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Multivariable Based Decision-making for the Maintenance Strategy of Process Equipment

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Nowadays, several pieces of equipment are running over their expected life-time. An equipment revamping could solve the situation, but, it is often not possible for economical reasons, regulatory constraints, etc.. The aging of the equipment can also cause safety problems: between 1980 and 2006, the Health and Safety Executive estimated that around 28% of the major incidents occurred in the period, corresponding to 96 accidents, could be traced back to plant aging. These accidents costed more than 17,000,000 € (Horrocks et al., 2010).
A correct maintenance of the equipment can extend the plant life, increase the plant efficiency and maintain an adequate level of safety. Plant management can choose among different maintenance strategies. The choice can be influenced by parameters as: the maintenance cost, the equipment condition before the maintenance, the lack of production cost, the safety of the operator during the maintenance and during the normal operations.
In this paper, a multivariable Fuzzy approach is proposed in order to support the decision between different maintenance strategies through the analysis of their peculiarities, helping the management to weight the pros and cons of the alternatives. This approach is applied to a case study related to the maintenance of process equipment: it highlighted that the full refurbishment of a turbine blades system is a maintenance approach as valid as the current maintenance procedure, while the adoption of new technologies resulted not convenient.

1. Introduction

A good maintenance design is fundamental for a company. Maintenance can extend the plant life-time, increase the plant efficiency and the energy saving (Demichela at al., 2018, Darabnia and Demichela, 2013).
The maintenance can be designed in a reactive or in a preventive way.
In the reactive approach, the equipment is fully used, and the maintenance is carried on only after faults. But, in this way, the plant stop is unplanned, with consequently higher costs and loss of production (Weil, 1998). In order to minimize the cost and the time of maintenance, the company has to adopt extensive spare part storage. Moreover, the equipment faults can also cause incidents and environmental release (Gallimore and Penlesky, 1988).
On the contrary, the preventive maintenance requires to perform the activities at given time intervals, before a fault occurs. In this way, the plant stop can be planned (Gits, 1992) and the spare part supply is rationalized. Different studies show the convenience of the preventive maintenance, like i.e. Lee (2005).
The preventive maintenance is particularly suitable for the aging of the equipment. Aging can be dangerous for a company, e.g. between 1980 and 2006, the process of aging plant is co-responsible in the 28% of the major accident recorded by the Major Accident Reporting System data base (Horrocks et al., 2010). Aging plants negatively affect productivity too: because of their traditional and not updated technology, they are less flexible in terms both of product quantity and type (Reay et al., 2013), and allow lower energy saving (Baldissone et al., 2017).
In order to carry out a preventive maintenance approach, the plant management can adopt different maintenance solutions: one or more devices can be replaced (with an analogus one, or with new models) or they can be only checked and restored. Obvioulsy, each maintenance solution has different pros and cons

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that embrace different aspects, such as the cost, the productivity or the maintenance duration. In order to guide the plant managers to choose the best options, keeping into account all these parameters, the proposed method, was developed: using fuzzy logic, it allows comparing the different strategies on the basis of an unique value.
Literature reports different methods to optimize the maintenance strategy (Ding and Komaruddin, 2015), such as: analytic hierarchy process, weighted sum method and elimination, choice translating reality. Some of these methodologies apply fuzzy logic too, to deal with the data uncertainties, but they can be quite complex and time-spending. The proposed approach can function as a quick method to rapidly identify the best maintenance strategy; then, further doubts and clarifications can be tested and analysed using the existing techniques.
In this paper, a multivariable method for the comparison between maintenance strategies is described. The proposed method uses 6 variables to verify if a maintenance option is globally advantageous or not with respect to a reference one.

2. Material and methods

The proposed method compares different maintenance options with a reference one on the basis of a set of relevant parameters. The maintenance option used as reference (standard maintenance strategy) can be the one usually adopted in the company or the one suggested by the equipment producer. The results of the proposed method are a global assessment of the advantages or disadvantages of the proposed strategy with respect to the standard one.
The proposed method is based on the fuzzy logic. Fuzzy logic approach is adopted for different multivariable problems: e.g. the occupational risk assessment as in Papazoglou et al. (2017) and, for a more a specific field of application, the steel industry, in Murè and Demichela (2009) or construction sites, as in Gürcanli and Müngena (2009). It has been also adopted in maintenance decision making, as in Vafaei et al (2019) and Borjalilu and Ghambari (2018).
The fuzzy logic adoption requires to define the input and output variables and a set of rules describing how the input variables influence the output variable.

