CHEMICAL ENGINEERING TRANSACTIONS

VOL. 67, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Valerio Cozzani, Bruno Fabiano, Davide Manca

ISBN 978-88-95608-64-8; **ISSN** 2283-9216

Risk Based Decision-Making Approach for Define the Maintenance Strategy of Gas Turbine Blades

Gabriele Baldissone*, Micaele Demichela, Lorenzo Comberti

Politecnico di Torino, DISAT Dipartimento Scienza Applicata e Tecnologia, Torino, Italy
gabriele.baldissone@polito.it

Nowadays several plants have aging problem. This type of problem occurs because the whole plant or some pieces of equipment are still in operation well beyond their design expected life, due e.g. to economical reason, regulatory constrain, or other issues.
In this case a correct maintenance can prolong the plant life, maintaining the plant efficiency and the operational safety.Plant management can usually choose among different maintenance strategies, but identifying the best one is not an easy task. In fact different parameters affect the choice, as: the maintenance cost, the equipment condition before the maintenance, the plant stop cost, the safety of the operator during the maintenance and during the normal operation.
In this paper the Integrated Dynamic Decision Analysis methodology is used to analyse and compare different solutions and provide the plant manager with a full picture of the possible unwanted events to support the decision making. This approach is applied to a practical case study related to the maintenance of gas turbine blades.

1. Introduction

Nowadays different plants have past the expected life time defined during their design phase. This occur because there are same difficulties for the plant revamping, related to economical, regulatory and environmental constraints.Plant aging, when incorrectly managed, can bring to serious accidents. Between 1980 and 2006, the Health and Safety Executive identified in the MARS database 96 incidents related to plant and equipment aging, corresponding to the 23% of the major incidents occurred in the same period (Horrocks et al., 2010). Those incidents had high costs both in economical terms (more than 170,000,000 €) and on the people (11 dead, 183 injuries) and environment.
Moreover, the use of ageing equipment reduces the competitivity of the company, since they usually requires more energy, more maintenance and often expensive raw materials. Instead the adoption of modern plants, developed with new philosophies, as process intensification *(Baldissone et al., 2016, 2017*), or with an increased attention to the sustainability, can use less energy, and they can increase the plant flexibility both for the product quantity than for the type of production (Reay et al., 2013).
But the adoption of the new technology and the plant revamping require high investment cost. In case the company could not afford the investment or could be bonded by other constraints, the solutions could be of increasing the plant lifetime, and in given condition also plant efficiency and energy saving (Darabnia and Demichela, 2013 Demichela at al., 2018), with a correct maintenance.
The maintenance strategy are usually to be chosen among the reactive maintenance and the preventive maintenance, while, with the technological development the condition based maintenance is rising its awareness, till arriving to a whole prognostic and health management approach.
In the reactive maintenance the equipment is used until its failure. In this type of maintenance strategy, the equipment is full used (Paz and Leigh, 1994), with un-programmed plant stop following the failure and restoring operations and consequently higher costs (e.g. productivity losses, reputation, …) (Weil, 1998). To minimize previously listed costs, the company needs an extensive spare parts storage. Furthermore, the

equipment failure can be a precursor or a direct cause of incidents and environmental releases (Gallimore and Penlesky, 1988).
In preventive maintenance the maintenance activity is done in scheduled period (Gits, 1992), in order to avoid the equipment failure. This type of maintenance reduces the unwanted plant stop, and the consequences of the equipment fault. But the maintenance is done on not faulty equipment, and the equipment is not fully used. Different studies shown the benefit of the preventive maintenance such as Lee (2005).
But for an effective preventive maintenance it is important to correctly plan the maintenance activity and the maintenance schedule. The maintenance schedule is defined to increase the plant lifetime and to avoid the equipment fault. It can be based on: the producer indication, the analysis of the equipment parameter for evaluate the real equipment degradation or the company historical data.
Instead, defining the maintenance activities requires to minimize the spare part and the maintenance time. Again, maintenance activities definition relies on producer indication, plant operational experience, etc.
A risk bases approach to decide between different alternatives of maintenance strategy is here discussed. It analyses the risk associated to the different maintenance strategies, starting from the possible equipment condition at the moment of the maintenance.
The risk assessment is made through the Integrated Dynamic Decision Analysis (IDDA). The proposed approach is applied to the case study of the maintenance of gas turbine blades.

2. Material and methods

2.1 Risk based decision making initial approach

The Risk Analysis Method allows companies to adopt a quantitative analysis to evaluate the probability of occurrence of equipment failures and, moreover, the related consequences for its operation, correlating probability and consequence.

