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Studying the Advance Maintenance Practice & Computerised Maintenance

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Abstract
Many companies think of maintenance as an inevitable source of cost. For these companies maintenance operations have a corrective function and are only executed in emergency conditions. Today, this form of intervention is no longer acceptable because of certain critical elements such as product quality, plant safety, and the increase in maintenance department costs which can represent from 15 to 70% of total production costs. The managers have to select the best maintenance policy for each piece of equipment or system from a set of possible alternatives. For example, corrective, preventive, opportunistic, condition-based and predictive maintenance policies are considered in this paper.

I. Introduction

It is particularly difficult to choose the best mix of maintenance policies when this choice is based on preventive elements, i.e. during the plant design phase. This is the situation in the case examined in this paper, that of an Integrated Gasification and Combined Cycle plant which is being built for an Italian oil company. This plant will have about 200 facilities (pumps, compressors, air-coolers, etc.) and the management must decide on the maintenance approach for the different machines. These decisions will have significant consequences in the short-medium term for matters such as resources (i.e. budget) allocation, technological choices, managerial and organisational procedures, etc. At this level of selection, it is only necessary to define the best maintenance strategy to adopt for each machine, bearing in mind budget constraints. It is not necessary to identify the best solution from among the alternatives that this approach presents.

The maintenance manager only wants to recognise the most critical machines for a pre-allocation of the budget maintenance resources, without entering into the details of the actual final choice. This final choice would, in any case, be impossible because the plant is not yet operating and, as a consequence, total knowledge of the reliability aspects of the plant machines is not yet available. In other words, the problem is not whether it is better to control the temperature or the vibration of a certain facility under analysis, but only to decide if it is better to adopt a condition-based type of maintenance approach rather than another type. The second level of decision making concerns a fine tuned selection of the alternative maintenance approaches (i.e. definition of the optimal maintenance frequencies, thresholds for condition-based intervention, etc.). This level must be postponed until data from the operating production system becomes available.

Several attributes must be taken into account at this first level when selecting the type of maintenance. This selection involves several aspects such as the investment required, safety and environmental problems, failure costs, reliability of the policy, Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) of the facility, etc. Several of these factors are not easy to evaluate because of their intangible and complex nature. Besides, the nature of the weights of importance that the maintenance staff must give to these factors during the selection process is highly subjective. Finally, bearing in mind that the plant is still in the construction phase, some tangible aspects such as MTBF and MTTR can be only estimated from failure data concerning machines working in other plants (in this case oil refineries) under more or less similar operating conditions. Furthermore, they will affect each single facility analysed in a particular way and, as a consequence, the final maintenance policy selection.

It is therefore clear that the analysis and justification of maintenance strategy selection is a critical and complex task due to the great number of attributes to be considered, many of which are intangible. As an aid to the resolution of this problem, some multi-criteria decision making (MCDM) approaches are proposed in the literature. Almeida and Bohoris discuss the application of decision making theory to maintenance with particular attention to multi-attribute utility theory. Triantaphyllou et al. suggest the use of Analytical Hierarchy Process (AHP) considering only four maintenance criteria: cost, reparability, reliability and availability. The Reliability Centered Maintenance (RCM) methodology (see, for example,) is probably the most widely used technique. RCM represents a method for preserving functional integrity and is designed to minimise maintenance costs by balancing the higher cost of corrective maintenance against the cost of preventive maintenance, taking into account the loss of potential life of the unit in question .

One of the tools more frequently adopted by the companies to categorise the machines in several groups of risk is based on the concepts of failure mode effect and criticality analysis technique (FMECA). This methodology has been proposed in different possible variants, in terms of relevant criteria considered and/or risk priority number formulation . Using this approach, the selection of a maintenance policy is performed through the analysis of obtained priority risk number. An example of this approach has also been followed by our oil company, which has developed its own methodology internally. This approach makes it possible to obtain a satisfying criticality clustering of the 200 facilities into three homogeneous groups. The problem is to define the best maintenance strategy for each group.

To integrate the internal “self-made” criticality approach, this paper presents a multi-attribute decision method based on the AHP approach to select the most appropriate maintenance strategy for each machine group. In this procedure, several costs and benefits for each alternative maintenance strategy are arranged in a hierarchic structure and evaluated, for each facility, through the use of a series of pairwise judgements. Finally, considering that the maintenance manager can never be sure about the relative importance of decision making criteria selected when dealing with this complex maintenance problem, to improve the AHP effectiveness the methodology is coupled with a sensitivity analysis phase.

