock-based maintenance (respectively referring to the time that a system achieves a certain age and a particular calendar time, as underlined by Ahmadi et al., 2010). Faghihinia and Mollaverdi (2012) cite Wang (2002) specifying the existence of other categories depending on different criteria (for instance failure or repair limit) as well as the need to elaborate preventive maintenance models to be as much as possible adherent to the given problems.
   2.2. Condition-based maintenance. It belongs to the preventive maintenance category, but includes a combination among condition monitoring, investigation and testing, by performing analyses on results of maintenance actions. Interventions are scheduled not at established intervals but as needed on the basis of asset conditions. Predictive maintenance is a type of condition-based maintenance carried out based on predictions derived by collecting results from repeated analyses on significant parameters related to the wearing process of items (BS EN 13306:2010). As underlined by Sahu and Palei (2020), including

an effective fault prediction process in the preventive maintenance policy can be strategic to significantly reduce failures and downtimes of systems.

3. Opportunistic maintenance. This strategy aims to combine preventive and corrective maintenance strategies. In other words, when a component of a system fails, not only is the action of corrective maintenance performed, but also interventions of preventive maintenance are carried out on other units not yet failed in order to prevent future failures (Laggoune et al., 2009). Khazraei and Deuse (2011) discuss the usefulness of establishing a strategy to decide which kind of preventive maintenance is more suitable in each specific case.

It is fundamental to underline that maintenance management strategies have to be adapted and integrated based on the characteristics of the industrial context one is dealing with (Ding et al., 2014a), in accordance to needs, equipment and location. Each equipment is characterised by specific designation and features, having then associated a specific value of probability of failure and reliability. This is the reason why the present section aims to offer a detailed literature review about techniques used to select the best maintenance strategy on the basis of a company's practical needs along with current topics related to risk evaluation practises.

2.1. Frameworks used in the literature for the problem of maintenance strategy selection

The existing literature shows plenty of works aimed at providing management with tools for selecting the best maintenance strategy based on the specific needs of the industrial reality of reference. The frameworks mainly used (Figure 1) have been summarized by Ding and Kamaruddin (2015), which related them to specific conditions of analysis.

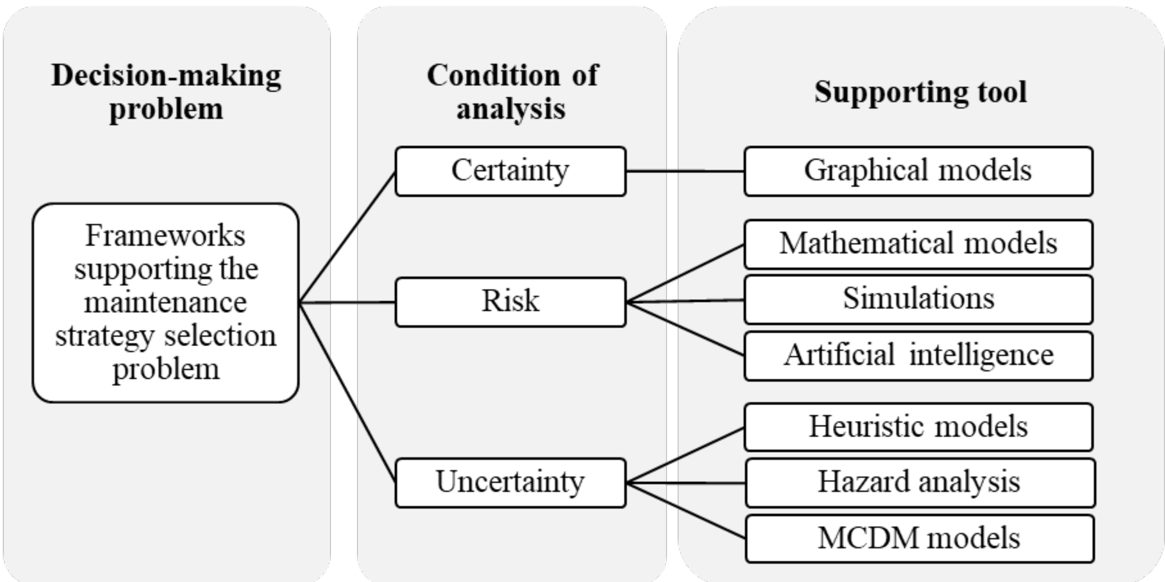

Figure 1. Frameworks used in the literature for the problem of maintenance strategy selection in diverse conditions of analysis (Ding and Kamaruddin, 2015)

With relation to conditions of analysis, Ding and Kamaruddin (2015) take into account the three possible degrees of certainty defined by the certainty theory continuum (Tersine, 1985). The considered scenarios refer to certain, risk-based and uncertain contexts, being each one of them related to the degree of information available about the states of the system under analysis. Risk-based and uncertainty conditions respectively refer to the possibility to contemplate different assumptions and to the presence of vague information. On the one hand, risk conditions are associated to known states of systems that can be stochastically described to predict future conditions useful for establishing which maintenance strategy is more appropriate. On the other hand, uncertain conditions of analysis reflect unknown states of systems for which information has to be collected on the basis of subjective evaluations.

As we can observe, graphical models are suitable when dealing with certain contexts. In this case, a maintenance strategy can be selected on the basis of the most desirable outcomes without using complicated optimisation procedures. The same authors underline as, given the difficulty to assume conditions of analysis as certain and determined, results produced by graphical models have been criticised for lack of accuracy, and, as a result, various risk-based stochastic methods have been proposed to overcome such an issue. As examples we may cite the use of Motecarlo simulations (Borgonovo et al., 2000; Leite da Silva et al., 2004), Markov methods (Gürler and Kaya, 2002; Zio and Compare, 2013) or mathematical models based on probabilistic approaches (Jiang and Liu, 2020; Daneshkhah et al., 2017). However, despite the wide use of stochastic approaches in the existing literature, their main and more obvious disadvantage is the high degree of complexity for application, what makes this type of models suitable just for theoretical research and not for real-life applications (Ding and Kamaruddin, 2015).

As highlighted by Vinodh and Varadharajan (2012), MCDM methods are among the most popular and effective tools adopted in maintenance strategy selection processes. Despite these techniques being heuristic, thus not guaranteeing the optimality of final solutions (Tomashevskii and Tomashevskii, 2019), they enable to consider multiple and often conflicting objectives of decision-making problems, apart from effectively dealing with uncertainty. Many studies have approached the problem of maintenance policy selection under a MCDM perspective by considering the large number of tangible and intangible aspects involved (Lashgari et al., 2012). MCDM methods assure high measurement efficiency with less unrealistic assumptions (Ding and Kamaruddin, 2015), being then capable to help in collecting a comprehensive understanding about maintenance management without limitations derived from the use of financial aspects as the unique parameter of analysis.

The Analytical Hierarchy Process (AHP), first developed by Saaty (1980), has been widely used to deal with many diverse analysis problems. Bertolini and Bevilacqua (2006) implemented a programming method based on AHP to select the best maintenance strategy for an Italian oil refinery. Chandima Ratnayake and Markeset (2010) used the method to perform a selection of maintenance strategies in the oil and gas sector by considering health, safety, environment, awareness and cost as evaluation criteria. Muinde et al. (2014) suggested the same technique for a cement factory in Kenya by involving the maintenance staff during the stage of pairwise comparisons' formulation. Furthermore, the AHP was applied by Vishnu and Regikumar (2016) to select a maintenance strategy for the whole set of equipment of a metal process plant manufacturing, and by Chandrahas et al. (2015) to select the best maintenance strategy by following the philosophy of total productive maintenance.

