CHEMICAL ENGINEERING TRANSACTIONS

VOL. 77, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Genserik Reniers, Bruno Fabiano

ISBN 978-88-95608-74-7; **ISSN** 2283-9216

DOI: 10.3303/CET1977169

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

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Nowadays different plants have aging problem, since in many cases the plants are used over their design useful life. But in different cases it is not possible to do a revamping, for economical reason, regulatory constraints, and so on. The aging of the equipment became also a safety problem. Between 1980 and 2006 the Health and Safety Executive estimated that around 28% of the major incidents occurred in the reference period, corresponding to 96 accidents, can be traced back to plant aging. These accidents costed more than 170,000,000 € (Horrocks et al., 2010).
In these cases a correct maintenance can prolong the plant life, increasing the plant efficiency and maintaining an adequate level of safety. Plant management can choose among different maintenance strategies, whose choice is influenced by different parameters, as: maintenance cost, equipment condition before maintenance, plant trip cost, safety of the operator during the maintenance and during the normal operations.
In this paper a multivariable Fuzzy approach is proposed to support the decision-making among different maintenance strategies, through the analysis of the peculiarities of the different strategies, helping the management to weight the pros and cons of the alternatives. This approach is applied to the maintenance of process equipment case study.

1. Introduction

Since many pieces of equipment are still in use after the expected life time has passed, plant aging is becoming a problem. The incorrect management of the aging equipment can have negative impact on the plant safety, as demonstrated by the Health and Safety Executive (Horrocks et al., 2010), that within MARS database, traced back the 28% of the major accidents occurred between 1980 and 2006, the to the aging equipment. Those accidents have caused around 170M€, 11 dead and 183 injures.
The best way for solve the equipment aging problem should be to install new equipment, increasing the plant competitivity and maximising the energy saving of the plant (Baldissone et al., 2017), and increasing the plant flexibility both for the product quality (Comberti et al., 2018a) and for product type (Reay et al., 2013). Plant revamping has some resistance usually related to economical or regulatory constraints.
The second way to prolongue the plant lifetime is the maintenance, that also allows increasing the plant efficiency (Demichela et al. 2018) and energy saving (Darabnia and Demichela, 2013).
The maintenance can be reactive or preventive. In the reactive approach, maintenance is carried on after an equipment fault: the plant trip is not planned and the costs increase (Weil, 1998), furthermore, in order to minimize the plant stop the company needs extensive spare part storage. On the other hand, this type of maintenance allow the equipment to be used along its full lifetime. Letting the equipment fail can be dangerous because the fault can be the initiator of incidents (Comberti et al., 2018b) and environmental releases (Gallimore and Penlesky, 1988).
In the preventive approach, the maintenance activities are planned and scheduled (Gits, 1992), without waiting the equipment to fail. The consequences of the fault and the unwanted plant trip are minimized, but the equipment is not fully used. Different studies discuss the preventive maintenance benefits, as, for example, Lee (2005).

Paper Received: 3 December 2018; Revised: 6 April 2019; Accepted: 29 June 2019

Please cite this article as: Baldissone G., Demichela M., Leva C., 2019, Multivariable based decision-making for the maintenance strategy of process equipment, Chemical Engineering Transactions, 77, 1009-1014 DOI:10.3303/CET1977169

In case of the preventive maintenance adoption the plant management need to choose the correct maintenance strategy between high numbers of options, characterised by different pros and cons. Multiple methods have been developed to address the problem of maintenance optimization. In Ding and Komaruddin (2015) a review of different methodologies is reported. An important group of optimization methodologies falls under the multiple variable decision-making name: more parameters are analysed for a global optimization.
In this paper a multivariable decision-making based on the fuzzy logic is proposed. The proposed approach allows comparing different maintenance strategy based on 5 parameters and evaluating which strategy present global advantages or partial ones.

