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How sustainability factors influence maintenance of water distribution systems feeding manufacturing industries

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Abstract

This work aims to analyse the role played by relevant sustainability factors towards the implementation of maintenance interventions in the manufacturing industrial sector. In this context, we focus on industrial water distribution systems, on whose effective work depends the functioning of core plants as well as general industrial facilities. In detail, we propose a Multi-Criteria Decision-Making (MCDM) application based on the use of the Analytic Network Process (ANP) as a methodological way to prioritise maintenance interventions while considering the influence of some of the most relevant sustainability factors identified in literature. The main advantage of such an approach consists in the elaboration of a flexible maintenance procedure for companies based on a well-known and reliable multi-criteria application. The novelty of our work refers to the development of a structured link between sustainability factors and maintenance management of industrial water distribution systems, something that is fundamental in manufacturing but also in other fields of application.

Keywords: Sustainability Factors; Maintenance Management; Mulit-Criteria Decision-Making; ANP; Idustrial Systems

1. Introduction and research goals

Effective maintenance management of core complex systems support companies to guarantee the achievement of many strategic objectives such as saving costs, improving workplace safety, enhancing productivity, and minimising human errors. In addition, the implementation of a quality maintenance system is fundamental to uncover maintenance trends, by exploring systems' state on a frequent basis and quickly identifying potential sources of under-performance. Despite initial investments and required set-up times, the maintenance function is nowadays more and more important within the industry, as it aims to streamline company processes while protecting assets and preventing failures. In this context, minimising the environmental impact is certainly crucial.

In the modern era, it is indeed indispensable to think about practices of sustainable maintenance aimed at developing interventions based on environmentally friendly principles with a special focus on waste reduction and impact minimisation. This is a current challenge for manufacturing industries, since the related maintenance interventions may likely require the use of materials and energy producing such hazardous byproducts as dust or emissions, with a consequent strong environment impact.

The present work analyses the influence of important sustainability factors against the implementation of interventions related to specific maintenance policies. In detail, we focus on a specific type of system, that is the water distribution system feeding industrial plants. This choice derives from the evidence that the effective functioning of this system impacts the whole set of plants as well as the level of safety and hygiene of workplaces for human resources. As a methodological procedure, we propose the use of the Analytic Network Process (ANP) to capture relations of dependence existing among sustainability factors and the most significant maintenance elements.

This paper is organised as follows. A comprehensive literature review on sustainable maintenance management and related applications is reported in Section 2. Section 3 includes the explanation of the decision-making problem in terms of significant factors and alternatives taken into account along with relevant methodological details. Section 4 discusses final results and section 5 reports conclusions and potential future lines of research.

2. Literature review

As highlighted by Vrignat et al. (2022), the integration of concepts and obligations promoting sustainable development within maintenance strategies is an active part of sustainable manufacturing, representing a concern in Industry 4.0. The authors stress as proactive and sustainable maintenance management has to adapt and promptly respond to the increasing complexity of industrial processes, being the design of innovative approaches and methods strategic for prognostics and health management. Qin et al. (2022) point out as developing a reliable equipment maintenance scheduler is essential, especially in those industrial realities dealing with large-scale problems and complex constraints. In these situations, manual scheduling methods struggle to meet managers' needs towards the optimisation of equipment reliability and cost efficiency. With relation to the last objective, Xu and Guo (2022) discuss as the budget dedicated to maintenance is naturally limited, requiring proper allocation, so that not all of the maintenance requests can be simultaneously satisfied. Similarly, systems to be maintained need to be prioritised according to their degree of criticality. Abdi and Taghipour (2019) develop a model for decision aid on equipment maintenance by analysing the causal relationship among maintenance, equipment reliability and greenhouse gases emissions. The authors aim to contribute to the identification of risks and benefits while reducing life cycle economic and environmental burdens of main assets. When it comes to life cycle analyses, Sénéchal (2016) observe as they include several environmental issues, such as consumption of energy and raw materials, pollution and emissions, disposal of solid waste, impact on water, protection of biodiversity, and so on. The amount of data required to perform these analyses can be huge, and dedicated environmental impact databases, developed by certified laboratories, are available to ease the process of diagnosis and health management of systems and/or functional units. Considering the heavy COVID-19 effects on society, economy, and environment as main sustainability pillars (Ranjbari et al., 2021), sustainable transition opportunities in maintenance should be promoted for sustainable manufacturing (Franciosi et al., 2020).