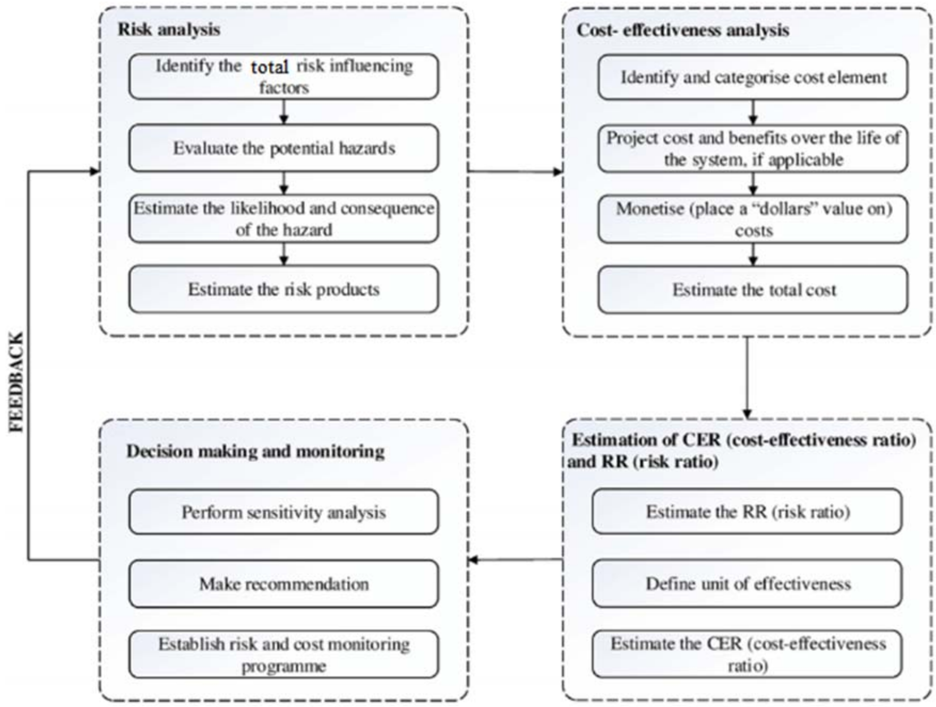

Figure 1 - Risk analysis / Cost-effectiveness ratio

As Figure 1 shows, the approach can be divided by these four areas setting, that are related to the principal deferring maintenance steps, and the dependence of each one from the others is necessarily evident. The first selection is the evaluation of the total risk influencing factors, including risks related to aging causes, and the evaluation of the potential hazards is used to identify relevant accident scenarios. These steps are powerful to estimate their consequences, and so the risk products. The second step is an analysis about the cost-effectiveness of the solution gained through the risk analysis by identifying and categorizing each single element, by monetizing the risk and estimating the total amount of costs.

An estimation of the cost-effectiveness ratio and risk ratio is necessary to define unit of effectiveness, by which make a decision and then monitor the solution, by sensitivity analysis and programs to establish risk and cost monitoring. Through this last section, companies can have a feedback to define the right solution, this is the most significant step of the Risk Analysis Method, within which evaluations are made on the operational choices that can vary considerably the financial performance of a company.
The methods used in the industrial sector for which to define a risk index are among the most disparate, both at a system level and at a graphic level. It is necessary to point out that companies need to commit the shortest time and the least possible efforts for the risk assessment, obtaining however results that are as optimal as possible Risk assessment methods are commonly used when planning equipment maintenance, in order to show the cost impact of the proposal solution, based only on the past experiences related to a specific component. In fact, this method requires a wide deal of data in order to asses both probabilities and consequences. The second steps consist of quantifying and evaluating the risk, in order to obtain a proper solution, to which is related a proper acceptability/tolerance.
When the series of item are assessed, the risk is evaluated thought a matrix which can display and evaluate the necessity of intervention, for values 8, 12 and 16, or just the study of the potential injury to identify PPE, if the value identified is 6. When deciding the value of the corresponding matrix, the choice of the parameters is entirely based on the characterization of the same figure, through a trivial and concise description, that’s why it is assumed to be a concept dictated by the experience of each company.
As discussed before, the principal aim is obtaining a ‘rough and ready’ assessment rather than a detailed analysis, using sophisticated software, which usefulness is strictly connected to the number of data sheet disposed. In this way it could be possible to identify and score even over a 100 tasks in a day, the problem is simply related to guarantee a remarkable reliability, compared to what could be achieved through more detailed calculations and inspections.
If we have to focus on this method, the necessity to monitor and control all hazardous systems is critically evident. Furthermore, the identification and the evaluation of all the individual tasks of this type are required only in view of a more in-depth data experimentation. Same thing about the equipment control and monitoring that will subsequently undergo this type of evaluation, through a risk assessment. Maintenance tasks are evaluated as operations tasks, even if there are some maintenance tasks presenting features that need to be viewed in a different way and observed more carefully that others, in fact the evaluation of the total score for a generical system company is influenced by the hazardousness, related to the assumption that several of the tasks, or maybe all of them, are performed whilst the system is alive, during its working phase. That’s why it is necessary to perform these tasks during the shutdown machine, in order to reduce critical issues. It’s important to create with this mind a trade-off between the impact on production related to a preventive maintenance and its task criticality.