Since the application of AHP in maintenance selection seems to have reached a state of maturity, the literature proposes the combination of other MCDM methods. For example, Karthik et al. (2017) optimise a maintenance strategy by integrating the AHP with the Project Evaluation and Review Technique (PERT) for systems simulation. Shyjith et al. (2008) adopted the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to select the optimal maintenance policy for ring frames of spinning mill systems in the textile industry. The TOPSIS was applied to determine that maintenance policy helpful in reducing systems' failure risk (Ding et al., 2014b) also in such particular cases as the palm oil industry (Ding et al., 2014a). The same technique has been integrated with the AHP (Özcan et al., 2017), also managing the uncertain nature of maintenance selection processes by using fuzzy numbers (Wang et al. 2007; Nezami and Yıldırım, 2013; Azadeh and Zadeh, 2016). Currently, the use of fuzzy data has been integrated within MCDM frameworks to obtain more robust tools that avoid crisp values, and treat strategic problems through triangular fuzzy numbers (Ding and Ling. 2005). Kirubakaran and Ilangkumaran (2016) proposed the fuzzy grey relational analysis (GRA), the fuzzy AHP (FAHP), and the fuzzy TOPSIS (FTOPSIS) to select the optimal maintenance strategy. The study was aimed at ordering selected corrective maintenance, predictive maintenance, time-based preventive maintenance and condition-based maintenance as alternatives on the basis of four criteria, namely safety, cost, added value, and feasibility. Borjalilu and Ghambar (2018) applied the FAHP to select the optimal maintenance strategy with relation to a set of five possibilities in order to improve production on a manufacturing unit. Abdulgader et al. (2018) combined three fuzzy MCDM methods to establish the best maintenance strategy for industrial application. They used the fuzzy DEcision MAking Trial and Evaluation Laboratory (DEMATEL) to identify interrelationship among criteria, the FAHP to calculate the vector of criteria weights, and the FTOPSIS to achieve a final ranking of alternatives.

What appears more relevant to sort out the problem of interest is that the evaluation criteria used to perform the selection of the best strategy are not independent among them. Considering the existence of these dependencies is crucial in such a fundamental issue as component maintenance since, as affirmed by such authors as Antomarioni at al. (2019), especially in the case of continuous processes, occurrence of an event may have a significant impact on other aspects (even in terms of potential occurrence of failures). In this context, particular attention should be dedicated to the preliminary reliability analysis of multi-state machining systems with common cause failure aimed at designing suitable safety measures (Shekhar et al., 2020). For this reason, the use of the Analytic Network Process (ANP) proposed in the present paper appears to be particularly suitable for various applications, i.e. railway systems (Cheng and Tsao, 2010), vehicle assembler (Chemweno et al., 2015), project management (Certa et al., 2009), and so on.

2.2. Relevant criteria and subcriteria

The existing literature highlights the following six criteria as mostly impacting maintenance strategy selection: safety and security, cost, reliability, availability, feasibility, and added value. A literature review synthetizing the mentioned criteria and the related subcriteria used to perform the selection of the most appropriate maintenance strategy is given in Table 1.

Table 1. Criteria, subcriteria and references

Criteria	Subcriteria	Reference
Safety and Security	Human safety	• Mohamed and Saad (2016); • Momeni et al. (2011); • Seiti et al. (2017); • Kirubakaran and Ilangkumaran (2016).
	Environment safety	• Mohamed and Saad (2016); • Momeni et al. (2011); • Seiti et al. (2017); • Kirubakaran and Ilangkumaran (2016).
	Facility and machinery safety	• Mohamed and Saad (2016); • Akhshabi (2011); • Seiti et al. (2017); • Kirubakaran and Ilangkumaran (2016).
Cost	Damage and loss in production	• Mohamed and Saad (2016); • Wang et al. (2007); • Akhshabi (2011); • Kirubakaran and Ilangkumaran (2016).

	Spare parts costs/hardware	• Mohamed and Saad (2016); • Momeni et al. (2011); • Seiti et al. (2017); • Kirubakaran and Ilangkumaran (2016).
	Programming maintenance and software	• Mohamed and Saad (2016); • Akhshabi (2011); • Seiti et al. (2017); • Kirubakaran and Ilangkumaran (2016).
	Training cost	• Xie et al. (2013); • Wang et al. (2007); • Akhshabi (2011).
	Replacement	• Kirubakaran and Ilangkumaran (2016).
	Fault identification	• Kirubakaran and Ilangkumaran (2016).
	Labour cost	• Mohamed and Saad (2016); • Momeni et al. (2011); • Akhshabi (2011); • Seiti et al. (2017); • Kirubakaran and Ilangkumaran (2016).
Reliability	Average time between failures	• Mohamed and Saad (2016); • Xie et al. (2013).
	Inspection accessibility and errors-free	• Mohamed and Saad (2016); • Wang et al. (2007); • Akhshabi (2011).
	Reliability of techniques	• Wang et al. (2007); • Akhshabi (2011); • Kirubakaran and Ilangkumaran (2016).
Availability	Average time for repair	• Mohamed and Saad (2016); • Wang et al. (2007); • Akhshabi (2011).
	Inherent availability	• Mohamed and Saad (2016)
	On demand availability	• Mohamed and Saad (2016)
Feasibility	Acceptance by personnel	• Xie et al. (2013); • Wang et al. (2007); • Kirubakaran and Ilangkumaran (2016).
	Policy effectiveness	• Xie et al. (2013);

	Technology accessibility	• Momeni et al. (2011).
Added-Value	Production quality	• Momeni et al. (2011); • Akhshabi (2011); • Kirubakaran and Ilangkumaran (2016).
	Waste reduction	• Momeni et al. (2011); • Akhshabi (2011); • Kirubakaran and Ilangkumaran (2016).
	Spare parts inventory	• Momeni et al. (2011); • Akhshabi (2011); • Kirubakaran and Ilangkumaran (2016).
	Maintainability	• Kirubakaran and Ilangkumaran (2016).
	Procedure	• Kirubakaran and Ilangkumaran (2016).

2.3. Evaluating risks related to the selected maintenance strategy

Once selected the most suitable maintenance strategy, performing an effective risk evaluation is a fundamental step for a globally effective maintenance management. As asserted by Fukushige et al. (2018), the phase of risk assessment is of utmost importance to support and select an appropriate maintenance scenario. The authors define the simulation of effects of maintenance as a promising approach to systematic maintenance service design. By making use of the classical risk definition, Tan et al. (2011) investigate both the probability of occurrence and the impact of possible failures, under the support of risk-specific code, to prioritise and plan inspections in the oil and gas industries. In such a way, the authors aim to support companies in making decisions about suitable maintenance tasks and techniques with a multiple purpose, in other terms, shifting from a reactive maintenance regime to a proactive one, promoting teamwork spirit and implementing effective risk management tools. By pointing out the dynamic nature of maintenance, Seiti et al. (2019) underline as the presence of both predictable and unpredictable factors may negatively influence equipment reliability. The authors propose a new model based on different risk scenarios for preventive maintenance planning. Yu et al. (2018) stress the benefit derived from applying the ELimination Et Choix Traduisant la REalité (ELECTRE) methods to solve the so called "prioritised decision-making problems". For these kinds of problems, criteria are assumed interdependent since a sort of prioritisation among them exists. The authors explain this concept by providing as examples safety and cost criteria: safety has always higher priority than cost. Hashemi et al. (2016) contribute to this issue by affirming as comparisons among elements cannot be completely definitive because of vague information about evaluations of criteria and alternatives. This is the reason why the authors integrate ELECTRE III with the intuitionistic fuzzy set theory. Fancello et al. (2014) propose ELECTRE III algorithms to sort out a real case study involving various sections of a motorway with respect to safety conditions, and to identify intervention priorities by ranking critical sections.

We claim that ELECTRE III methods can be effectively used to rank the risks involved in the execution of maintenance actions and, consequently, to get a comprehensive understanding about how to prioritise interventions aimed at reducing/preventing highly critical risks. Moreover, this method will be integrated with the ANP technique so that dependence existing among the main aspects of maintenance problems can be captured.

3. Methods and materials

The present research suggests first the application of the ANP to select that maintenance strategy representing the best trade-off according to a set of interdependent criteria, and second ELECTRE III is used to suitably rank the risks. These two particular methods have been chosen for the following reasons:

1) ANP allows to consider dependencies existing among the main elements of the problem, thus to offer results more adherent to the actual industrial reality;
2) ELECTRE III is efficient to rank a set of alternatives on the basis of outranking relations and by establishing specific indifference, preference and veto thresholds on criteria;
3) the integration between both methods has been proved to be successful in various fields of literature (Certa et al., 2009), and it is applied for the first time to the problem under analysis.