II. The API oil refinery IGCC plant: a brief description

The Integrated Gasification and Combined Cycle (IGCC) plant , currently being assembled at The Falconara Marittima API oil refinery, will make it possible to transform the oil refinement residuals into the synthesis gases which will be used as fuel to produce electricity. The IGCC plan will be placed in a 47,000 m^2 area inside the oil refinery.

The electricity produced by the IGCC plant will be sold to ENEL (Italian electrical energy firm) while some 65,000 ton/h of steam will be used inside the oil refinery for process requirements. The total cost of the project amounts to about 750 million dollars.

In recent years, economic and legislative changes have led to increased co-operation between petrochemical and electrical firms. The adoption of strict environmental standards, both in Europe and in the United States, is forcing oil refinery firms to reduce the emissions of pollutants from the process plants and reduce the potential pollution of the refined products. The same pollution control requirements, mainly a reduction in the level of nitrogen and sulphur oxides, together with the increasing need to control operating and investments costs, is pushing electrical firms to search for more economic and cleaner production methods.

The combined effect of the above-mentioned factors has led several oil refineries to adopt IGCC technology for oil refinement heavy residuals processing. IGCC technology has proved to be a valid solution to the market requirement of efficient, clean, low consuming and environmentally orientated production technologies.

The API oil refinery uses a thermal conversion process and has a production capacity of about 4,000,000 tons of oil per year (80,000 barrels per day). The production cycle is typical of oil refineries with a similar production capacity: the current distilled yield is higher than 70% and the residuals are used to produce fuel oil and bitumen. Oil refinement heavy residuals with a high sulphur content will be partly converted into the synthesis gases “syngas” (which will be cleaned in the IGCC gasifiers) and partly used to produce bitumen.

The three main objectives of the oil refinery management are the following:

1. the elimination of heavy residuals used to produce fuel oil with high and low sulphur content;
2. the ability to process almost every type of heavy oil with a high sulphur content;
3. the substitution of the present low efficiency thermoelectrical power plant with a more efficient system, with lower levels of pollutant emissions.

III. Possible alternative maintenance strategies

Five alternative maintenance policies are evaluated in this case study. Briefly, they are the following.

Corrective maintenance. The main feature of corrective maintenance is that actions are only performed when a machine breaks down. There are no interventions until a failure has occurred.

Preventive maintenance. Preventive maintenance is based on component reliability characteristics. This data makes it possible to analyse the behaviour of the element in question and allows the maintenance engineer to define a periodic maintenance program for the machine. The preventive maintenance policy tries to determine a series of checks, replacements and/or component revisions with a frequency related to the failure rate. In other words, preventive (periodic) maintenance is effective in overcoming the problems associated with the wearing of components.

It is evident that, after a check, it is not always necessary to substitute the component: maintenance is often sufficient.

Opportunistic maintenance. The possibility of using opportunistic maintenance is determined by the nearness or concurrence of control or substitution times for different components on the same machine or plant. This type of maintenance can lead to the whole plant being shut down at set times to perform all relevant maintenance interventions at the same time.

Condition-based maintenance. A requisite for the application of condition-based maintenance is the availability of a set of measurements and data acquisition systems to monitor the machine performance in real time. The continuous survey of working conditions can easily and clearly point out an abnormal situation (e.g. the exceeding of a controlled parameter threshold level), allowing the process administrator to punctually perform the necessary controls and, if necessary, stop the machine before a failure can occur.

Predictive maintenance. Unlike the condition-based maintenance policy, in predictive maintenance the acquired controlled parameters data are analysed to find a possible temporal trend. This makes it possible to predict when the controlled quantity value will reach or exceed the threshold values. The maintenance staff will then be able to plan when, depending on the operating conditions, the component substitution or revision is really unavoidable.

IV. The IGCC plant maintenance program definition

An electrical power plant based on IGCC technology is a very complex facility, with a lot of different machines and equipment with very different operating conditions. Deciding on the best maintenance policy is not an easy matter, since the maintenance program must combine technical requirements with the firm's managerial strategy. The IGCC plant complex configuration requires an optimal maintenance policy mix, in order to increase the plant availability and reduce the operating costs. Maintenance design deals with the definition of the best strategies for each plant machine or component, depending on the availability request and global maintenance budget. Every component, in accordance with its failure rate, cost and breakdown impact over the whole system, must be studied in order to assess the best solution; whether it is better to wait for the failure or to prevent it. In the latter case the maintenance staff must evaluate whether it is better to perform periodic checks or use a progressive operating conditions analysis.