2.2 Integrated Dynamic Decision Analysis

IDDA was developed by Remo Galvagni and proposed in the eighties of the twentieth century (Galvagni and Clementel, 1989, Clementel and Galvagni 1984). IDDA was then applied to different case studies to support the risk-based decision making: an allyl-chloride production plant design (Turja and Demichela 2011, Demichela and Camuncoli, 2014), the LPG tank pressure test procedure optimization (Gerbec et al., 2017), the overflowing of a tank (Demichela and Piccinini, 2008), a formaldehyde plant modification (Demichela et al. 2017).
The IDDA methodology links a logical – probabilistic model and a phenomenological model; the analysis framework is shown in Figure 2.
The logical-probabilistic model, based on the general logic theory, is built according to its own syntactic system to shape an enhanced event tree structure, through:

1. The functional analysis of the system and the construction of a list of levels, with questions and affirmations on the functionality of each element; each level represents the elementary matter of the logical model and also a node in an event tree,
2. The construction of a ‘reticulum’ indicating the addresses (subsequent level) to be visited depending on the response in each level, and a comment string that allows the user to read the logical development of a sequence;
3. The association to each level of a probability value, which represents the expected degree of occurrence of a failure or an unwanted event and of an uncertainty ratio, which represents the distribution of the probability.
4. The definition of the logical and probabilistic constraints, which allow modifying run time the model, to fit it to the current knowledge status

The logic – probabilistic model is built according to an appropriate syntax, and modelled through IDDA software, which can develop all the possible sequences of events that the plant could undergo. Each sequence of events is correlated with its probability of occurrence.
A phenomenological model, together with the logical modelling, must be prepared to describe the physical behaviour of the system. The phenomenological model could influence the updating of the logical model generating a better description of the real behaviour of the system, i.e. indicating if, after the failure of a piece of equipment, the other components are able to compensate its dearth and complete the operation, or if cumulative effects can appear and diverge the system from its normal behaviour.
The phenomenological model can provide a direct estimation of the consequences for each single sequence to obtain a risk estimation, the evaluation of the overall risk of the system and the expected value of the consequence. The latter is calculated as a weighted average of the consequences, according to their probability.

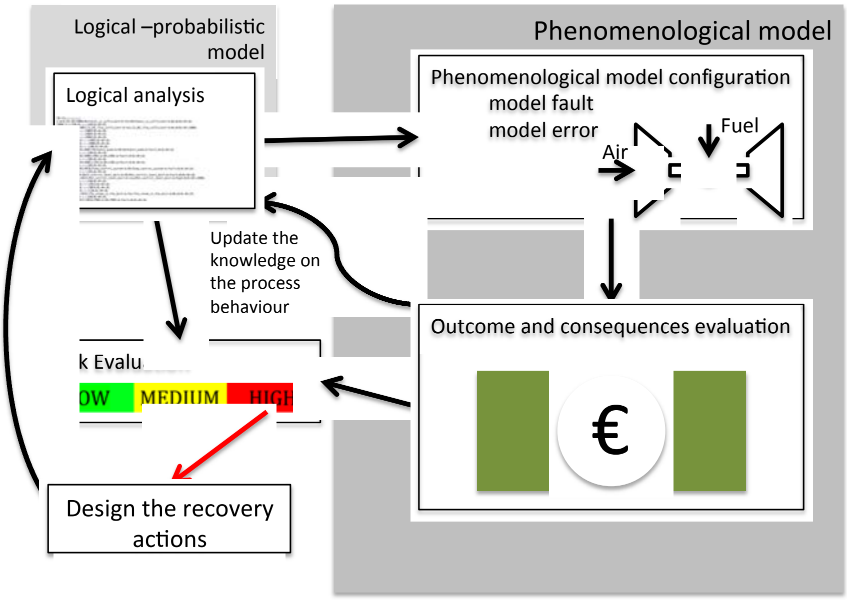

Figure 2: The interaction between logical–probabilistic and phenomenological model