The ELECTRE III ranking of the risks related to the execution of maintenance interventions is done with a twofold objective (INAIL, 2019): 1) guaranteeing the best level of safety and security for all the workers and stakeholders involved in maintenance operations; 2) responding to the existing standards about safety and security related to work environment and equipment.

To the best of the authors' knowledge, it is the first time that a framework integrating ANP and ELECTRE III is applied in the field of maintenance strategy selection with relation to the risk evaluation process. This framework tool is eventually implemented in a real-world industrial context, namely a marine salt manufacture firm, with relation to maintenance operations to be performed on critical machines belonging to the production system. Figure 2 details the proposed approach for the process of maintenance strategy selection and following risk prioritisation.

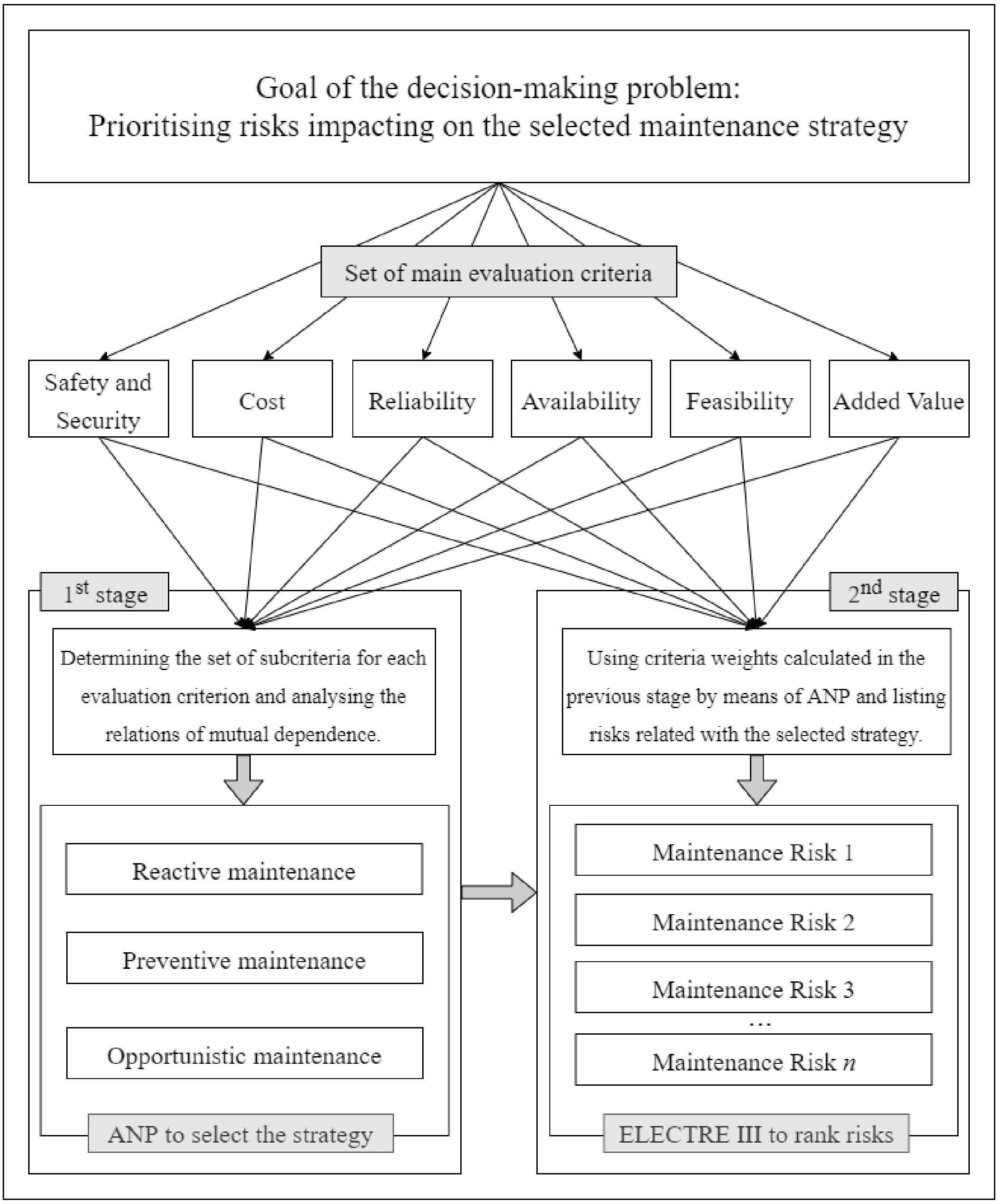

Figure 2. Proposed MCDM framework

We specify that the application of our framework for a real industrial system is supposed to follow a careful preliminary evaluation about the different potential maintenance strategies in terms of difficulty/possibility of implementation (for instance due to the large amount of historical failure data to be collected or to the possibility of monitoring systems condition, and so on). These preliminary evaluations will allow to outline and design maintenance strategies on the basis of the particular system/components' characteristics. Such a task usually takes place in the company, resulting from the cooperation among the diverse stakeholders such as general management staff, maintenance responsible, maintenance crew, and technical consultant, what will allow to gain a complete and complementary overview about the whole process. As soon as the diverse maintenance strategies will be thoroughly internally evaluated, our framework will be applied to achieve as final output the prioritisation of risks connected to the selected maintenance strategy.

3.1. The ANP to weight criteria and to select the maintenance strategy

AHP is a powerful MCDM method with several advantages of application, including simplicity, flexibility, and possibility to review consistency of judgments. Since AHP is typically top-down (unidirectional), its main drawback consists in the impossibility of dealing with interdependent elements of the same level or cluster, and bottom-up (feedback) relations. For this reason, it is difficult to represent many real-world decision-making problems in industry, since the various elements involved may present various degrees of interaction (Zaim et al., 2012). This is often the case of real complex maintenance problems, due to the existence of high degrees of dependency among the main involved aspects. First of all, components of systems, especially the critical ones, are generally not independent of each other, what leads to the necessity of evaluating and modelling their mutual influences to not neglect important effects derived from their interactions. The same consideration is valid when it comes to the evaluation criteria related to maintenance analysis. It is not realistic to assume that some relevant maintenance aspects, such as for instance safety and cost, are independent. Similarly, it is possible that perfectly consistent results are actually not feasible or ineffective. The ANP was proposed by Saaty (1999) to capture dependence and feedback among decision-making elements to produce more effective and reliable results; this is why ANP seems to be particularly useful for real maintenance applications. ANP considers elements (also called nodes), namely objective, criteria, subcriteria and alternatives, grouped in clusters according to common characteristics (typically, for a linear hierarchy, as we consider in this paper, the clusters are the objective, the set of criteria, the set of subcriteria, and the set of alternatives). Elements and clusters integrate the network (García-Melón et al., 2008). Dependence between elements may be internal, for elements in a same cluster, and external, for elements of different clusters; also, dependence between entire clusters is considered to weigh relations between elements of different clusters. In addition, (back-propagation) feedback may also be considered. The ANP method can be performed through five steps as detailed next.

Step 1: building a model and representing a decision-making problem through a network structure. After identifying the clusters, it is necessary to build the network structure. A brainstorming may help identify all the possible relationships of interdependence and feedback among the considered elements and clusters. Relationships are represented by links between the elements involved. Links may go between clusters, and between elements in the same cluster (inner dependence) or in different clusters (outer dependence). In the case of inner dependence between two elements of the same cluster, the cluster is linked to itself and a loop appears. Once this structure is fully clear, it is possible to build the so-called influence matrix, a square block matrix of the size of the number of elements, with blocks corresponding to the clusters. An entry $a_{ij,kl}$ equal to one denotes that there is a link between element j in cluster i and element l in cluster k. Otherwise that entry will be 0. The influence matrix serves as a guide for the non-zero elements of the supermatrix to be built in the next step.