2.1 Input variables

6 input variables are used for the proposed method: some refer to the maintenance activities themselves (Cost, Duration, Economical risks and Safety), other to the equipment state after the maintenance (Time and Performance). The input variables are defined as comparisons between the data regarding the analysed maintenance strategy and the reference one, as shown by the following Equations.
The input variables are:

- Cost (*C*); comparison between the economical cost conveniences, Eq.(1):

$$C = \frac{c_0}{c_1} \tag{1}$$

  Where c_0 is the cost of the reference maintenance activity and c_1 is the cost of the analysed one.
- Time (*T*); comparison of the time required before the next planned maintenance , Eq. (2):

$$T = \frac{t_1}{t_0} \tag{2}$$

  Where t_1 is the time to the next maintenance foreseen by the analysed strategy, and t_0 is the time to the next maintenance foreseen by the reference strategy.
- Performance (*P*); comparison between the performances of the equipment, Eq. (3):

$$P = \frac{p_1}{p_0} \tag{3}$$

  Where p_1 is the performance (in terms of power produced, productivity, …) of the equipment after the analysed maintenance strategy; p_0 is the performance of the equipment after the reference maintenance strategy.
- Duration (*D*); comparison between the equipment stops due to the maintenance activity, Eq. (4):

$$D = \frac{d_0}{d_1} \tag{4}$$

  Where d_1 is the duration of the equipment stop due to the analysed maintenance strategy and d_0 is the duration of the stop due the reference maintenance strategy.

- Risk (*R*); comparison between the possible unwanted events due to the maintenance activity Eq. (5):

$$R = \frac{r_0}{r_1} \quad (5)$$

Where r_0 is the Economical risk related to the reference maintenance strategy, and r_1 is the Economical risk related to the analysed strategy.

- Safety (S); comparison between the risks related to the occupational safety for the operators carrying on the maintenance, Eq. (6):

$$S = \frac{s_0}{s_1} \quad (6)$$

Where s_0 is the maximum value of risk for the reference maintenance strategy, and s_1 is the same value for the analysed maintenance strategy.

The input variables range between 0 to 2, only Performance (P) ranges between 0.9 and 1.1, because it is not expected that the productivity should vary more than ±10%.
For each variable, if the value is lower than 1, the analysed maintenance strategy can be considered worse than the reference one as far as it concerns the considered variable; when the value is higher than 1, the analysed maintenance strategy is better than the reference one.
The input variables are divided in 3 membership functions (Figure 1):

- Worse: data of the analysed maintenance strategy are worse than the reference maintenance strategy;
- Similar: data of the analysed maintenance strategy are comparable to the reference maintenance strategy;
- Better: data of the analysed maintenance strategy show an improvement with respect to the reference maintenance strategy.

A trapezoidal shape is used for all the membership functions of the input variables. The trapezoidal membership function was adopted because this generic shape can represent data whose detailed distribution is not available. In the further development of the methodology, following the increasing precision of data and results, the adoption of more complex shapes will be considered.

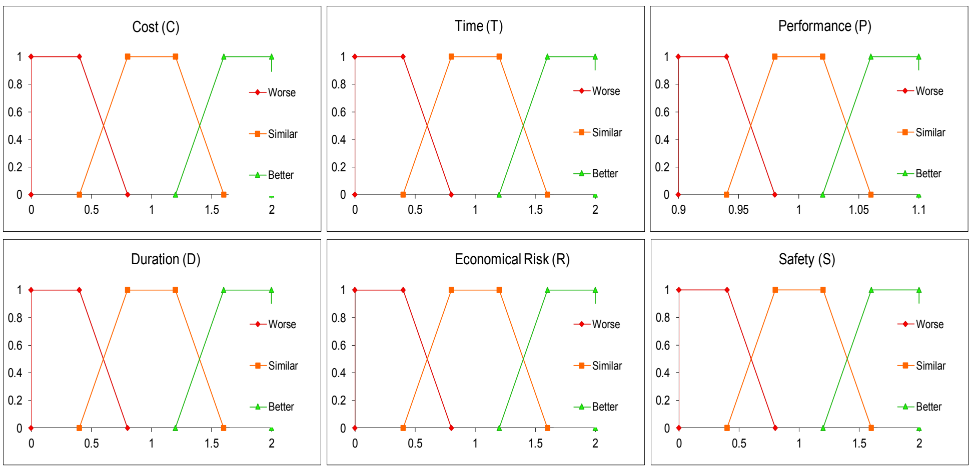

Figure 1: The input variables membership functions

2.2 Output variable

The output variable represents a global judgement on the opportunity of adopting the analysed maintenance strategy with respect to the reference one. The output variable is divided in 3 membership functions (Figure 2):

- Disadvantageous: the analysed maintenance strategy has a worse global performance with respect to the reference one;
- Neutral: the analysed maintenance strategy and the reference one are equivalent;
- Advantageous: globally, the analysed strategy has a better performance with respect to the reference one.