It is clear that a good maintenance program must define different strategies for different machines. Some of these will mainly affect the normal operation of the plant, some will concern relevant safety problems, and others will involve high maintenance costs. The overlapping of these effects enables us to assign a different priority to every plant component or machine, and to concentrate economic and technical efforts on the areas that can produce the best results. One relevant IGCC plant feature is the lack of historical reliability and maintenance costs data (the plant start-up is proposed for March 2000). Initially, the definition of the maintenance plan will be based upon reliability data from the literature and on the technical features of the machines. This information will then be updated using the data acquired during the working life of the plant. The analysis system has been structured in a rational way so as to keep the update process as objective as possible. This has been accomplished through the use of a charting procedure, using well-understood evaluations of different parameters and a simple and clear analysis of corrective interventions. The maintenance plan developed for the machines of the IGCC plant is based on the well-known FMECA technique [7 and 8]. The analysis results have provided a criticality index for every machine, allowing the best maintenance policy to be selected.

4.1. The maintenance strategy adopted by the oil refinery company

The internal methodology developed by the company to solve the maintenance strategy selection problem for the new IGCC plant is based on a "criticality analysis" which may be considered as an extension of the FMECA technique. This analysis takes into account the following six parameters:

- safety;
- machine importance for the process;
- maintenance costs;
- failure frequency;
- downtime length;
- operating conditions; with an additional evaluation for the
- machine access difficulty

Note that, the six parameters presented below derived from an accurate pre-analysis to select all of the relevant parameters that can contribute to the machine criticality. As reported by the maintenance manager, 12 criteria have initially been considered:

a. *Safety.* Considering the safety of personnel, equipment, the buildings and environment in the event of a failure.

b. *Machine importance for the process.* The importance of the machine for the correct operation of the plant. For instance, the presence of an inter-operational buffer to stock the products can reduce the machine criticality since the maintenance intervention could be performed without a plant shutdown.

c. *Spare machine availability.* Machines that do not have spares available are the most critical.
d. *Spare parts availability.* The shortage of spare parts increases the machine criticality and requires a replenishment order to be issued after a failure has occurred.

e. *Maintenance cost.* This parameter is based on manpower and spare parts costs.

f. *Access difficulty.* The maintenance intervention can be difficult for machines arranged in a compact manner, placed in a restrict area because they are dangerous, or situated at a great height (for example, some agitators electric motors and air-cooler banks). The machine access difficulty increases the length of downtime and, moreover, increases the probability of a failure owing to the fact that inspection teams cannot easily detect incipient failures.

g. *Failure frequency.* This parameter is linked to the *mean time between failures* (MTBF) of the machine.

h. *Downtime length.* This parameter is linked to the *mean time to repair* (MTTR) of the machine.

i. *Machine type.* A higher criticality level must be assigned to the machines which are of more complex construction. These machines are also characterised by higher maintenance costs (material and manpower) and longer repair times.

l. *Operating conditions.* Operating conditions in the presence of wear cause a higher degree of machine criticality.

m. *Propagation effect.* The propagation effect takes into account the possible consequences of a machine failure on the adjacent equipment (domino effect).

n. *Production loss cost.* The higher the machine importance for the process, the higher the machine criticality due to a loss of production.

To restrict the complexity (and the costs) of the analysis to be performed, the number of evaluation parameters is reduced by grouping together those that are similar and by removing the less meaningful ones. An increase in the number of parameters does not imply a higher degree of analysis accuracy. With a large number of parameters the analysis becomes much more onerous in terms of data required and elaboration time. Besides, the quantitative evaluation of the factors described is complex and subject to the risk of incorrect estimates. The following “clusters” were created.

The “spare machine availability” mainly affects the uninterrupted duration of the production process and can therefore be linked to the “machine importance for the process” and the “production loss cost”. In terms of spare parts, the “maintenance cost” can include the “machine type” factor, while the manpower contribution to the maintenance cost can be clustered with the “downtime length” attribute. System “safety”, “failure frequency”, “access difficulty” and “operating conditions” are considered to be stand-alone factors by the maintenance staff.
For every analysed machine of the new IGCC plant, a subjective numerical evaluation is given adopting a scale from 1 to 100. Finally, the factors taken into consideration are linked together in the following criticality index CI:

$$CI=[(S\times1.5)+(IP\times2.5)+(MC\times2)+(FF\times1)+(DL\times1.5)+(OC\times1)]\times AD \quad (1)$$

where S=safety, IP=machine importance for the process, MC=maintenance costs, FF=failure frequency, DL=downtime length, OC=operating conditions, AD=machine access difficulty.
In the index, the machine “access difficulty” has been considered by the management to be an aggravating aspect as far as the equipment criticality is concerned. It is therefore suitable to evaluate the effect of the machine “access difficulty” as an “a posteriori” factor. For this reason with this approach the machine criticality index has been multiplied by the machine “access difficulty”.