2.3 Case study

An important step of the gas turbine maintenance is the control and replacement of the blades in the low-pressure turbine. This step is important both for the cost and for the time of the turbine stop for maintenance.
One problem is that the more used way for discover the number of the blades fault is opening the turbine. But spare blades are expensive and to reduce the management cost usually the number of spare blades is small. In the other hand if the number of spare blades is not sufficient, buying other blades can require long time, with a consequent important loss of production.
A risk-based approach is here proposed to analyse the alternative maintenance solution that follows:

- Option 1: LP Module cover lift for inspection, without new blade stored,
- Option 2: LP Module cover lift for inspection, with a stock of new blades stored (7 blades are usually stored, based on the previous company experience)
- Option 3: LP Module cover lift and replacement of all the blades.
- Option 4: LP inner block replacement (rotors & carriers)

The logical – probabilistic model, in the IDDA method, describes all the possible configuration of the turbine could present at the beginning of the maintenance operation, with reference to the number of blades failed. In Figure 3 an example of logical – probabilistic analyses represented as Event Tree is shown. The probability of blade fault is evaluated according to (Millwater and Wu, 1993).
Instead, in the phenomenological model, the cost and the maintenance duration are evaluated, according to the configuration described in the logical probabilistic model. The cost and duration data were provided by the plant management.

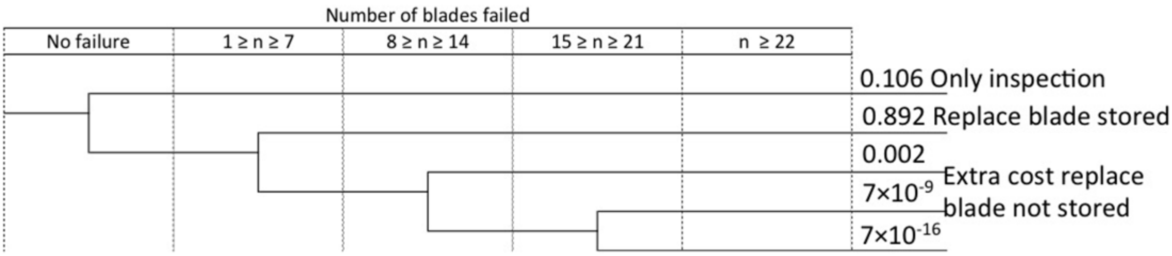

Figure 3: Event tree of the logical – probabilistic model for the option 2

3. Result

The 4 proposed maintenance strategies for the low-pressure turbine are tested to obtain the risk value in term of cost and time request for the maintenance, also based on the condition of the rotor found during the maintenance.Table 1 shows the results of the data elaboration.

Option 1 (no spare parts stored) has a risk of 2023k€, that decreases to 1845k€ for Option 2 (7 blades stored), since the spare parts are available, and no plant trip is required longer than the planned one. Option 1 results also confirms the company decision on the number of blades to be stored, since the failure of 7 blades or less is the one that shows the higher probability of occurrence (about 99%).

The risk increases for the other two options: Option 3 shows a risk of 3399k€ and Option 4 of 5799k€, since in both cases the substitution of all the blades is required (Option 3) and of the rotors and carriers (Option 4), involving higher costs.

Table 1: Risk value for the maintenance strategy

	Monetary risk (k€)	Interval before the next maintenance (y)	Annualized monetary risk (k€/y)	Duration risk (d)
Option 1	2023	4	506	85
Option 2	1845	4	461	54
Option 3	3399	8	425	60
Option 4	5799	8	725	38

On the other hand, these two last options allow an extension of the maintenance periodicity: 8 years for the 3 and 4 Options against 4 years for 1 and 2 Options. Thus, actualizing the risk values to the yearly maintenance risk, the following figures are obtained: Option 3 with a risk value of 425 k€/y appears to be the most convenient, against the 461 k€/y for Option 2, 506k€/y for Option 1 and 725 k€/y for Option 2. Option 4 appears to be in both cases the less convenient, but it should be considered that the complete renovation of the inner parts of the turbine should bring also to an improvement of the plant productivity, that should compensate the higher investment costs. Unfortunately, the productivity data were not still available when this paper was extended, thus the model does not consider this aspect at the moment.

Instead for the maintenance duration the Option 1 have a risk of 85 d, the Option 2 58 d, the Option 3 60 d and the Option 4 d. In this case more convenient is the Option 4 that have higher costs. The Option 2 and 3 have similar results in terms of maintenance duration and cost annualized, but the cost of the Option 3 is higher than the Option 2. The Option 1 have high risk value in term of duration but lower in term of cost.