Triangular membership functions were employed for the output variable too.
The output variable ranges between 0 to 1.

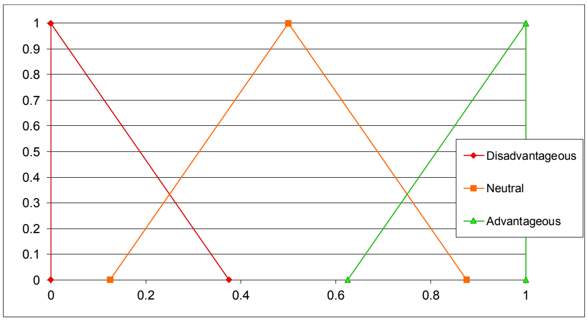

Figure 2: The output variable membership functions

2.3 Rules

The rules are used to describe how the input variables can influence the output variable result. I.e.The rule "If … Then …" is applied this way: "IF Cost is Worse AND Time is Worse AND … THEN the Maintenance is Disadvantageous". The rules should cover all the 243 possible membership function permutations.
Each rule is defined according to Eq. (7):

$$\sum_i w_i \cdot W_{ij} = W_O \quad (7)$$

Where w_i is the weight of the variable *i*, W_{ij} is the weight of the membership function *j* in the variable *i* and W_O is the value used to evaluate the output membership function.
The values of W_{ij} are shown in Table 1, the same value of W_{ij} is used for all the input variables.

Table 1: Value of W_{ij}

	Worst	Similar	Better
W_{ij}	-1	0	1

For the case study presented in Paragraph 2.4., the plant manager assigned the same degree of relevance to each input variables. Therefore, the value w_i is 1 for all the input variables. If the plant management had given more importance to one or more of the input variables, an higher value of w_i should have been assigned.
W_O is used to define the output membership function. If W_O is lower than 0, the "disadvantageous" membership function is assigned, representing the situation of more declining conditions than increasing ones. If W_O is equal to 0, the membership function "neutral" is assigned, representing equivalent pros and cons. The membership function "Advantageous" is assigned if W_O is higher than 0, because in this case the better performance of the analysed maintenance strategy with respect to the standard one are prevailing on the lower performance.
The min-max interference technique was used for the rules aggregation, so that the degree of relevance of each rule on the output could be taken into account (Klir and Yuan, 1995). The defuzzification of the results was based on the centroid method, in order to consider also the degree of relevance of each membership function of the output value (Pedrycz W., 1993).

2.4 Case study

In power plants, the maintenance of the turbo gas equipment is a critical step. The paper analyses different maintenance strategies for the Low Pressure Turbine (LP) of a Power plant Company.
The standard maintenance strategy usually adopted in the Company is: the LP turbine is opened, the blades are tested and, in case of failed blades, they are replaced. In order to minimise maintenance stops, a small amount (7) of new blades is stored.
Two other maintenance strategies have been proposed:

- Strategy 1: lifting of the LP module cover lifting, and replacement of all the blades, with a decrease of the maintenance time since the test of the blades is made after the turbine has been refurbished and restarted;
- Strategy 2: LP inner block replacement (rotor and carriers), with a power increase.

The plant manager provided the data on the maintenance strategy (Table 2), the Economical risk value calculation is described in Baldissone et al. (2018).

Table 2: Maintenance strategy data

Maintenance strategy	Cost [M€]	Interval between next maintenance [y]	Power (MW)	Maintenance duration [d]	Monetary risk [k€]	Safety (risk index)
Standard	0.5	4	260	35	1845	6
1	1.02	8	260	60	3399	7
2	2.42	8	263.5	38	5799	10

3. Results

The two possible new maintenance strategies were analysed with the proposed methodology. The result of the Strategy 1 analysis (Figure 3) is neutral (0.453): in fact, the disadvantages are balanced by the advantages with respect to the reference maintenance. As shown by Figure 3, the Cost (C), Duration (D) and Economical Risk (R) related to the Strategy one are slightly worse, the Performance (P) and Safety (S) are similar and the Time (T) is better.