Diverse sustainability factors influencing maintenance have been studied in the existing literature and various models have been developed accordingly. Sari et al. (2021) develop a hierarchical framework to assess cleaner maintenance performance by embedding sustainability issues in maintenance management practices. Singh et al. (2020) combine expert experience to build a maintenance management systems based on significant aspects including environmental impact and material applications. Specifically, their multi-level model analyses different variables and sub-variables connected to sustainable maintenance management, *g.g.*. energy production/loss, digitalization as improvement of sustainability-related performance, water resource management in terms of supply, pollution, shortage, and so on. Liu et al. (2022) consider the necessity of including the evaluation of environmental effectiveness within the whole evaluation of maintenance system effectiveness, mostly based on economic criteria. Suresh and Dharunanand (2021) propose a model capable to measure the interactions among relevant sustainability factors identified in literature, so as to offer sustainable maintenance specifics to manufacturing industries. The authors focus on twelve major factors and propose an approach based on the integration between the Total Interpretive Structural Modeling (TISM) and the Matrice d'Impacts Croises Multiplication Appliques a un Classement (MICMAC), identifying a reduced set of key factors.

The reduced set of key sustainability factors influencing maintenance identified by Suresh and Dharunanand (2021) will constitute part of our input data. As highlighted by the authors, these factors are highly interdependent with each other. This is the main reason why the integration of a Multi-Criteria Decision-Making (MCDM) approach based on the use of the ANP may be extremely beneficial for maintenance prioritization. ANP has been largely applied (Vujanović et al., 2012; Gupta and Mishra, 2018; Carpitella and Izquierdo, 2022), being considered as adequate to enable decision makers to better understand dependence relationships existing in complex decision-making problems, something that improves the quality of final decisions (Van Horenbeek and Pintelon, 2014).

Despite the fact that MCDM methods have been largely applied in literature to deal with the evaluation of both sustainability indicators (Li et al., 2020) and general maintenance issues (Ahmed et al., 2021; Benítez et al., 2019), such authors as Olugu et al. (2021) notice as limited research has been produced on maintenance decision-making as a driver for sustainable management. To the best the authors' knowledge, an ANP-based approach evaluating the influence of sustainability factors for the prioritisation of maintenance interventions has never been proposed for optimising such critical systems as industrial water distribution networks. The present research aims to bridge this gap in order to provide manufacturing companies with a reliable tool towards the optimisation of their own industrial processes directly impacted by the efficient state of the mentioned water systems.

3. Materials and methods

This section describes the main elements of analysis by also reporting methodological details of interest. Particularly, we are going to formalise how to evaluate the influence of sustainability factors towards the implementation and prioritization of potential maintenance interventions belonging to different policies. As already mentioned, interventions refer to an industrial water distribution system, given the main role played by these kinds of networks in serving manufacturing facilities. First of all, the decision-making problem is going to be exemplified by defining the decision-making elements (*i.e.* criteria and alternatives) relevant to the analysis. Secondly, a brief description of the ANP is recalled.

3.1. The decision-making problem

The general goal of our decision-making problem consists in prioritising maintenance interventions for the water network which feeds the industrial plants and facilities of a manufacturing company operating in the alimentary sector and located in the South of Italy (Carpitella et al., 2018). As evaluation criteria we assume the main relevant sustainability factors influencing maintenance management in manufacturing contexts, as resulting from the study led by Suresh and Dharunanand (2021). The same authors highlight as water is among the most important resources in the manufacturing sector, since it contributes to the quality of final products, and this consideration strengthens the purpose of our application. Table 1 reports those sustainability factors considered as more influential, and whose interdependence may likely impact long-term maintenance in manufacturing sectors. These factors occupy the first positions of the MICMAC ranking, as it can be checked in (Suresh and Dharunanand, 2021).

Once defined the set of evaluation criteria, the list of alternatives, *i.e.* maintenance interventions to be prioritised, is reported in Table 2. The ANP is going to be first described in the next subsection and then practically applied in the following section to analyse relations existing within the set of elements and to eventually derive a ranking of interventions on the basis of sustainability factors.

Table 1. Sustainability factors identified by Suresh and Dharunanand (2021)

Factor	Description
$\mathbf{SF_1}$: Availability rate	It refers to two aspects that are raw materials and skilled labor, both fundamental for maintenance activities.
$\mathbf{SF_2}$: Government policies	They are responsible to provide a safe and suitable environment for human resources by impacting on internal and external factors of the company.
$\mathbf{SF_3}$: Training and education	It is one of the main driving forces for organizational growth, promoting the integration of modern technologies and innovative learning methods.
$\mathbf{SF_4}$: Machine modernization	Upgraded machines help in being competitive and sustainable by optimising performance and product quality while minimising breakdowns and failures.
$\mathbf{SF_5}$: Employee competence	It refers to the competence of employees in executing their own job on the basis of their level of skills. Improving competence supports organizations towards sustainable maintenance involved in manufacturing processes.