2. Material and methods

2.1 Fuzzy logic

The fuzzy logic approach is used to analyse different multivariable problems: as the occupational risk assessment as summarized in Papazoglou et al. (2017) or a similar application for a specific field, steel industry, in Murè and Demichela (2009) or construction sites, as in Gürcanli and Müngena (2009).
In this paper the fuzzy logic is used to evaluate if a maintenance strategy is better or not respect the standard maintenance activity. The variables used to compare the different options has been: the cost, the duration of the maintenance, the interval between two maintenances, the performance after the maintenance and the economic risk.
The fuzzy logic shows its potentiality in the case where the variable division in categorical category is not clear, because in this case the fuzzy logic permit the attribution of one data at more category with different degree of relevance.
The whole fuzzy logic system requires the following aspects to be defined:

- The input variables and their membership functions;
- The correlation between the input variables and the output variables (rules);
- The output variables and their membership functions.

These parts are described in the following section.

2.1.1 Input variables

In the first step in the fuzzy logic approach the input variables and their membership functions are defined. In this case 5 input variables are used and namely:

- The cost (*C*) representing the cost of the maintenance activity analysed with respect to the standard maintenance activity; this variable is evaluate through Eq.(1):

$$C = \frac{c_0}{c_1} \quad (1)$$

  Where c_0 is the cost of the standard maintenance activity and c_1 is the cost of the analysed maintenance activity. The range between 0 to 2 is used for the variable *C.* If the cost of the analysed maintenance strategy is lower than the half of the standard maintenance activity at the variable C is assigned the value of 2.
- The time between the next maintenance activity (*T*); also to assess this value the ratio between the time value for the considered option and the one of the standard maintenance activity is used. The value of the variable T is evaluated with the Eq(2):

$$T = \frac{t_1}{t_0} \quad (2)$$

  Where t_1 is the time before the next maintenance in the case of analysed strategy, and t_0 is the time before the next maintenance in the case of the standard maintenance activity. The range of the variable T is between 0 to 2: if the time between the next maintenance activity is higher than the double of the same time in the referring condition, at the variable *T* is given the value 2.
- Performance (*P*), this value is used for evaluate if the analysed maintenance increases or decreases the performance of the equipment. This value is evaluated with the Eq(3):

$$P = \frac{p_1}{p_0} \quad (3)$$

  Where p_1 is the performance (in terms of power produced, productivity, …) of the equipment after the analysed maintenance strategy, instead the p_0 is the performance of the equipment after the standard maintenance activity. The variable P is ranged between 0.9 to 1.1, considering that the maintenance strategy can move the performance only of the ±10%; in case the performance should move more the variable P is assigned the minimum or maximum value.

- Duration (*D*), this value takes into account the equipment stop for the maintenance activity and its evaluated with the Eq(4)

$$D = \frac{d_0}{d_1} \quad (4)$$

Where d_1 is the equipment stop for the analysed maintenance strategy and d_0 is the same value in the standard maintenance strategy. For the *D* value a range between 0 to 2 is used; if the value evaluates is higher than the maximum value, the value of 2 is assigned to *D*.

- The economical risk (*R*), this value is used for consider the possible unwanted event could occur during the maintenance activity, this variable is evaluated according to Eq(5):

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

Where r_0 is the economical risk in the standard maintenance strategy, instead r_1 is the same value in the analysed strategy. The range for the variable *R* is 0 to 2, if *R* is higher than 2 the variable assumes the value of 2.

The input variables are defined in this way because if the variable is lower than 1, the analysed maintenance strategy have worse performance in the descripted parameter. Instead if the value of the variable is higher than 1 the analysed maintenance strategy show an improvement.

The input variables are divided in 3 membership function:

- Worse: if the analysed maintenance strategy show worse performance respect the standard one;
- Similar: if the analysed maintenance strategy show similar performance respect the standard one;
- Better: if the analysed maintenance strategy show better performance respect the standard one;

A trapezoidal shape is used for the membership function, as shown in Figure 1.