Step 2: Comparing nodes. In this step, all the nodes for which a connection exists with a given element are pairwise compared with respect to this element, and this comparison is performed by attributing values from the Saaty's nine-point scale (Saaty and Vargas, 2006). The AHP method is used to obtain the weights associated to the comparisons performed, which correspond to corresponding 1-entries in the influence matrix. This enables to build the so-called unweighted super-matrix, expressing various effects of interdependency on different elements of the process (Matin at al., 2020). In this step, the clusters' mutual influence is also compared, and a vector of corresponding priorities is obtained and put aside.

Step 3: Generating the weighted supermatrix. This supermatrix is obtained by modifying the unweighted supermatrix by coherently multiplying its elements by the weights obtained from de comparisons of clusters and normalizing the columns to sum one. This way the weighted super-matrix becomes stochastic (columns with non-negative entries summing to one), something essential for the next step.

Step 4: Calculating the limit matrix, whose columns are equal and represent the global priorities (Fernandez Portillo at al., 2019). To obtain the limit matrix, the weighted matrix is raised to successive powers. As the weighted supermatrix is stochastic, its largest eigenvalue is equal to one, and the limit of these powers exists (Meyer, 2000). Each power of the matrix captures all transitivities of the order of that power. This way, all order transitivities are captured by this series of powers. The priorities of the alternatives (or any set of elements in a cluster) are obtained by normalizing the corresponding values in the appropriate places of the limit matrix. Observe that when the supermatrix has zeros and is reducible the limit can cycle and a Cesàro average over the different limits of the cycles is taken.

Step 5: Extracting the sought information from the accumulated interdependencies revealed by the limit matrix. For example, if the main objective is selecting the best alternative in an existing cluster of alternatives (usually placed last) to meet a given objective (usually placed first), the final weights of the considered alternatives are accessible from the last block of the first column in the limit supermatrix. As usual, the alternative with the associated largest weight is considered the best choice.

3.2. The ELECTRE III to prioritise risks related to the chosen maintenance strategy

As previously pointed out in the literature review section, ELECTRE methods are very useful to deal with prioritised decision-making problems, such as the problem of maintenance-based risks prioritisation. The integration of the ELECTRE III application in the proposed framework would allow, once selected the most suitable maintenance strategy by means of the ANP application, to effectively rank for prioritisation purposes the risks involved in the execution of maintenance actions. This will help with achieving a structured knowledge about the practical organisation of maintenance interventions as well as in implementing effective measures of risks reduction/prevention.

ELECTRE III permits achieving a final ranking of alternatives across different application areas (Govindan and Jepsen, 2016). Such a ranking may be built by means of two procedures, known under the name of ascending and descending distillation chains (Vincke, 1992). The method considers a fuzzy outranking. The outranking relation has actually associated the function $\delta(A_i, A_j)$, varying within the range $[0,1]$, and expressing the degree of credibility related to the preference of alternative A_i with respect to alternative A_j.

The ELECTRE III method requires the preliminary collection of the following input data: 1) set of alternatives to be ranked, A_i ; 2) evaluation criteria, B_k; 3) vector of criteria weights, w_k; 4) numerical evaluation of alternatives with respect to the considered criteria, $u_k(A_i)$. Moreover, three numerical thresholds have to be fixed for each criterion (Corrente et al., 2017), to properly take into account uncertainty affecting alternatives evaluation. These thresholds thus refer to the difference $u_k(A_j) - u_k(A_i)$, which is the difference between the numerical evaluations of the two alternatives A_i and A_j under the criterion B_k. In particular, the indifference threshold I_k is the minimal difference considered significant to express a preference between two alternatives; the strong preference threshold S_k is the minimal difference to express a strong preference between two alternatives; the veto threshold V_k expresses the minimum value beyond which the two alternatives are considered not comparable. The condition $I_k \leq S_k \leq V_k$ has always to be verified.

Once collected the input data in a matrix and established the mentioned thresholds for all criteria, the development of the procedure is organized in two phases.

The first phase is made up of the following four steps.

Step 1.1. Building the matrices of concordance indices $C_k(A_i, A_j)$, one matrix for each criterion.

Concordance indices can be calculated by means of the rules:

$$\text{if} \quad u_k(A_i) \geq u_k(A_j), \text{ then } C_k(A_i, A_j) = 1; \tag{1}$$

$$\text{if} \quad u_k(A_i) < u_k(A_j), \text{then } C_k(A_i, A_j) = \begin{cases} 1 & \text{if } u_k(A_j) - u_k(A_i) \leq I_k; \\ \frac{[u_k(A_i)+S_k-u_k(A_j)]}{S_k-I_k} & \text{if } I_k < u_k(A_j) - u_k(A_i) \leq S_k; \\ 0 & \text{if } u_k(A_j) - u_k(A_i) > S_k. \end{cases}$$

This first step produces as output a number of squared matrices equal to the number of criteria, each matrix reporting the concordance indices $C_k(A_i, A_j)$ obtained for each pairwise comparison.

Step 1.2. Building the aggregated concordance matrix $C(A_i, A_j)$.

The output of this step will be a single squared matrix $C(A_i, A_j)$ whose elements are obtained by aggregating and weighting the relative elements belonging to the former matrices of concordance indices.

Step 1.3. Building the matrices of discordance indices $D_k(A_i, A_j)$, one matrix for each criterion.

Discordance indices are determined by following these rules:

$$D_k(A_i, A_j) = \begin{cases} 0 & \text{if } C_k(A_i, A_j) \neq 0; \\ \frac{[u_k(A_j) - u_k(A_i) - S_k]}{V_k - S_k} & \text{if } S_k \leq u_k(A_j) - u_k(A_i) < V_k. \\ 1 & \text{if } u_k(A_j) - u_k(A_i) \geq V_k. \end{cases} \quad (2)$$

The output of this step consists of as many squared matrices as the number of criteria and, in each matrix, the discordance indices $D_k(A_i, A_j)$ are obtained for each pairwise comparison.

Step 1.4. Building the outranking credibility matrix $\delta(A_i, A_j)$.

The outranking credibility matrix requires the following rules:

$$\begin{aligned} &\text{if } \forall\, k\ D_k(A_i, A_j) = 0, \text{ then } \delta(A_i, A_j) = C(A_i, A_j); \\ &\text{if } \exists\, k \text{ for which } D_k(A_i, A_j) > 0, \text{ then } \delta(A_i, A_j) = C(A_i, A_j) \text{ if } \forall\, k\ \ D_k(A_i, A_j) < C(A_i, A_j); \quad (3) \\ &\text{if } \exists\, k^* \text{ for which } D_{k^*}(A_i, A_j) \geq C(A_i, A_j), \text{ then } \delta(A_i, A_j) = C(A_i, A_j) \cdot \prod_{k^*} \frac{[1 - D_{k^*}(A_i, A_j)]}{[1 - C(A_i, A_j)]}\ \forall k^*. \end{aligned}$$

The output will be a square matrix in which elements express the degree of credibility related to the preference of alternative A_i with respect to A_j.

Once the first phase is accomplished, the second phase consists of the next three steps.

Step 2.1. Determining the minimal value of outranking credibility, δ_0.

This value corresponds to:

$$\delta_0 = \delta_{max} - s(\delta_{max}); \quad (4)$$

δ_{max} being the maximum numerical value of the elements belonging to the outranking credibility matrix $\delta(A_i, A_j)$, and $s(\delta_{max})$ the discrimination threshold, the latter obtained as:

$$s(\delta_{max}) = -0.15 \cdot \delta_{max} + 0.3. \quad (5)$$

Step 2.2. Building the Boolean matrix $T(A_i, A_j)$.

This matrix can be calculated on the basis of the following test:

$$T(A_i, A_j) = \begin{cases} 1 & \text{if } \delta(A_i, A_j) \geq \delta_0 \text{ and } \delta(A_i, A_j) - \delta(A_j, A_i) > s(\delta_{max}) \\ 0 & \text{otherwise} \end{cases}. \quad (6)$$

Step 2.3. Defining the qualification degree of alternatives and building the final ranking.