Table 2. Maintenance interventions to be prioritised

Mainten. policy	Intervention description
Preventive	$\mathbf{MI_1}$: Redundant electric pumps.
Corrective	$\mathbf{MI_2}$: Preliminary supply of special parts. $\mathbf{MI_3}$: Intensification of plants flexibility. $\mathbf{MI_4}$: Availability of a back-up water storage.
Predictive	$\mathbf{MI_5}$: Implementing a tele-surveillance system.

3.2. Steps to apply the ANP

The ANP is an established MCDM technique which was developed by Thomas Saaty (Saaty, 2004) as an advancement of the Analytic Hierarchy Process (AHP) (Saaty, 1977). ANP is commonly implemented to support decision-making problems by evaluation their mostly relevant elements (*i.e.* nodes). The final output consists in the calculation of a vector of weights by taking into account the existence of relations of dependence among nodes. Nodes have to be categorised as criteria, subcriteria and alternatives (*i.e.* clusters) so that the decision-making problem can be represented through an exemplifying hierarchical structure. As in the case of the AHP technique, weights of alternatives are evaluated with respect to criteria and subcriteria, while weights of subcriteria are calculated with respect to criteria and, lastly, weights of criteria are determined with respect to the general goal of the problem, previously established. As recalled in a previous work (Carpitella et al., 2021), the ANP technique is implemented as follows.

- Representing the problem under analysis by first building a hierarchical structure, where nodes and clusters are clearly defined and codified. Once formalised such a structure, we will proceed by identifying relations of dependence bounding nodes with each other, something that has to be analysed both among nodes of the same clusters and among nodes of different clusters. To such an aim, reliable opinions elicited by a suitable decision-making panel made of experienced stakeholders are going to be crucial.
- Drawing up the influence matrix which formalises the relations of dependence among nodes that had been previously identified. The influence matrix is a square block matrix, its size corresponding to the total number of nodes, its blocks to the total number of clusters, and its entries a_{ij} being equal to 1 if a relation of dependence between element j over element i is identified, 0 otherwise. The influence matrix can be assumed as a sort of a template for building the unweighted supermatrix.

- Compiling the unweighted supermatrix, something that is done according to the non-zero-entry structure of the previously described influence matrix. Specifically, those nodes for which a relation of dependence exists ($a_{ij} = 1$) are going to be pairwise compared, and the weights for the corresponding elements in each cluster are calculated by means of, for instance, the AHP or one of the other techniques commonly known in literature. The obtained weights will be the entries of the unweighted supermatrix, for which the sums of the columns must equal the number of clusters for which a comparison has been performed.
- Building the weighted supermatrix through a suitable normalisation procedure, for which the sums of the columns will be equal to one. In such a way, the matrix gets stochastic.
- Calculating the limit matrix by raising to powers the previously obtained weighted supermatrix. All the columns of the limit matrix are equal, and each one of them represents the global priorities, to be eventually normalised with relation to each cluster in order to formalise the final vector of weights.
- Formalising the final vectors of weights, embodying the dependencies accumulated throughout the successive powering of the weighted supermatrix. Specifically, those elements associated with higher values of weights should be considered with priority to carry out the decision-making process under analysis.

3.3. Real case study

We are going to apply the previously described ANP by first formalising the hierarchy structure related to the decision-making problem analysed. Such a structure is reported in Figure 1, which shows the dependence relations identified within the sets of elements, *i.e.* sustainability factors (criteria) of Table 1 and maintenance interventions (alternatives) of Table 2. This stage has been accomplished with the support of the maintenance chief currently in charge at the company. Specifically, for each pair of decision-making elements, the maintenance chief has been asked whether, according to his opinion, a relation exists or not. As it can be noticed, we have used the grey colour to represent connections between two different clusters (*i.e.* connections between goal and criteria and connections between criteria and alternatives), while we have used the black colour for connections identified within the same clusters (*i.e.* connections between pairs of criteria and connections between pairs of alternatives).

Once formalised relations as well as the influece matrix (herein not reported for the sake of space), the unweighted supermatrix (Table 3) and the weighted supermatrix (Table 4) are given. By raising to powers the weighted supermatrix, we calculate the limit matrix, reported in Table 5. Various practical considerations can be formulated by normalising any of the columns of the limit matrix with relation to each cluster to obtain the final vector of weights.