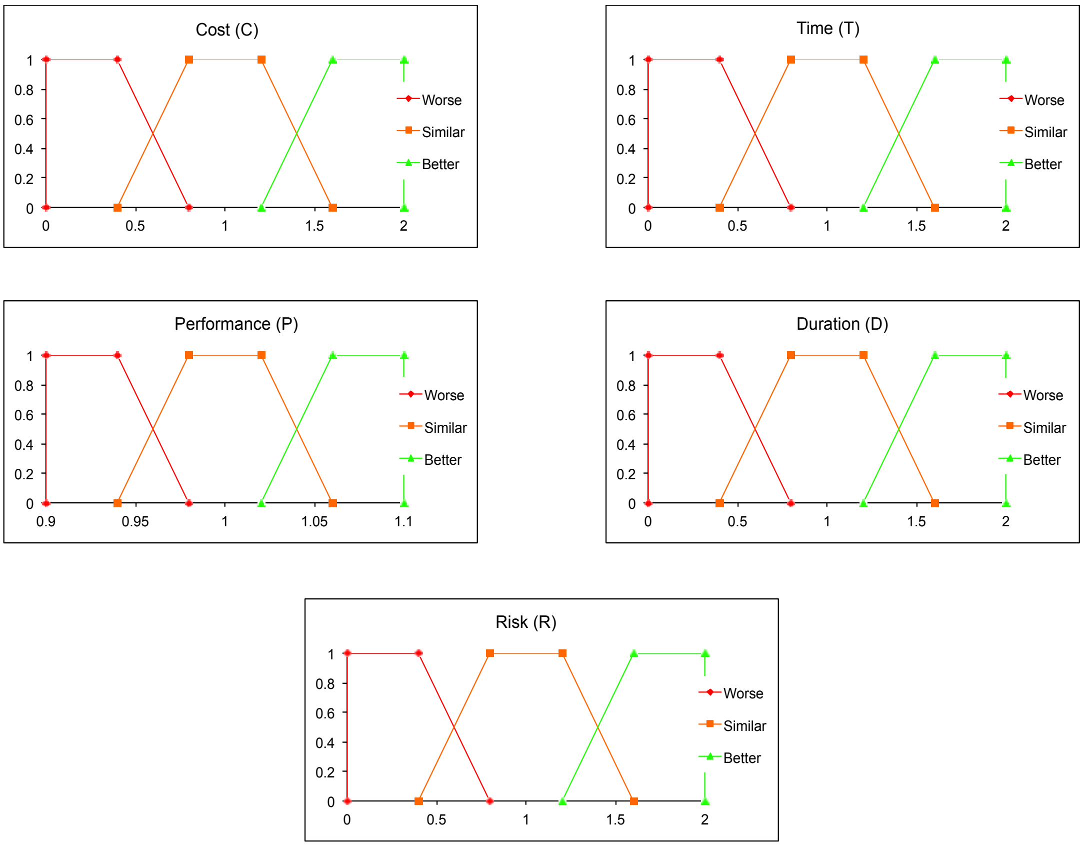


Figure 1: The input variables membership function

2.1.2 Output variable

In this step the output variables are defined. In this case only one output variable is used: It represents the opportunity of adopting the analyzed maintenance strategy with respect to the standard one. The output variable ranges between 0 to 1 and it is divided in 3 triangular membership function:

- Disadvantageous: this output membership function represents the case where the analysed maintenance option has worse global performance with respect to the standard one;
- Neutral: in this case the analysed and the standard maintenance strategies are equivalent;
- Advantageous: if the analysed strategy has globally better performance with respect the standard one.

The shape of the output membership function is shown in Figure 2.