4. Conclusions

Nowadays in different industrial plant the aging of the equipment is becoming an increasing problem. It can cause incidents, increase energy expenditure and generate extra costs.

A way to control the equipment aging is the correct maintenance. This paper proposes a risk-based approach to analyze the pros and cons of the different maintenance strategies to be adopted. A full picture of all possible scenarios can occur during the maintenance can be obtained thanks to the adoption of the Integrated Dynamic Decision Analysis. The proposed approach is tested on low-pressure turbine blades maintenance. In this case study 4 different maintenance strategy are analyzed, considering the risk associated to deferred maintenance. From the result obtained appears that the option of storing a certain number of blades as spare parts is a good compromise between the monetary risk and the duration risk. Storing 7 blades, as done at the moment by the company based on its previous operational experience was confirmed to be the optimal number within the company characteristics and constraints. Generalizing the proposed approach, the management should have have enough data to choose the best solution on the basis of the set priority.

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

References

Baldissone, G., Fissore, D., Demichela, M., 2016, Catalytic after-treatment of lean VOC–air streams:Process intensification vs. plant reliability. Process Safety and Environmental Protection, 100, 208-209.

Baldissone, G., Demichela, M., Fissore, D., 2017, Lean VOC-Air Mixtures Catalytic Treatment: Cost-Benefit Analysis of Competing Technologies. Environments, 4(3), 1-18.

Clementel, S., Galvagni, R., 1984, The use of the event tree in the design of nuclear power plants. Environment international, 10(5), 377-382.

Darabnia B., Demichela M, 2013, Data field for decision making in maintenance optimization: An opportunity for energy saving, Chemical Engineering Transactions, 32, 259-264

Demichela, M., Baldissone, G., Camuncoli, G., 2017, Risk-Based Decision Making for the Management of Change in Process Plants: Benefits of Integrating Probabilistic and Phenomenological Analysis. Industrial & Engineering Chemistry Research, 56(50), 14873–14887

Demichela, M., Baldissone, G., Darabnia, B., 2018. Using Field Data for Energy Efficiency Based on Maintenance and Operational Optimisation. A Step towards PHM in Process Plants. Processes, 6(3), 1-15.

Demichela, M., Camuncoli, G., 2014, Risk based decision making. Discussion on two methodological milestones. Journal of Loss Prevention in the Process Industries 28, 101-108.

Demichela, M., Piccinini, N., 2008, Integrated dynamic decision analysis: a method for PSA in dynamic process system. Proceedings of CISAP 3, Rome, Italy, 11-14 May 2008; AIDIC: Milano, Italy.

Galvagni, R., Clementel, S., 1989 Risk analysis as an instrument of design. Chapter In: Safety design criteria for industrial plants, Cumo, M., Naviglio, A., CRC Press, Boca Raton, USA, Volume 1.

Gallimore K.F., Penlesky R.J., 1988, Framework for developing maintenance strategies, Production and Inventory Management Journal, 29(1), 16-22.

Gerbec, M., Baldissone, G., Demichela, M., 2017, Design of procedures for rare, new or complex processes: Part 2 – Comparative risk assessment and CEA of the case study. Safety Science, 100(B), 203-215.

Gits C.W., 1992, Design of maintenance concepts, International Journal of Production Economics, 24(3), 217-226.

Horrocks P, Mansfield D., Thomson J., Parker K., Winter P., 2010, Plant Agening Study. Phase 1 Report, Health and Safety Executive, Warrington, UK.

Lee H.H., 2005, A cost/benefit model for investments in inventory and preventive maintenance in an imperfect production system, Computers & Industrial Engineering 48, 55-68.

Millwater H. R., Wu Y.-T., 1993, Computational Structural Reliability Analysis of a turbine blade.In: Proceedings of the international gas turbine and aeroengine congress and exposition, Cincinnati, OH, 24–27 May 1993

Paz N., Leight W, 1994, Maintenance scheduling: Issues results and research needs, International Journal of Operations and Production Management, 14(8), 47-69.

Reay D., Ramshaw C., Harvey A., 2013, Process intensification. Engineerin for efficiency, sustainability and flexibility, Elsevier, Oxford, UK.

Weil N.A., 1998, Make the most of maintenance, Manufacturing Engineering, 120(5), 118-120.

Turja, A., Demichela, M., 2011, Risk based design of allyl chloride production plant. Chemical Engineering Transactions 24, 1087-1092