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PRIORITIZATION OF MAINTENANCE ACTIONS IN WATER DISTRIBUTION SYSTEMS

S. Carpitella[1,2], F. Carpitella[3], J. Benítez[2], A. Certa[1] and J. Izquierdo[2]

1: Dipartimento dell'Innovazione Industriale e Digitale (DIID), Ingegneria Chimica, Gestionale, Informatica, Meccanica
Università degli Studi di Palermo
Piazza Marina, 61, 90133 Palermo, Italy
e-mail: {silvia.carpitella@unipa.it, antonella.certa@unipa.it}, web: http://www.unipa.it/dipartimenti/diid

2: Instituto de Matemática Multidisciplinar
Universitat Politècnica de València
Camino de Vera s/n, 46022 Valencia, Spain
e-mail: {jbenitez@mat.upv.es, jizquier@upv.es}, web: http://www.imm.upv.es/

3: Studio di Ingegneria Carpitella Management Consulting
Via Nicolò Fabrizi, 3, 91100 Trapani, Italy
e-mail: fortunato.carpitella@ordineingegneritrapani.it

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Abstract *Industrial water distribution systems are paramount in many manufacturing systems to optimise the related industrial plant availability and consequently the level of production. They also play an important part in keeping right standards of hygiene of workplaces and machines. A strategic action of planning and implementing of suitable maintenance activities is necessary to assure the standards previously described. The present contribution proposes the prioritization of maintenance actions for industrial water distribution systems through a multi-criteria decision making approach, since some of the elements integrated in maintenance-related aspects are not easily quantifiable and, on the contrary, may be classified as subjective and intangible. This prioritization seeks to pursue technological innovation and may represent a long-term strategy for the organization based on personnel expertise. The AHP technique is suggested to obtain a ranking of maintenance actions. Actions with a lower degree of priority will be postponed on the basis of appropriate time planning. A case study on the real industrial water distribution system belonging to a manufacturing firm is finally presented.*

1. INTRODUCTION

Industrial water distribution systems (IWDSs) are crucial for many industries [1,2] because of the primary need to enhance availability of systems [3]. Indeed, water naturally represents the most important resource by means of which any industrial activity can be carried out. Not only does this resource permit to run production, but also it is indispensable to respond to regulation standards in terms of hygiene [4] of workplaces and machines. With this perspective, manufacturing firms broadly dedicate many efforts to improve water management [5] and to reduce wastewater [6].
Various faults may affect IWDSs that have a negative impact on the related industrial plant and may possibly lead to the worst event of a plant shutdown [7]. Different maintenance actions, tailored for the features of the IWDS under analysis, can be implemented [8], based on the kind of maintenance policy [9] preferred by the organization and according to different criteria. This choice depends on the operative context and business strategies [10].
Given the primary importance of this aspect in industrial environment, the present research deals with the optimisation of IWDSs by means of a multi-criteria decision-making approach. In particular, this paper proposes the Analytic Hierarchy Process (AHP) [11], a multi-criteria decision-making method, as a tool for prioritizing different maintenance activities and pursuing technological innovation. The alternatives of the decision problem are represented by maintenance actions belonging to predictive and preventive maintenance policies. The alternatives are evaluated by means of various criteria weighted by a panel of experts. Decision makers have different weights in the decisional process.
The research is organised as follows: section 2 provides the reader with a description of the main categories of maintenance policies; section 3 presents the AHP technique; section 4 shows the application of a case study related to a manufacturing firm; and, lastly, conclusions close the work.

2. MAINTENANCE POLICIES

IWDS can be considered as one of the most critical sub-systems of a generic industrial plant. Indeed, service disruption caused by a number of system malfunctions may be a dangerous cause of plant shutdown. For this reason, the process of maintenance management of an IWDS positively influences the main functions of the relative industrial plant in terms of productivity, reliability and availability.
Several kinds of maintenance interventions can be led with the aim of keeping IWDSs in effective conditions of work. The analysis of these actions through a multi-criteria perspective is helpful in implementing a strategy globally oriented towards optimisation of industrial processes management.
Maintenance actions refer to three main groups of maintenance policies, which are corrective [12], preventive [13] and opportunistic [14]. Their descriptions, strengths and weaknesses are reported in Table 1. Moreover, the preventive maintenance policy can be developed and improved by means of diagnostic tools to monitor the degrading state of components [15]. Generally, the purpose consists in predicting in the most reliable way the instant of time for the execution of maintenance interventions. This kind of action is

called predictive maintenance [16] and represents a current challenge faced by organisations.