The qualification of alternative A_i, $q(A_i)$, corresponds to the difference between the number of alternatives outranked by A_i and the number of alternatives outranking A_i. Two rankings have to be lastly built by means of two procedures of distillation, namely ascending and descending distillation chains (Vincke, 1992). These procedures respectively consist in deleting the row and column from the outranking credibility related to the alternative characterised by the highest and lowest qualification degree, and in reiterating the second phase until all the alternatives have been assigned in both rankings. If two alternatives are characterized by the same qualification degree, a distillation procedure has to be carried out just for the two rows and columns related to the two alternatives of the outranking credibility matrix $\delta(A_i, A_j)$. The two rankings must coincide, thus constituting the final ranking of the whole set of alternatives. If the two rankings were not equal, it would mean that incomparability among alternatives occurs.

3.3. Use case

The present use case refers to an Italian marine salt manufacture firm. We focus on a core subsystem belonging to the packaging plant of the company, called "cardboard boxes line". Specifically, upon the production stage, marine salt is ready to be distributed to the packaging plant, to be then dispatched and/or stored. The packaging plant is made of as many different lines as the number of different kinds of packages for the final product (plastic bags, cardboard boxes, big bags). Being the activity of the company directly related to the correct functioning of the mentioned subsystems, planning and executing suitable maintenance interventions is fundamental to guarantee the normal course of activity. Our case study focuses on the "cardboard boxes line" of the packaging plant, represented in Figure 3 through a block diagram.

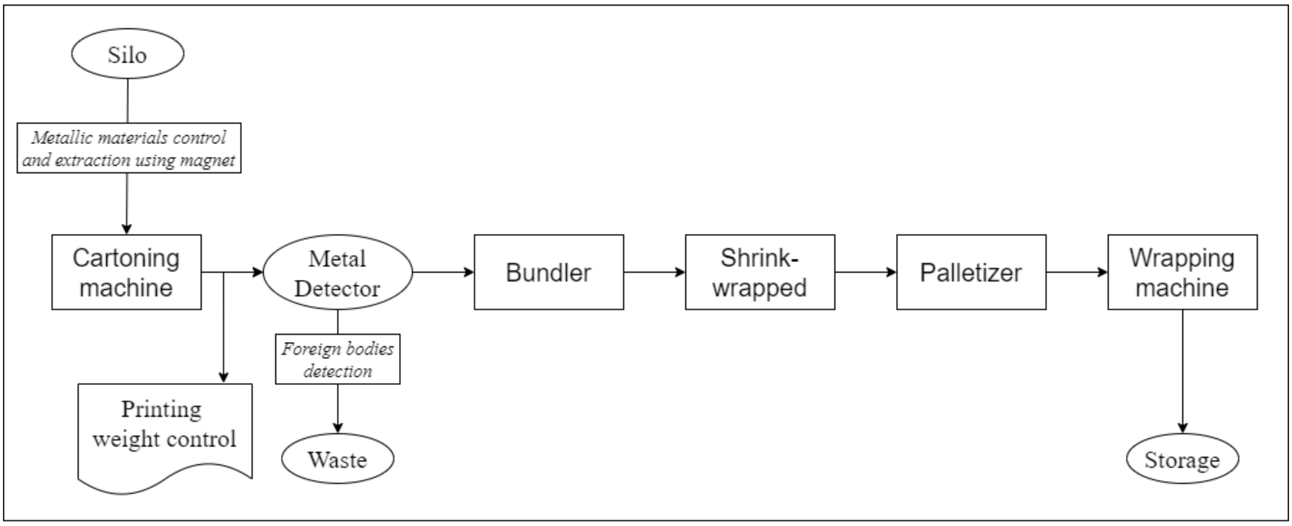

Figure 3. Block diagram representing the "cardboard boxes line"

By observing the block diagram, we can note as manufactured and controlled salt is lead into the cartoning machine from the silo by means of a dedicated loading hopper. Empty cardboard boxes to be filled with salt are manually inserted in the cartoning machine by a dedicated operator, who is in charge of managing and supervising the filling operation. After having passed a further control of foreign bodies (salt would be discarded otherwise), boxes pass to the bundler, where another operator will organise packaging materials and will supervise the passage of loads to the shrink-wrapped and successively to the palletizer. Assembled pallets will lastly travel towards the wrapping machine through a specific roller conveyor and wrapped pallets will be moved to the storage area by the forklift driver.

With relation to the described system, we will proceed by first identifying the most relevant subcriteria (among those resulting from the literature analysis process and reported in Table 1) to perform the selection of the most suitable maintenance strategy by means of the ANP.

Secondly, once selected the strategy, the corresponding maintenance operations will be analysed to highlight the potential related risks, which will be evaluated and prioritised by means of the ELECTRE III method. Such a prioritisation will be carried out according to the same criteria used by the ANP, together with the corresponding vector of weights.

With reference to the first objective, criteria shown in Table 1 –those emerged from the literature review (section 2.2.) –, have been further analysed to manage and reduce redundancy existing among some subcriteria. Table 2 presents the subcriteria considered as mainly relevant for our case study, along with the related justifications. The choice of subcriteria derives from a long process of brainstorming undertaken with the maintenance stakeholders of the company. Their contribution was fundamental to identify which aspects should have played an important part in the selection process, and which aspects could have been omitted, being not really relevant for the particular case study setting. Example of subcriteria that have been herein omitted are “inspection accessibility and errors/free” and “reliability of techniques” with relation to the “reliability” criterion. This choice was justified by the evidence that the MTBF would have been an exhaustive indicator to represent the whole criterion. The same consideration has been made for the criterion “availability”, when deciding to omit the subcriteria “inherent availability” and “on demand availability” to consider just the MTTR as relevant indicator. Other examples can be made, with relation, for instance, to the added/value criterion. Maintenance stakeholders agree that, for the specific industrial process of reference, the most important aspects are “production quality” and “waste reduction”, so that the other subcriteria (namely “spare parts inventory”, “maintainability” and “procedure”) were excluded from the analysis.

Table 2. Justified selection of criteria and sub-criteria

Criteria	Subcriteria	Justification of choice
C_1 (Safety and Security)	**SC_{11}**: Human safety	The main objective of maintenance consists in keeping safe equipment, machines and work environment. Maintenance Managers have the duty to guarantee safety of operations for each worker.
	SC_{12}: Environment safety	
	SC_{13}: Facility and machine safety	
C_2 (Cost)	**SC_{21}**: Damage and loss in production	Damage and loss in production are among the less desirable events for managers, leading to consistent financial loss and also increasing risks for customer warranty.
	SC_{22}: Spare parts costs/hardware	Spare parts are one of the main aspects leading to costs increasing in maintenance operations. Hardware refers to operations to be undertaken through/on informatics devices.
	SC_{23}: Manpower cost	Cost related to manpower, extra workers or training represents a financial constraint for maintenance management. A maintenance strategy cannot be effective without thinking about the optimal manpower organisation.
C_3 (Reliability)	**SC_3**: Average time between consecutive failures	The average or mean time between failures (MTBF) is the predicted time interval between two consecutive failures of a system, occurred during normal condition of system operation. The MTBF indicates whether maintenance operations improve equipment reliability and is a fundamental indicator to track company effectiveness.
C_4 (Availability)	**SC_4**: Average time for repair	The average or mean time to repair (MTTR) is a basic measure of maintainability for repairable items. It represents the average time required to repair a failed component or device. The MTTR is a key indicator used to track the reactivity of maintenance operations and the effectiveness of interventions of preventive maintenance.
C_5 (Feasibility)	**SC_{51}**: Acceptance by personnel	Workers involved in maintenance technically know equipment features and their impact on machines. They have to be completely aware about the strategy and share its principles, since a possible resistance to change can lead to acts of sabotage with negative consequences in terms of acceptance and cooperation.

	SC_{52}: Policy effectiveness	Changing strategy requires an initial cost and has various implication. The investment needs to be profitable and the implemented changes have to be effective.
C_6 (Added-Value)	**SC_{61}**: Production quality	The modern attitude towards maintenance is centred on continuous improvement in terms of operations to enhance production quality and strengthen company competitiveness.
	SC_{62}: Waste reduction	An efficient waste management is another pillar in improving efficiency and competitiveness of company by controlling maintenance costs.