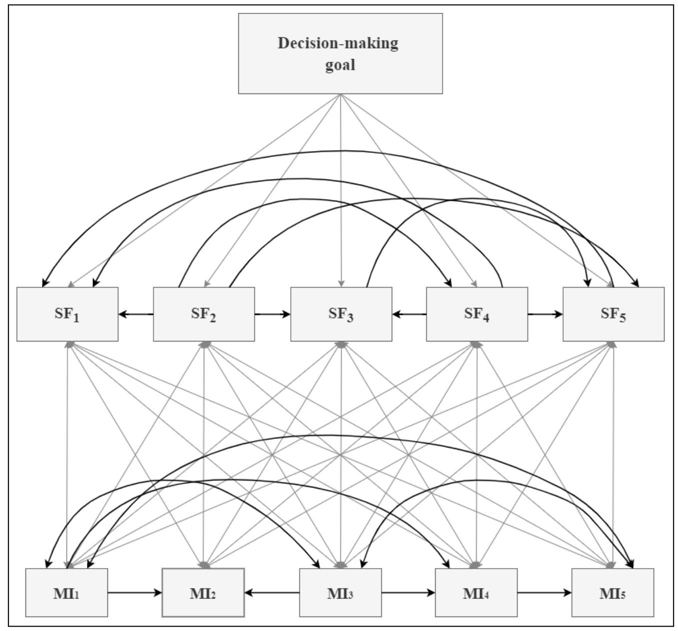

Figure 1. ANP hierarchy structure representing dependence relations

We specify that weights reported in Table 3 have been assigned by the general manager of the company during a dedicated brainstorming session. Details about the mathematical procedure to get the limit matrix are recalled in a previous work (Carpitella et al., 2018). The final results of the ANP procedure are formalised in Table 6 where, for each decision-making element (*i.e.* criterion and alternative) the corresponding normalised value of any of the columns of the limit matrix is reported along with the related weight, the last one expressed in percentage.

4. Results and Discussion

At a practical level, we may appreciate as the availability rate is the sustainability factor having associated the highest weight, that is the factor which influences more the process of maintenance interventions scheduling. This factor is followed, in order, by machine modernization and employee competence, both of them perceived as having the same importance, and by the criterion of training and education. Despite impacting all of the remaining factors, government policies have associated the lowest weight since their formulation depends more on exogenous actions. By considering such a combination of weights for criteria, the ANP technique recommends to carry out the prioritisation of maintenance interventions by implementing an intelligent monitoring system aiming at potentiating the control on the industrial water distribution network, and consequently minimising the shutdown risk. This intervention may be followed by the redundancy of pumps, belonging to the preventive maintenance policy. Interventions of corrective maintenance may be postponed, having the less beneficial impact on the availability rate and on sustainability on the whole.

Table 3. Unweighted supermatrix

	Goal	SF$_1$	SF$_2$	SF$_3$	SF$_4$	SF$_5$	MI$_1$	MI$_2$	MI$_3$	MI$_4$	MI$_5$
Goal	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SF$_1$	0.200	0.000	0.100	0.000	0.600	0.200	0.500	0.600	0.600	0.600	0.200
SF$_2$	0.300	0.000	0.000	0.000	0.000	0.000	0.200	0.100	0.100	0.100	0.200
SF$_3$	0.100	0.000	0.300	0.000	0.400	0.000	0.100	0.100	0.100	0.100	0.200
SF$_4$	0.300	0.000	0.300	0.000	0.000	0.800	0.100	0.100	0.100	0.100	0.200
SF$_5$	0.100	0.000	0.300	1.000	0.000	0.000	0.100	0.100	0.100	0.100	0.200
MI$_1$	0.200	0.300	0.300	0.200	0.200	0.200	0.000	0.000	0.250	0.000	0.500
MI$_2$	0.150	0.030	0.100	0.150	0.050	0.100	0.300	0.000	0.250	0.000	0.000
MI$_3$	0.200	0.050	0.100	0.150	0.200	0.250	0.300	0.000	0.000	0.000	0.500
MI$_4$	0.150	0.020	0.100	0.100	0.050	0.050	0.100	0.000	0.250	0.000	0.000
MI$_5$	0.300	0.600	0.400	0.400	0.500	0.400	0.300	0.000	0.250	1.000	0.000