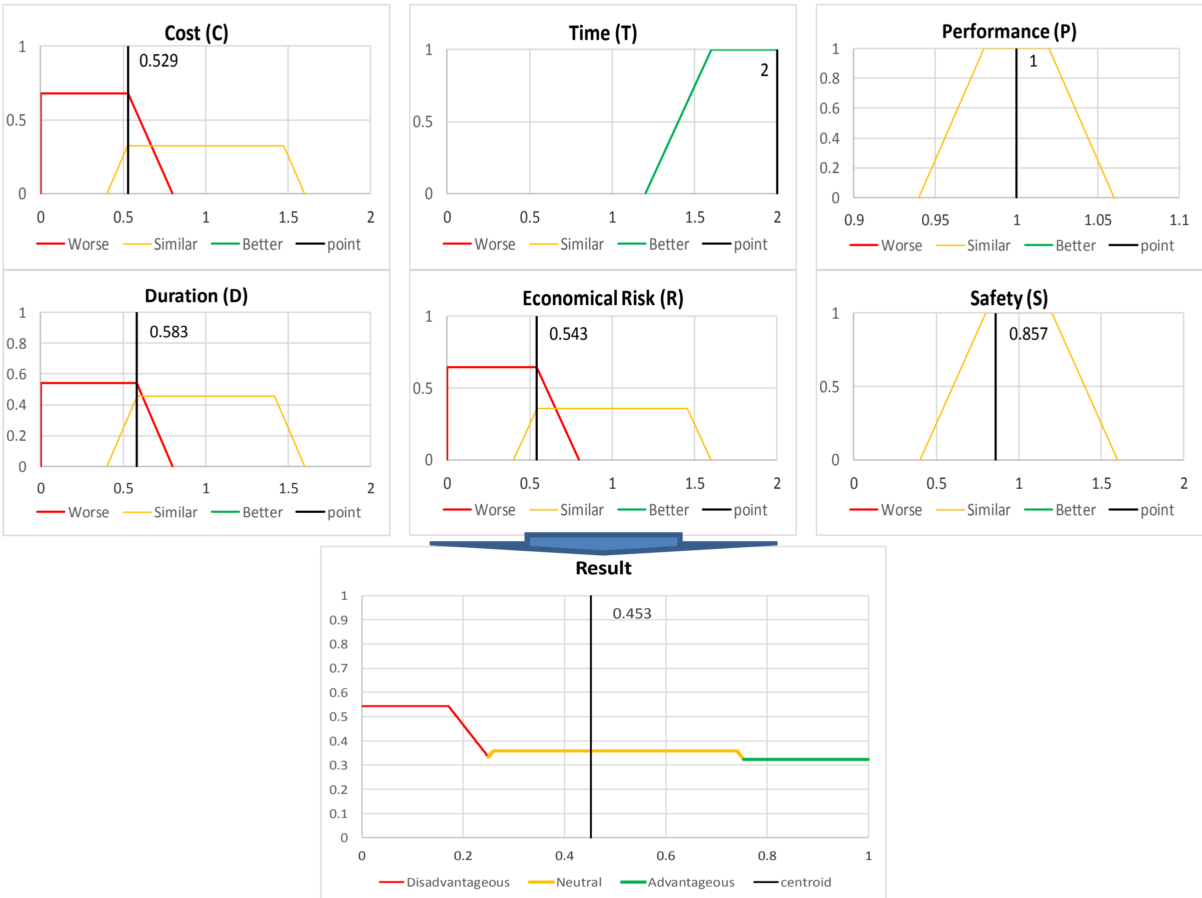

Figure 3: Analysis of the Strategy 1

The result of the Strategy 2 analysis is Disadvantageous (0.146), because the disadvantages are not balanced by advantages. For Strategy 2, Cost (C) and Economical Risk (R) are worse, Safety (S) is similar – worse, Duration (D) and Performance (P) are similar and Time (T) is better.

Following the results of the methodology, the plant managers were able to compare the strategies based on different variables and decided to keep the original maintenance strategy developed on the basis of operational experience.

4. Conclusion

In industrial plants, maintenance is a key element for the plant productivity; it can become particularly critical in case of ageing equipment. Multiple maintenance strategies can be adopted to grant the productivity and maintain an adequate level of safety, but how to choose the best one?
In order to support the plant management decision making, a method based on the comparison of different maintenance strategies was proposed; it returns a global judgement on the advantage or disadvantage of the analysed maintenance strategy with respect ot the reference one. The proposed method, based on the Fuzzy Logic, uses 6 different variables that describe both maintenance activity parameters (Cost, Duration, Economical Risk and Safety) and equipment performance after the maintenance (Time to the next maintenance and Performance).
The method has been tested on the case study of a Low Pressure turbine maintenance, comparing two maintenance strategies with the one usually adopted in the company, based on operational experience.
Within the new maintenance strategies proposed, one of them gave similar results with respect to the strategy adopted in the company, with a neutral global evaluation. The more invasive strategy (Strategy 2) shown an increased complexity not counterbalanced by the advantages on the restored equipment.

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