All the selected subcriteria in Table 2 are thus relevant for the topic herein treated. The same criteria will be used both in the ANP and in the ELECTRE III applications. Figure 4 and Figure 5, respectively, present the hierarchy structure of the decision-making problem, and the network of relationships linking criteria and subcriteria. The maintenance strategies described in section 2, namely reactive (A_1), preventive (A_2), condition-based (A_3) and opportunistic (A_4), are considered as alternatives for the ANP application.

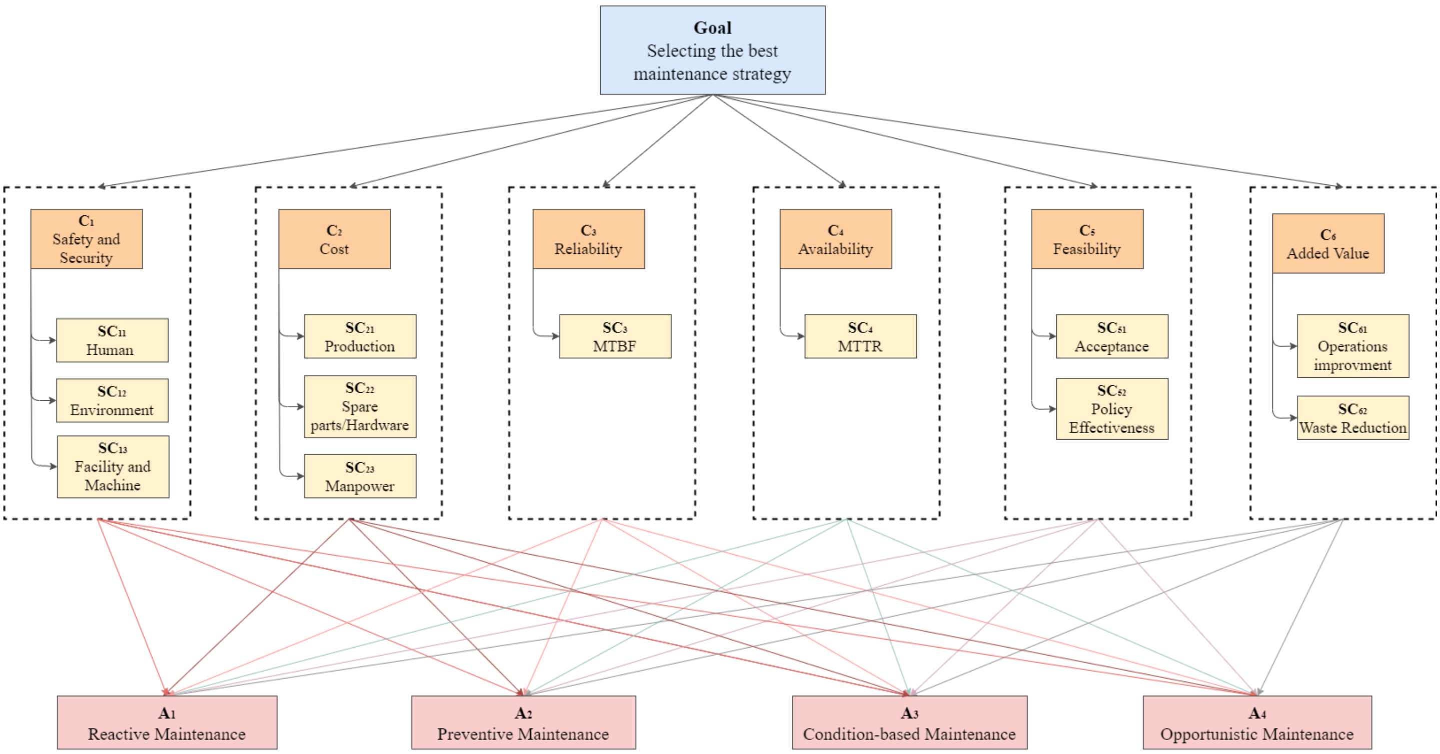

Figure 4. Hierarchy structure representing the process of selection of the best maintenance strategy

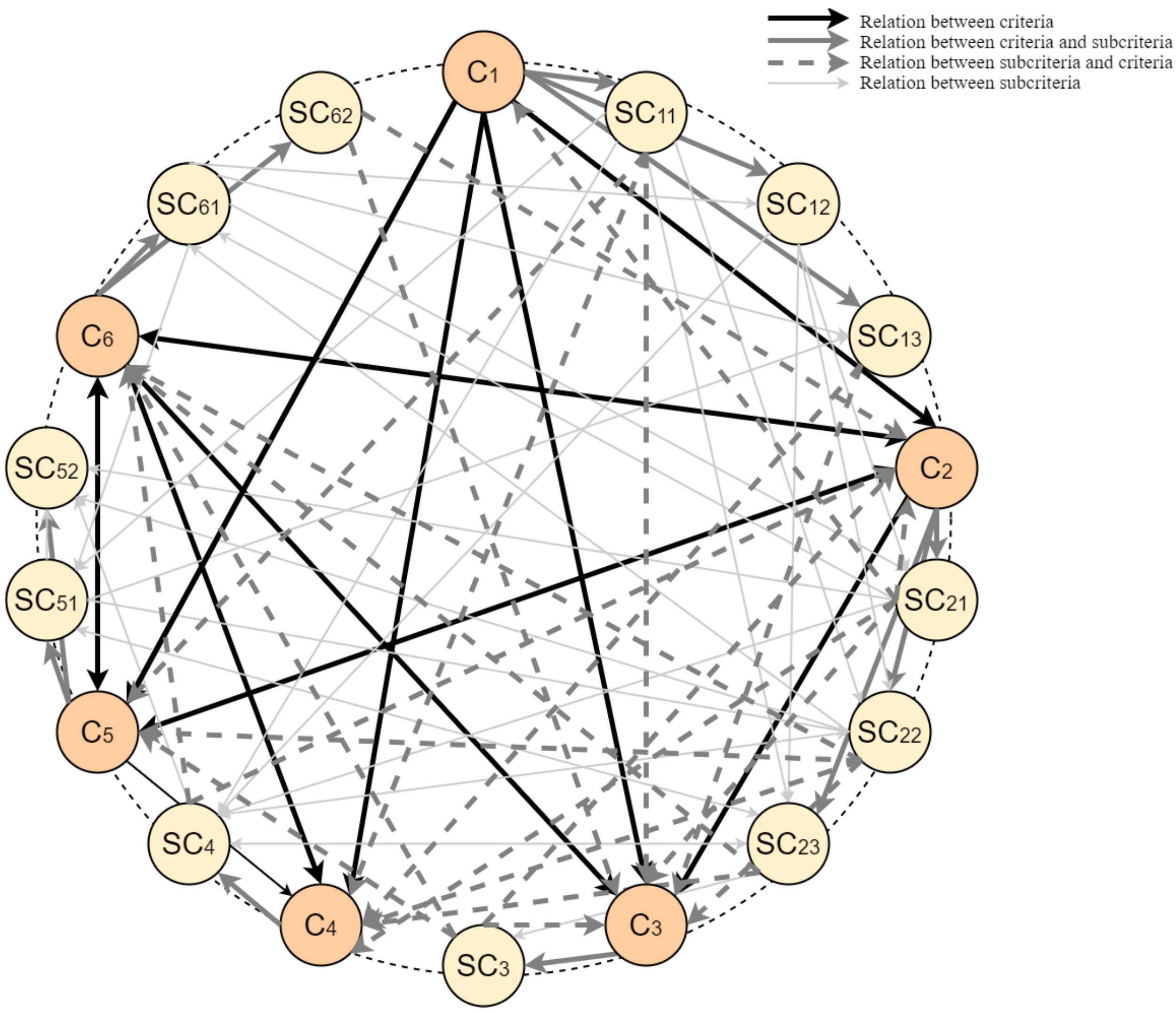

Figure 5. Relationships linking criteria and subcriteria

4. Results and discussion

The present section reports the results of the ANP and ELECTRE III applications for the above described real use case. Discussion about final results in terms of practical implications for the company are aimed at highlighting the advantages that can be derived by the integration of our MCDM framework in the management system of the company.