A rational quantification of the seven factors has been defined and based on a set of tables. In particular, every relevant factor is divided into several classes that are assigned a different score (in the range form 1 to 100) to take into account the different criticality levels. The weighted values assigned by the maintenance staff to the different parameters are shown in Table 1.

Table 1. Weight values assigned to the relevant parameters considered in FMECA analysis

Parameter	Weight
Safety	1.5
Machine importance for the process	2.5
Maintenance costs	2
Failure frequency	1
Downtime length	1.5
Operating conditions	1

The weight assigned to safety is not the highest because in an IGCC plant danger is intrinsic to the process. The operating conditions are weighted equal to one in accordance with the hypothesis of a correct facility selection as a function of the required service. The breakdown frequency is weighted equal to one in virtue of the fact that failure rates are currently estimated values only. The CI index has been used to classify about 200 machines of the plant (pumps, compressors, air coolers, etc.) into three different groups corresponding to three different maintenance strategies, as shown in Table 2. Note that only corrective, preventive and predictive maintenance strategies have been taken into account by the refinery maintenance management.

Table 2. Maintenance policy selection based on criticality index

Criticality index	Maintenance policy
	Predictive
290–395	Preventive
<290	Corrective

The main features of the three groups are the following:

• *Group 1.* A failure of group 1 machines can lead to serious consequences in terms of workers' safety, plant and environmental damages, production losses, etc. Significant savings can be obtained by reducing the failure frequency and the downtime length. A careful maintenance (i.e. predictive) can lead to good levels of company added-value. In this case, savings in maintenance investments are not advisable. This group contains about the 70% of the IGCC machines examined.

• *Group 2.* The damages derived from a failure can be serious but, in general, they do not affect the external environment. A medium cost reduction can be obtained with an effective but expensive maintenance. Then an appropriate cost/benefit analysis must be conducted to limit the maintenance investments (i.e. inspection, diagnostic, etc.) for this type of facilities (about the 25% of the machines). For this reason a preventive maintenance is preferable to a more expensive predictive policy.

• *Group 3.* The failures are not relevant. Spare parts are not expensive and, as a consequence, low levels of savings can be obtained through a reduction of spare stocks and failure frequencies. With a tight budget the maintenance investments for these types of facilities should be reduced, also because the added-value derived from a maintenance plan is negligible. The cheapest corrective maintenance is, therefore, the best choice. Group 3 contains 5% of the machines.

4.2. Critical analysis of oil company maintenance MCDM methodology

Some aspects of the criticality index CI proposed and prepared by the maintenance staff are open to criticism. Eq. (1) represents a "strange" modified version of the weighted sum model (WSM), which probably represents the simplest and still the most widely used MCDM method . But, in this case, there are some weaknesses.

(a) The WSM is based on the "additive utility" supposition . However, the WSM should be used only when the decision making criteria can be expressed in identical units of measure.
(b) The AD factor should be added and not used as a multiplying factor.
(c) Dependencies among the seven attributes should be carefully analysed and discussed.
(d) The weight values reported in Table 1 are not justified in a satisfying manner. The maintenance staff also have serious doubts about these values, which would suggest that they have little confidence in the final results obtained by the MCDM model. Moreover, no sensibility analyses have been conducted to test the robustness of the results. This fact is probably due to (i) a sensitivity analysis is not an easy matter, and (ii) the absence of a software package supporting this request.

Despite these problems, the classification produced using the CI index has made it possible to define three homogeneous groups of machines. The composition of the clusters confirms the expectations of the maintenance staff and is considered to be quite satisfactory. On the other hand, the doubts of the maintenance staff mainly concern the maintenance strategy to adopt for each group of machines. This factor has been used as the starting point for the development of an AHP approach to assign the "best" maintenance strategy to each cluster element, taking into account several possible aspects.

V. Conclusions

Proper maintenance of plant equipment can significantly reduce the overall operating cost, while boosting the productivity of the plant. Although many management personnel often view plant maintenance as an expense, a more positive approach in looking at it is to view maintenance works as a profit center. The key to this approach lies in a new perspective of proactive maintenance approach.

Reviewing the most likely ways that equipment will fail has been a major concern in reliability-centered maintenance (RCM) to ensure that proactive, predictive and preventive maintenance activities during turnaround could be planned and carried out. So often that maintenance department will adopt a more cautious approach of playing safe and relying on the conventional or usual method of equipment maintenance rather than trying a proven method which has been tested to be efficient just to avoid any complicated matter arising from the method.

Hence another perspective of looking at maintenance function is not only to maintain but also to enhance the process or the plant operation system as a result of turnaround planning. Thus rather than restoring or trying to restore the equipment to its original performance, planning a turnaround could better still aimed at enhancing the process and performance of a plant, equipment or any system.

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