Policy	Description	Strenghts	Weaknesses
Corrective maintenance	Interventions of corrective maintenance are carried out upon the occurrence of failures. An action of replacement or repair should be accomplished in the minimal time as possible.	• Exploitation of the whole useful life of components; • Minimisation of the number of interventions.	• High risk of plant shutdown; • Negative impact on production, reliability and availability.
Preventive maintenance	Interventions of preventive maintenance are generally realized at constant intervals. The research of the optimal value of interval is aimed at continuously increasing system condition.	• Positive impact on production, reliability and availability; • Control of costs.	• Execution of several interventions, even if not always necessary.
Opportunistic maintenance	This kind of policy considers the possibility of exploiting a period of plant shutdown to conduct maintenance interventions on components for which the planned time of intervention is close but not totally reached.	• Positive impact on production, reliability and availability; • Minimisation of the time to be dedicated to maintenance interventions.	• Execution of several interventions, even if not always necessary.

Table 1. Maintenance policies

Within the mentioned policy categories, several maintenance interventions can be planned and implemented. In particular, according to the strategic choices undertaken by the organisation, interventions need to be scheduled, eventually evaluating possibilities of integration among them.

The multi-criteria decision-making method AHP is herein proposed to support the scheduling process of maintenance actions with relation to IWDSs. Actually, the AHP [11] technique is particularly useful in ranking decisional alternatives on the basis of different evaluation criteria. The obtained ranking of maintenance actions suggests a possible order to be followed in implementing them. In particular, the mentioned alternatives are ranked upon having been pairwise compared by means of judgments expressed by an expert or a group of decision makers.

3. AHP TECHNIQUE DESCRIPTION

The application of the AHP technique is carried out by decomposing the decision problem into different levels of a hierarchical structure. The objective of the problem represents the topmost level, the evaluation criteria are placed in the intermediate level, whereas the alternatives to be ranked occupy the last level of the structure. The elements reported in each level are pairwise compared with relation to a specific element of the immediate upper level. The pairwise comparison judgments are expressed by using the numerical values proposed in the Saaty scale [17], and then collected in the pairwise comparison matrix. In particular, when a group of differently weighted decision makers is involved [18], it will be necessary to follow these steps: 1. asking to each decision maker to express a pairwise comparison between each couple of criteria; 2. aggregating judgments in a single matrix, called aggregated pairwise comparison matrix.

A typical way to carry out the second step consists in aggregating judgments through the geometrical mean, in order to assure the property of reciprocity.

Moreover, an aspect that needs to be taken into account regards the consistency of pairwise comparisons [19]. If the consistency ratio (*CR*) exceeds the allowed threshold [11], it means that judgments could not be reliable and should be formulated again.

The following case study proposes the use of the AHP technique to rank five alternatives, which are maintenance actions related to the optimisation of a real IWDS.

4. CASE STUDY

The present case study refers to a manufacturing firm that has to decide about implementing one or more among five maintenance actions (MA_1, MA_2, MA_3, MA_4, MA_5) aimed at keeping a well-functioning IWDS and, consequently, minimizing the plant shutdown risk. These actions are tailored on the industrial water distribution system which feeds the plants of the same firm. In particular, the firm has established to prioritize the actions, with the purpose of finding a trade-off between improving plant condition while not shouldering the simultaneous implementation of many interventions. The AHP technique is applied to obtain the final ranking. The maintenance actions belong to the following categories of maintenance policies: preventive, corrective and predictive. The description of the actions focused on the IWDS with relation to their policy categories is provided in Table 2.