4.1. ANP results

As said before, the ANP method is used to calculate the importance weights of the four maintenance strategies. These values will allow us to classify them, and to select the best maintenance strategy, namely that with the highest weight.

After having identified the relationships among the elements of the problem, the AHP is extensively used to obtain, through suitable pairwise comparisons, the weights for the various relationships, giving the priorities in bold in Table 3, which presents the unweighted matrix.

Table 3. Unweighted matrix

	G	C_1	C_2	C_3	C_4	C_5	C_6	SC_{11}	SC_{12}	SC_{13}	SC_{21}	SC_{22}	SC_{23}	SC_3	SC_4	SC_{51}	SC_{52}	SC_{61}	SC_{62}	A_1	A_2	A_3	A_4
G	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C_1	0.326	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.573	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.401	0.361	0.314	0.296
C_2	0.191	0.435	0.000	0.000	0.000	0.575	0.277	0.000	0.000	0.000	0.176	0.000	0.000	0.450	0.833	0.000	0.000	0.000	0.833	0.136	0.153	0.089	0.155
C_3	0.146	0.202	0.303	0.000	0.000	0.250	0.113	0.539	0.000	0.751	0.158	0.407	0.000	0.260	0.000	0.000	0.000	0.000	0.167	0.156	0.181	0.169	0.155
C_4	0.110	0.278	0.000	0.000	0.000	0.000	0.305	0.297	0.000	0.249	0.093	0.208	0.751	0.000	0.000	0.000	0.000	0.000	0.000	0.228	0.137	0.169	0.138
C_5	0.158	0.085	0.607	0.000	0.000	0.000	0.305	0.163	0.000	0.000	0.000	0.288	0.000	0.170	0.000	0.000	0.000	0.000	0.000	0.049	0.109	0.160	0.174
C_6	0.070	0.000	0.090	0.000	0.000	0.175	0.000	0.000	0.000	0.000	0.000	0.097	0.249	0.120	0.167	0.000	0.000	0.000	0.000	0.030	0.059	0.098	0.081
SC_{11}	0.322	0.732	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_{12}	0.042	0.157	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.107	0.000	0.000	0.000	0.000	0.000
SC_{13}	0.056	0.111	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.534	0.000	0.534	0.000	0.445	0.000	0.000	0.000	0.000	0.000
SC_{21}	0.039	0.000	0.634	0.000	0.000	0.000	0.000	0.000	0.481	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.165	0.000	0.000	0.000	0.000	0.000
SC_{22}	0.065	0.000	0.260	0.000	0.000	0.000	0.000	0.535	0.276	0.000	0.000	0.000	0.000	0.319	0.656	0.319	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_{23}	0.069	0.000	0.106	0.000	0.000	0.000	0.000	0.119	0.103	0.000	0.000	0.000	0.000	0.093	0.186	0.093	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_3	0.115	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.198	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_4	0.119	0.000	0.000	0.000	1.000	0.000	0.000	0.187	0.140	0.000	0.490	0.539	0.490	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_{51}	0.046	0.000	0.000	0.000	0.000	0.700	0.000	0.159	0.000	0.000	0.000	0.000	0.312	0.000	0.000	0.000	0.000	0.283	0.000	0.000	0.000	0.000	0.000
SC_{52}	0.039	0.000	0.000	0.000	0.000	0.300	0.000	0.000	0.000	0.000	0.198	0.297	0.000	0.055	0.158	0.055	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_{61}	0.042	0.000	0.000	0.000	0.000	0.000	0.700	0.000	0.000	0.000	0.312	0.163	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_{62}	0.045	0.000	0.000	0.000	0.000	0.000	0.300	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A_1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.455	0.000	0.127	0.082	0.530	0.000	0.000	0.250	0.199	0.250	0.067	0.545	0.000	0.000	0.000	0.000
A_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.263	0.000	0.236	0.235	0.115	0.634	0.641	0.250	0.404	0.250	0.538	0.182	0.000	0.000	0.000	0.000
A_3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.141	0.000	0.373	0.449	0.221	0.106	0.206	0.250	0.188	0.250	0.165	0.128	0.000	0.000	0.000	0.000
A_4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.141	0.000	0.264	0.235	0.133	0.260	0.153	0.250	0.209	0.250	0.230	0.146	0.000	0.000	0.000	0.000

Table 4. Weighted matrix

	G	C_1	C_2	C_3	C_4	C_5	C_6	SC_{11}	SC_{12}	SC_{13}	SC_{21}	SC_{22}	SC_{23}	SC_3	SC_4	SC_{51}	SC_{52}	SC_{61}	SC_{62}	A_1	A_2	A_3	A_4
G	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C_1	0.163	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.149	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.401	0.361	0.314	0.296
C_2	0.095	0.217	0.000	0.000	0.000	0.288	0.139	0.000	0.000	0.000	0.046	0.000	0.000	0.117	0.217	0.000	0.000	0.000	0.333	0.136	0.153	0.089	0.155
C_3	0.073	0.101	0.151	0.000	0.000	0.125	0.057	0.140	0.000	0.300	0.041	0.106	0.000	0.068	0.000	0.000	0.000	0.000	0.067	0.156	0.181	0.169	0.155
C_4	0.055	0.139	0.000	0.000	0.000	0.000	0.152	0.077	0.000	0.100	0.024	0.054	0.195	0.000	0.000	0.000	0.000	0.000	0.000	0.228	0.137	0.169	0.138
C_5	0.079	0.043	0.304	0.000	0.000	0.000	0.152	0.042	0.000	0.000	0.000	0.075	0.000	0.044	0.000	0.000	0.000	0.000	0.000	0.049	0.109	0.160	0.174
C_6	0.035	0.000	0.045	0.000	0.000	0.088	0.000	0.000	0.000	0.000	0.000	0.025	0.065	0.031	0.043	0.000	0.000	0.000	0.000	0.030	0.059	0.098	0.081
SC_{11}	0.161	0.366	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_{12}	0.021	0.079	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.043	0.000	0.000	0.000	0.000	0.000
SC_{13}	0.028	0.056	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.139	0.000	0.214	0.000	0.178	0.000	0.000	0.000	0.000	0.000
SC_{21}	0.020	0.000	0.317	0.000	0.000	0.000	0.000	0.000	0.481	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.066	0.000	0.000	0.000	0.000	0.000
SC_{22}	0.033	0.000	0.130	0.000	0.000	0.000	0.000	0.139	0.276	0.000	0.000	0.000	0.000	0.083	0.171	0.127	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_{23}	0.035	0.000	0.053	0.000	0.000	0.000	0.000	0.031	0.103	0.000	0.000	0.000	0.000	0.024	0.048	0.037	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_3	0.057	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.051	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_4	0.059	0.000	0.000	0.000	1.000	0.000	0.000	0.049	0.140	0.000	0.128	0.140	0.128	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_{51}	0.023	0.000	0.000	0.000	0.000	0.350	0.000	0.041	0.000	0.000	0.000	0.000	0.081	0.000	0.000	0.000	0.000	0.113	0.000	0.000	0.000	0.000	0.000
SC_{52}	0.020	0.000	0.000	0.000	0.000	0.150	0.000	0.000	0.000	0.000	0.051	0.077	0.000	0.014	0.041	0.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_{61}	0.021	0.000	0.000	0.000	0.000	0.000	0.350	0.000	0.000	0.000	0.081	0.042	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SC_{62}	0.023	0.000	0.000	0.000	0.000	0.000	0.150	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A_1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.218	0.000	0.076	0.039	0.255	0.000	0.000	0.120	0.119	0.250	0.040	0.327	0.000	0.000	0.000	0.000
A_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.126	0.000	0.142	0.113	0.055	0.304	0.308	0.120	0.243	0.250	0.323	0.109	0.000	0.000	0.000	0.000
A_3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.068	0.000	0.224	0.215	0.106	0.051	0.099	0.120	0.113	0.250	0.099	0.077	0.000	0.000	0.000	0.000
A_4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.068	0.000	0.158	0.113	0.064	0.125	0.073	0.120	0.126	0.250	0.138	0.087	0.000	0.000	0.000	0.000

From Table 3, following step 3 of the ANP method, we obtain the weighted matrix, given in Table 4. To normalize (to sum one) the unweighted matrix's columns, weights for the problem clusters, derived from straightforward application of AHP, have been used.