Table 4. Weighted supermatrix

	Goal	SF$_1$	SF$_2$	SF$_3$	SF$_4$	SF$_5$	MI$_1$	MI$_2$	MI$_3$	MI$_4$	MI$_5$
Goal	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SF$_1$	0.100	0.000	0.050	0.000	0.300	0.100	0.250	0.600	0.300	0.300	0.100
SF$_2$	0.150	0.000	0.000	0.000	0.000	0.000	0.100	0.100	0.050	0.050	0.100
SF$_3$	0.050	0.000	0.150	0.000	0.200	0.000	0.050	0.100	0.050	0.050	0.100
SF$_4$	0.150	0.000	0.150	0.000	0.000	0.400	0.050	0.100	0.050	0.050	0.100
SF$_5$	0.050	0.000	0.150	0.500	0.000	0.000	0.050	0.100	0.050	0.050	0.100
MI$_1$	0.100	0.300	0.150	0.100	0.100	0.100	0.000	0.000	0.125	0.000	0.250
MI$_2$	0.075	0.030	0.050	0.075	0.025	0.050	0.150	0.000	0.125	0.000	0.000
MI$_3$	0.100	0.050	0.050	0.075	0.100	0.125	0.150	0.000	0.000	0.000	0.250
MI$_4$	0.075	0.020	0.050	0.050	0.025	0.025	0.050	0.000	0.125	0.000	0.000
MI$_5$	0.150	0.600	0.200	0.200	0.250	0.200	0.150	0.000	0.125	0.500	0.000

Table 5. Limit matrix (normalised values)

	Goal	SF$_1$	SF$_2$	SF$_3$	SF$_4$	SF$_5$	MI$_1$	MI$_2$	MI$_3$	MI$_4$	MI$_5$
Goal	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SF$_1$	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168	0.168
SF$_2$	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049
SF$_3$	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065
SF$_4$	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081
SF$_5$	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081
MI$_1$	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147	0.147
MI$_2$	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
MI$_3$	0.109	0.109	0.109	0.109	0.109	0.109	0.109	0.109	0.109	0.109	0.109
MI$_4$	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034
MI$_5$	0.213	0.213	0.213	0.213	0.213	0.213	0.213	0.213	0.213	0.213	0.213

We specify that such results are valid according to the perception of the general manager of the company and on the basis of the dependence relations previously identified by the subject in charge of the maintenance function. Results may indeed change by varying the interviewed panel of experts and the company of reference. This confirms the flexibility of the proposed approach as an effective tool supporting decision-making and dealing with sustainability aspects interconnected with each other.

Table 6. Criteria and alternatives weights

Criteria/alternative	Normalised value	Weight (%)
SF$_1$	0.1682	37.97%
SF$_2$	0.0485	10.96%
SF$_3$	0.0646	14.59%
SF$_4$	0.0808	18.24%
SF$_5$	0.0808	18.24%
MI$_1$	0.1472	26.42%
MI$_2$	0.0541	09.71%
MI$_3$	0.1091	19.58%
MI$_4$	0.0341	6.11%
MI$_5$	0.2126	38.17%

5. Conclusions and future directions

This work explores the interconnections among significant sustainability factors analysed in literature and their influence on maintenance management in the manufacturing sector. We analysed factors and models studied and developed so far to come to a selected list of sustainability factors and maintenance interventions, interdependent with each other. In detail, we aim to optimise the functioning of water networks feeding industrial plants and facilities by considering sustainability factors as criteria and maintenance interventions as alternatives of the decision-making problem, herein solved via the ANP.

This technique is particularly adequate to take into account the existence of interdependence within a set of decision-making elements. Final results obtained for a real Italian manufacturing company operating in the alimentary sector confirm to be relevant when supporting the maintenance scheduling process. In detail, when it comes to implications in terms of sustainability, the application of the ANP guarantees the possibility to highlight relevant factors for maintenance planning and scheduling, while being cost effective and time saving. It indeed leads to the identification of availability rate, machine modernization and employee competence as the three sustainability factors having associated highest impacts on maintenance interventions. On their turn, maintenance interventions should be prioritised starting from the implementation of an intelligent monitoring system potentiating network control. The method highlights as the remaining sustainability factors, i.e. training and education and government policies, have associated lower impacts.

Potential future lines of research may refer to the implementation of a hybrid multi-criteria approach aimed at producing a multi-level sustainability matrix capable to contemplate the presence of diverse stakeholders. We may proceed towards the prioritisation of maintenance activities by simultaneously taking into account the importance attributed to sustainability factors by the company itself as well as the subjective perceptions about the same factors of external stakeholders, the last ones being directly or indirectly involved with the company business. Furthermore, the use of such mathematical tools as, for instance, the fuzzy set theory or the probability theory may be helpful to integrate considerations about uncertainty and vagueness of input evaluations in our model. Lastly, the ANP method could be extended also to potentiate other management areas not limited to the sustainability topic such as, for instance, the optimisation of safety and security in manufacturing by analysing interdependence among relevant human risks.

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