Policy	ID Alternative	Maintenance action description
Preventive	MA_1	Redundancy of electric pumps;
Corrective	MA_2	Preliminary supply of “special parts” (such as valves, fittings, pipes), to make eventual substitution interventions faster;
	MA_3	Intensifying plant flexibility by increasing the number of disconnection points in the water network, to close off those parts to be maintained, avoiding the plant shutdown;
	MA_4	Creation of a water storage, in case of sudden interruption of the water service;
Predictive	MA_5	Implementation of a tele-surveillance system for the water feeding, to keep monitored parameters as temperature, flow rate, pressure.

Table 2. Description of the maintenance actions to be ranked

The maintenance actions are evaluated by means of four different criteria (C_1, C_2, C_3, and C_4). The evaluation criteria taken into account are, respectively: security, cost, productivity, and hygiene.
In detail, the first criterion refers to the plant's compliance with the regulations in force. The second criterion regards the cost for implementing an action and facing a possible plant shutdown. The third criterion is related to the fulfilment of production standards and then to the need of keeping available the system. Lastly, the fourth criterion evaluates the respect of hygiene conditions referred to drinking water supply to the personnel and plant sanitation. The hierarchical structure of the problem is represented in Figure 1.

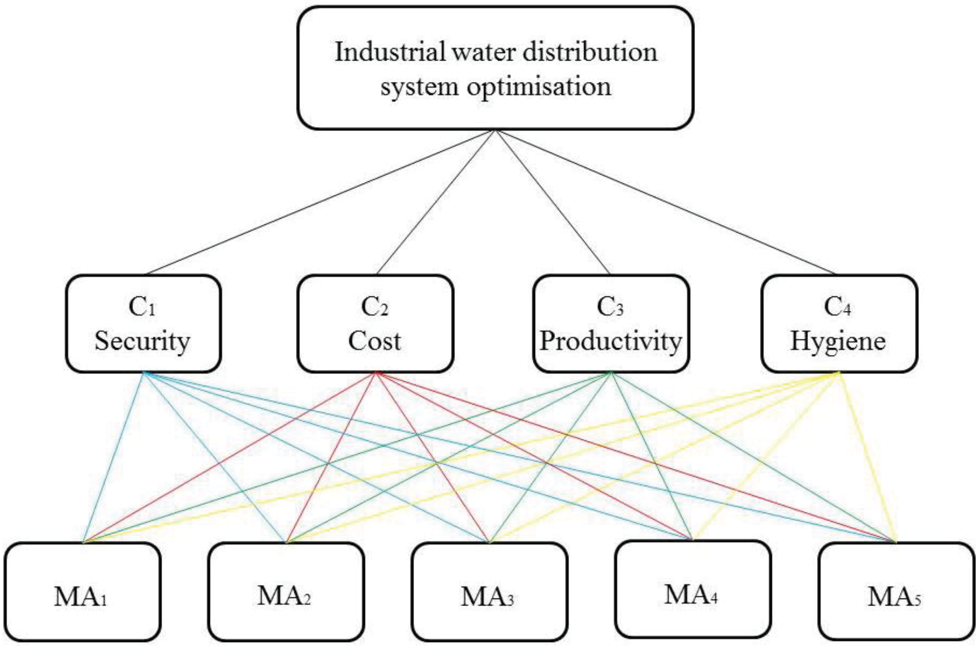

Figure 1. Hierarchical structure

The vector of criteria weights was obtained by involving a decision group, whose components (D_1, D_2, and D_3) are assumed to have different weights in the decision process. Table 3 shows the roles of each decision maker, their weights and the consistency values related to their pairwise comparison judgments, the last ones reported in Table 4.

Decision maker	**Role**	**Weight**	***CR***
D_1	Technical Responsible	40%	0.0724
D_2	Responsible of the Quality Management System	35%	0.0394
D_3	Responsible of Productivity	25%	0.0495

Table 3. Roles and weights of the decision makers

D_1	C_1	C_2	C_3	C_4
C_1	1	5	4	1
C_2	1/5	1	3	1/5
C_3	1/4	1/3	1	1/5
C_4	1	5	5	1

D_2	C_1	C_2	C_3	C_4
C_1	1	3	3	1
C_2	1/3	1	2	1/5
C_3	1/3	1/2	1	1/4
C_4	1	5	4	1

D_3	C_1	C_2	C_3	C_4
C_1	1	1/3	1/6	1/4
C_2	3	1	1/3	2
C_3	6	3	1	3
C_4	4	1/2	1/3	1

Table 4. Criteria evaluations respect to the decision makers

The pairwise comparison judgements are aggregated in a single matrix (Table 5) by means of the geometric mean method, and the vector of criteria weights has been evaluated via the power method.