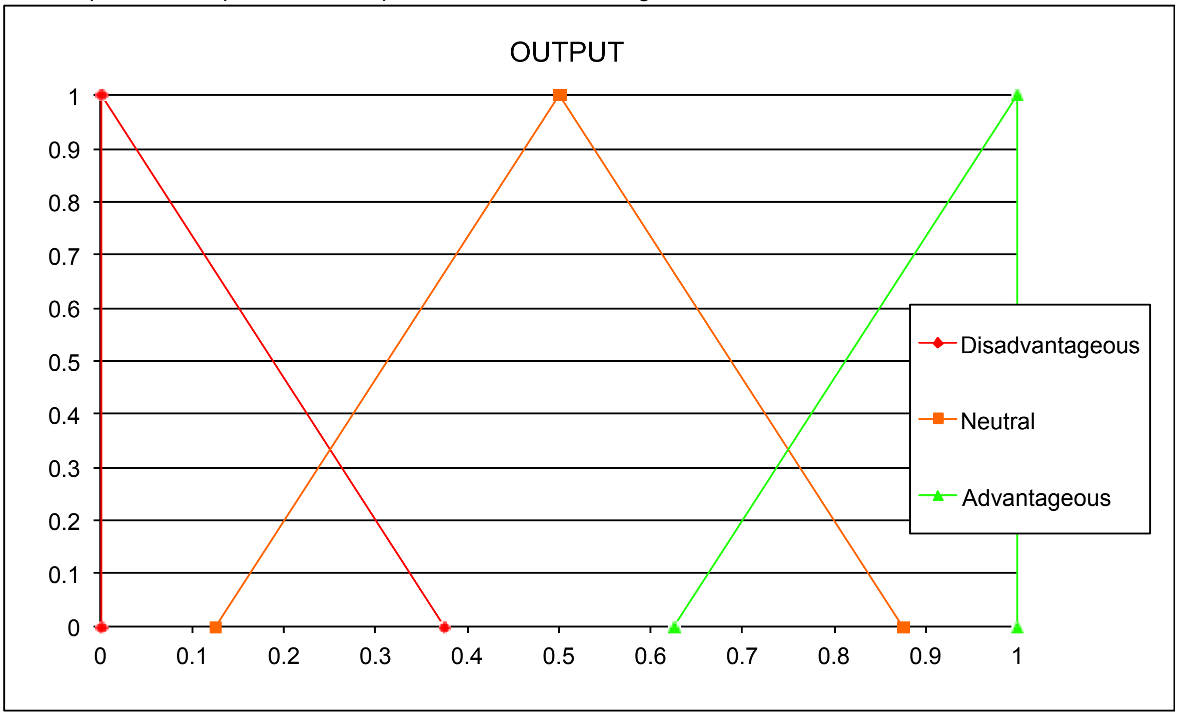


Figure 2: The output variable membership function

2.1.3 Rules

The fuzzy rules are type "If than", for example "If Cost is Worse AND Time is Worse AND Performance is Worse AND Duration is Worse AND Economical Risk is Worse THAN the Maintenance is Disadvantageous". The rules cover the 243 permutations of the input variables membership function.
The rule is defined according to Eq (6):

$$\sum_i w_i \cdot W_{ij} = W_O \tag{6}$$

Where w_i is the weight of the variable *i*, W_{ij} is the weight of the membership function *j* in the viable *i* and W_O is the value used for evaluating the output membership function.
The value of W_{ij} is set at -1 in case of "worse" membership function, 0 for "similar" and +1 for "better". According to the company management, the input variables have the same importance, thus for each variable the value of w_i is 1. In case the management should give more importance to one or more variables, the value of w_i could be set to values higher than 1.
The output is considered "Advantageous" if the better performances for the input variables are more numerous than the worse performances. Instead the output is "disadvantageous", if the worse performances for the input variables are more numerous than the better performances. The output is "neutral" only if the better and the worse performances are in the same number. In this way if W_O is lower than 0 the output membership function is "disadvantageous" and if W_O is higher than 0 the output membership function is "Advantageous". The output membership function is "neutral" only if the W_O is equal to 0.

For the rules aggregation, the min-max interference technique is used and for the defuzzification of the results the centroid method is used.