The limit matrix can be calculated as described in step 4, raising the weighted matrix of Table 4 until all the columns eventually have the same values. Any of these corresponds to the Perron eigenvector of the weighted matrix, whose eigenvalue, $\lambda = 1$, is semisimple (Meyer, 2000).

This vector has to be normalised to characterise the mutual importance of criteria, subcriteria and alternatives. Values related to criteria and alternatives are shown in Table 5 as well as the related weights expressed in percentage. These weights will be the input for the ELECTRE III application.

Table 5. Criteria and alternatives' weights

ID	Criteria/Alternative	Value	Weight
C_1	Safety & Security	0.0245	17.58 %
C_2	Cost	0.0321	23.02 %
C_3	Reliability	0.0298	21.39 %
C_4	Availability	0.0192	13.75 %
C_5	Feasibility	0.0232	16.69 %
C_6	Added Value	0.0105	7.57 %
A_1	Reactive Maintenance	0.0131	19,67 %
A_2	Preventive Maintenance	0.0238	35,83 %
A_3	Condition-based Maintenance	0.0160	24,08 %
A_4	Opportunistic Maintenance	0.0136	20,42 %

From Table 5, looking at the alternatives' weights, one can see that preventive maintenance represents the best trade-off under the whole set of criteria and subcriteria herein considered. For this reason, preventive maintenance will be the final solution of the considered decision-making problem, and the maintenance policy suggested to be implemented by the company.

4.2. ELECTRE III results

Once preventive maintenance has been selected as the most suitable maintenance strategy for the analysed system, the list of maintenance interventions referring to this policy is shown in Table 6, which presents the related risks as well. The highlighted risks are the following: R_1, physical/mechanical risks; R_2, electrical risks; R_3, chemical risks; R_4, biological risks; R_5, postural and ergonomic risks; R_6, tripping/entanglement/falling risks. Risks not mentioned are considered not present or insignificant for that specific maintenance intervention.

The given information has been collected thanks to the help of the Responsible of the Prevention and Protection Service, the Responsible of the Maintenance function and the Consultant of the company. We specify that interventions are carried out during a single working turn, and that all the operations of mechanical maintenance are executed after switching off the machines.

Table 6. Risks related to maintenance interventions belonging to the selected policy

Selected policy	Maintenance intervention	Maintenance Risk
Preventive Maintenance	Accomplishing for each work phase such periodic activities as greasing and lubricating, according to manuals of use and maintenance related to each machine.	R_1, R_3, R_4, R_5, R_6
	Managing and coordinating the necessary arrangements for the normalization operations and periodic settings.	R_1, R_4, R_5, R_6
	Organising and carrying out periodic emergency simulations.	R_1, R_2, R_4, R_5, R_6
	Controlling power supplies to machines' panels and checking operational functionality of each work section with particular regard to safety and shutdown elements.	R_1, R_2, R_4, R_5, R_6
	Functional checking of pneumatic supply including compressor and approved tank.	R_1, R_4, R_5, R_6
	Carrying out cleaning and sanitizing interventions of machines to adhere to the HACCP manual and to the COVID-19 protocol, including the necessity to keep safety distance of 1.5m among operators (INAIL, 2020).	R_1, R_3, R_4, R_5, R_6

All the highlighted risks may have a negative impact on the execution and the performance level of one or more maintenance interventions, apart from the safety for operators, that is the primary objective to consider. In this sense, prioritising risks represents a best practice to support the management of the company in understanding which risks are more critical for the adopted maintenance policy and should be thus managed with priority. To such an aim, we apply ELECTRE III by considering the same evaluation criteria used for selecting the best maintenance strategy, according to the evaluations provided and the threshold established by the decision-making team of the company. Specifically, risks have been evaluated in terms of their negative impact on the mentioned criteria by using a ten-point scale.

Table 7 and Table 8 respectively present input data for the ELECTRE III application and the outranking credibility matrix with the final ranking position for each risk, highlighting priorities.
We specify that the same ranking has been obtained by the ascending and descending distillation procedures, so we can affirm that no incomparability relations exist among the alternatives considered.

Table 7. Input data for the ELECTRE III application

	C_1	C_2	C_3	C_4	C_5	C_6
weights	**0.1758**	**0.2302**	**0.2139**	**0.1375**	**0.1669**	**0.0757**
thresholds	**0-1-4**	**0-1-4**	**0-1-4**	**0-1-4**	**0-1-4**	**0-1-4**
R_1	5	2	8	8	2	5
R_2	2	2	4	4	2	2
R_3	2	2	4	4	2	2
R_4	2	2	2	2	2	2
R_5	2	2	5	5	2	5
R_6	5	2	6	6	2	5

Table 8. Outranking credibility matrix and final ranking of risks

	R_1	R_2	R_3	R_4	R_5	R_6	Ranking position
R_1	-	1	1	1	1	1	1^{st}
R_2	0	-	1	1	0.833	0.273	4^{th}
R_3	0	1	-	1	0.833	0.273	4^{th}
R_4	0	0.667	0.667	-	0.833	0	5^{th}
R_5	0.403	1	1	1	-	0.833	3^{rd}
R_6	0.667	1	1	1	1	-	2^{nd}

4.3. Discussion and practical implication

The preventive maintenance policy has been selected among other maintenance strategies as an alternative satisfactorily matching the evaluation of six criteria (i.e. safety and security, cost, reliability, availability, feasibility and added value) and related subcriteria. Subcriteria have been chosen among those proposed by the existing literature to be relevant in a practical use case. The object of study is a core subsystem of the packaging line of an Italian manufacture company.
As we can see from the final results, some risks should be managed with priority when it comes to maintenance interventions belonging to the preventive policy. We can observe that the occurrence of physical/mechanical risks, tripping/entanglement/falling risks, and postural and ergonomic risks, apart from impacting on operators' safety, may have a negative influence on the general execution

and performance of interventions. On the contrary, despite being present, biological risks are less critical within the context of analysis. The final ranking of risks provides decision-makers with a useful input to plan preventive/mitigation measures aimed at reducing the negative impact of risks on maintenance interventions, with relation to the maintenance policy implemented by the company.

Each risk belonging to the ranking should also be further analysed with respect to the associated probability of occurrence, directly depending on such parameters as the time necessary to carry out interventions and the number of interventions carried out within a defined time lapse. Moreover, by observing Table 6, it is possible to note as the most critical risks are also those related to all the maintenance interventions planned by the company. This means these risks will also have associated higher probability of occurrence with respect to the other risks, what confirms their critical nature. Main preventive/mitigation measures, for instance, should aim at supporting the maintenance crew so that the workload can be shared among diverse human resources, with the objective of reducing the exposition time of each operator to main risks and, thus, of reducing the related degree of potential dangerousness.

5. Conclusions

The present paper proposes a MCDM framework for the evaluation of the main risks related to maintenance interventions. Specifically, the ANP is first used to select the best maintenance strategy as an alternative within a complex decision-making problem with many interdependent evaluation criteria and subcriteria. After a thorough analysis of the existing literature, we collected all the main aspects and selected, among them, those subcriteria relevant for our field of interest, and applied the problem to a salt manufacture firm based in South Italy. Once selected the most suitable maintenance policy for the case under study, the ELECTRE III method has been applied to rank a set of major risks related to the execution of interventions corresponding to the chosen maintenance strategy for a core subsystem of the packaging line of the mentioned manufacturer.

To the best of the authors' knowledge, it is the first time that this combination of methods is proposed to support the specific problem object of study. The obtained results are of practical interest for the company, since the approach represents a structured way to deal in advance with main criticalities so as to minimise the impact of potential risks on such a crucial process as maintenance management. The company has now implemented our framework in its management system. We specify that the proposed framework is very flexible and can be tailored to other specific industrial needs. We also claim that it can be straightforwardly extended to any system or subsystem in which performing maintenance activities is necessary.

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