	C_1	C_2	C_3	C_4	Weights
C_1	1	2.125	1.634	0.707	**28.70%**
C_2	0.471	1	1.503	0.356	**16.43%**
C_3	0.612	0.665	1	0.426	**14.92%**
C_4	1.414	2.812	2.350	1	**39.95%**

Table 5. Aggregated matrix and criteria weights

Table 6 reports the alternatives' evaluations related to the considered criteria. The last two columns, respectively, give the local priorities (being the Perron vectors of the matrices calculated via the power method), and the values of consistency ratios *CR*. In particular, the judgments' consistency is verified, because all the *CR* values do not surpass the threshold of 0.1 [11].

C_1	MA_1	MA_2	MA_3	MA_4	MA_5	Local priorities	*CR*
MA_1	1	5	4	2	1/3	0.2383	
MA_2	1/5	1	1	1/3	1/6	0.0579	
MA_3	1/4	1	1	1/3	1/3	0.0755	0.0748
MA_4	1/2	3	3	1	1/6	0.1387	
MA_5	3	6	3	6	1	0.4896	

C_2	MA_1	MA_2	MA_3	MA_4	MA_5	Local priorities	*CR*
MA_1	1	1/3	5	1/4	7	0.1162	
MA_2	3	1	2	1	9	0.3231	
MA_3	1/5	1/2	1	2	7	0.2620	0.0708
MA_4	4	1	1/2	1	9	0.2710	
MA_5	1/7	1/9	1/7	1/9	1	0.0278	

C_3	MA_1	MA_2	MA_3	MA_4	MA_5	Local priorities	*CR*
MA_1	1	6	5	4	1/4	0.2672	
MA_2	1/6	1	1/2	1/2	1/7	0.0461	
MA_3	1/5	2	1	3	1/5	0.1011	0.0838
MA_4	1/4	2	1/3	1	1/6	0.0640	
MA_5	4	7	5	6	1	0.5217	

C_4	MA_1	MA_2	MA_3	MA_4	MA_5	Local priorities	*CR*
MA_1	1	7	3	7	1/5	0.2449	
MA_2	1/7	1	1/4	1	1/7	0.0430	
MA_3	1/3	4	1	3	1/5	0.1143	0.0809
MA_4	1/7	1	1/3	1	1/7	0.0448	
MA_5	5	7	5	7	1	0.5530	

Table 6. Evaluation of alternatives with respect to criteria, local priorities and *CR* values

On the basis of criteria weights, the global score for each alternative has been obtained by applying the weighted sum of their local priorities and the final ranking is shown in Table 7.

Position	Alternative	Score
1st	MA_5	0.4438
2nd	MA_1	0.2252
3rd	MA_3	0.1255
4th	MA_4	0.1118
5th	MA_2	0.0938

Table 7. Ranking of maintenance actions

5. CONCLUSIONS

The present research supports the usefulness of assuming a multi-criteria decision making perspective concerning the optimisation of IWDSs, which have a fundamental impact on industrial plants performance. The proposed case study shows the application of the AHP technique to rank five maintenance actions tailored on the IWDS of a manufacturing firm.

The ranking achieved by means of the AHP technique suggests prioritizing the five maintenance actions starting from the MA_5 alternative, which belongs to the predictive

maintenance policy. Moreover, it is possible to note that the corrective policy has not a relevant priority in minimizing the plant shutdown risk, and the relative interventions may be postponed.
Further developments may regard the application of the AHP technique supported by the probability theory in the field of IWDS management optimisation. This support would aim to determinate the values of some pairwise comparisons characterised by uncertainty, in other terms, when decision makers are asked to express their judgments and they have some doubts about one or more values to assign.

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