2.2 Case study

For a correct functioning of a gas turbine within a process plant the maintenance of the Low Pressure Turbine (LP) is an important step. During the LP maintenance the turbine is opened and the blades are tested and replaced where needed. The plant management uses a standard maintenance strategy: the LP turbine is opened, the blades are tested and in case the blades failed they are replaced; to minimise maintenance stop a small number (7) of new blades is stocked.
Two other maintenance strategies have been proposed:

- Strategy 1: LP module cover lift and replace 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.

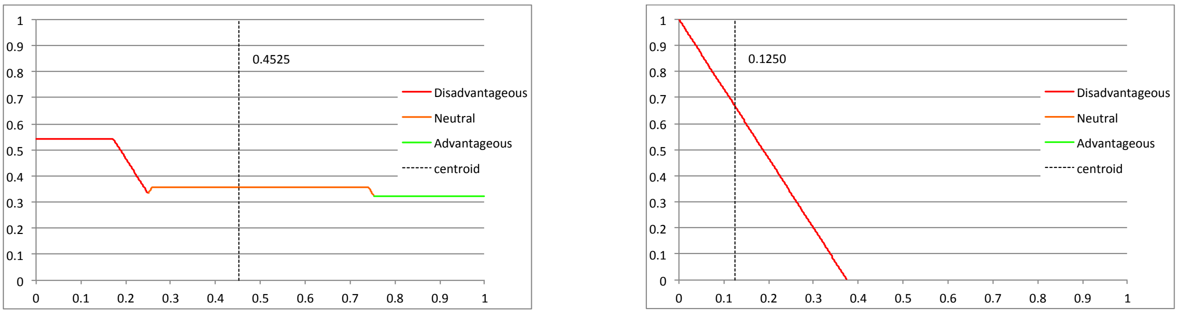
The management provide the 3 maintenance strategy (Table 1) data, and the monetary risk is evaluated in Baldissone et al. (2018).

Table 1: Maintenance strategy data

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

3. Results

The hypothesized maintenance strategies are compared with the standard one. The results showed that the opportunity to adopt the maintenance strategy 1 is neutral (Figure 3a), instead for the strategy 2 the analysis showed clear disadvantages (Figure 3b) with respect to the standard maintenance strategy.



(a) (b)

Figure 3: Graphical representation of the result: (a) strategy 1, (b) strategy 2

In fact, the strategy 1, shown “better” characteristics for the interval between the next maintenance, similar value for the equipment performance, similar-worse characteristic for the other input variables. In this way, the adoption of this maintenance strategy is neutral with respect to the standard one. The exact results (0.45) is a little shift towards the disadvantageous direction. Instead for maintenance strategy 2, only the interval between the next maintenance shows an improvement. The performance and the duration are classified as “similar”, while others variables show worse performance than the standard maintenance strategy. In this way the result of the maintenance strategy 2 is “disadvantageous” (0.125).

4. Conclusion

In different industrial plant the equipment aging is becoming an important problem also for the productivity and for the safety (Murè et al., 2017) . In most of the cases this process is managed through maintenance, and plant management has to deal with the choice of the best maintenance option among different alternatives.

In this paper a method to help the plant management in the decision phase is proposed: it compares the proposed maintenance strategies with the standard one on the base of relevant variables. The proposed methods analyses variable such as: the cost, the time between the next maintenance, the equipment performance after the maintenance, the maintenance activity duration and the economical risk. The methodology returns a global judgment on the advantage and the disadvantage of the different strategies.
The proposed method was tested on a Low Pressure turbine maintenance strategy, showing that the alternative maintenance procedures proposed are in one case similar to the procedure adopted at present (replacement of all the blades) while the more invasive one (changing also the rotor an carriers) is not advantageous.
The results obtained by the proposed method are confirmed by the evaluation of the plant management. The proposed method is only the first step of development and, in the future, other variables will be taken into account, as the operator's safety or the environmental risk.

Acknowledgments

This publication has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under Grant Number 14/IFB/2718 and by INAIL – project PROAGE 3rd Call SAF€RA

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