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Cost benefit evaluation of maintenance options for aging equipment using monetised risk values: a practical application

M.C. Leva[a], G. Baldissone[b], R. Caso[b], M. Demichela[b], L. Lawlor [c], B. Mcaleer [c]*

[a]*Dublin Institute of Technology Health And Safety Department, Dublin, Ireland*
[b]*Politecnico di Torino, DISAT Dipartimento Scienza Applicata E Tecnologia, Torino, Italy,* [c]*ESB Electricity Supply Board, Dublin, Ireland*

Abstract

With constant pressure to reduce maintenance costs as well as short-term budget constraints in a changing market environment, asset managers are compelled to continue operating aging assets while deferring maintenance and investment. The scope of the paper is to get an overview of the methods used to evaluate risks and opportunities for deferred maintenance interventions on aging equipment, and underline the importance to include monetised risk considerations and timeline considerations, to evaluate different scenarios connected with the possible options. Monetised risk values offer the opportunity to support risk-based decision-making using the data collected from the field. The paper presents examples of two different methods and their practical applicability in two case studies in the energy sector for a company managing power stations. The use of the existing and the new proposed solutions are discussed on the basis of their applicability to the concrete examples

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* Corresponding author. Tel.: +353 86-1613570;.
E-mail address: chiara.leva@dit.ie

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1. Introduction: Aging Equipment in the energy sector, risks and opportunities

Asset managers in the Energy sector are more and more required to maintain operational continuity with aging assets while deferring maintenance and investment. The consequences of such decisions are rarely immediate, deferring maintenance and investment can result in cost reduction in the short term, however it also required on the other end to set up an "intelligent prognostics" system, which can measure, control, and alert the operating personnel, detecting unavoidable risk degradation. [1]

Overall the situation calls for better monitoring and control on ageing equipment, to quantify the impact of operating modes on system reliability, to accurately estimate their residual life and to adapt the maintenance strategy, while respecting safety, regulation and operational performance.

Any power plant is required to supply the amount of energy demanded by the market and to comply with the regulatory requirements defined by government laws. To attain the objective, one of the most important aspects is to guarantee technical availability. This feature is not always easily achieved: during operation, the equipment that are used the most are gradually deteriorating, until they reach a deterioration failure, or other types of failures, such as fatigue or corrosion, induced by the specific operating conditions of the equipment itself.

New opportunities are given by monitored systems in modern process plants, whose data have to be integrated in DCS (distributed control systems) and PLC (programmable logic controller) to prevent potential dangerous outcomes. Data gained through the automated monitoring and control systems, but also through inspections, are fundamental and can bee used to support risk- based decision making, and ultimately the risk management of ageing equipment. To understand, identify, and manage critical states in aging or deterioration, it is necessary to develop mathematical models that represent the aging process to show the deterioration of power equipment, and determine the cause of aging. A review of the most recurrent causes of trips in a power generation company in The republic of Ireland showed that 43% of all the trips are attributed to equipment aging as root cause and in those 43% more than 65% explicitly mention equipment aging as the primary causes. Although aging and deterioration effects are unavoidable, it is desirable to find a way to slow down the deterioration rate, and to extend equipment's service life and this could be obtained by reducing exposure to the operating, environmental or transient conditions that cause or exacerbate deterioration.

The aim of this paper is to present a risk-based assessment for decision related to different maintenance intervention options as applied to the context of power generation [2] [3].

2. Asset management and Risk Analysis

The standard ISO 5500 for Asset management [4] [5] states that a proper evaluation of risks and opportunities are essential to the effective control and the governance of assets to achieve the desired balance of cost, risk and performance. Asset health indices provide a qualitative indication of probability of failure while asset criticality provides a qualitative indication of the consequences of an asset's failure, not only for the asset itself but also for the power system and the environment where the asset is located.

The aim of the asset management is to have a view of the asset operation and maintenance as a unity, to reach a perfect understanding of the whole life cycle costs. The asset management processes focus on Life Cycle Management of the power system equipment. Understanding the ageing processes of the equipment that can be affected by some common mechanism such as corrosion or fatigue, and the consequent impact on equipment performance is a critical factor for asset management to be able to address key questions on safe performance of the equipment. In terms of asset maintenance management within a modem power utility there are some important questions that need to be answered, particularly regarding the fatigue or corrosion issues: if there is an equipment in a safe condition sometimes companies don't know how to asses its performance, or what maintenance and testing regime to set, or whether to refurbish or replace it, or allow it to run to failure.

Appropriate asset management strategies allows companies to achieve risk reduction, opportunity identification or process improvement, which can be identified early in the implementation, and can be exploited to demonstrate returns and gain stronger stakeholder support. An asset management system can help in gaining an understanding of assets, their performance, the risks associated with managing assets, it supports a long-term and sustainable approach to decision making and the organization's risk-based decision making processes can become more effective by addressing asset and financial risks together, and by balancing performance, costs and risks.

A company asset management policy should also take into consideration the evolution of PACS (protection, automation and control system) as they should be developed keeping in mind the possibility of future extension, modification and functional upgrading until complete system refurbishment.

3. The need to evaluate risks and opportunities for deferred maintenance interventions on aging equipment

The ability to perform a risk-based decision making based on big data collected from the field and, whenever possible, integrated with the DCS data requires new capabilities for the design of operations. This will reduce human error in safety critical industries, demonstrating how an appropriate model Risk Assessment can significantly improve training market share and business and safety performance [6]

Managing power plants to operate at low cost and without excessive damage is the goal of every plant owner. However, cycling a unit poses a multi-dimensional problem for which forecasting of aging effects are difficult to estimate. The challenge expands progressively because "cycling operation" is a broad concept that encompasses load-following, low load, hot starts, warm starts, and cold start of a plant with different lengths of time between operations; it is definitely not solely time-based. Is it more financially prudent to shut down a particular unit at night to save fuel and incur the multitude of cycling costs or stay online at minimum load and burn fuel? The answer to that question is obviously unit/system-specific, but there are some trends based on client experience after the true cost of cycling has been determined. Thanks to some studies we can observe that many companies have reduced unit minimum loads to 5% to 20% of rated load on fossil boilers so that units can "simmer" overnight. This approach keeps the equipment hot and ready to quickly ramp up to full load (a big advantage in a competitive market), yet it uses minimum fuel at night.

Evaluating the likelihood of occurrence of equipment failures and their consequences for the power plant operation, through a quantitative analysis, integrating probability and consequence, are process well obtained by the Risk Analysis Method. It attempts to focus on the following objectives:

- To develop a data structure supporting consistent hazard identification and risk rating across different sites;
- To develop equivalent severity and frequency scales for different loss types and for application across different business units, such as operations, maintenance, finance, HR etc, in order to guarantee a uniform risk analysis;
- To embed the risk analysis within a risk management process and share good practices across the company.

When optimizing a process scheme or planning equipment maintenance, it's common to use methods, such as risk assessment, which can show the cost impact of the proposal solution. This number could be used to prioritize a series of items that have been risk assessed. Those methods require a great deal of data both for the assessment of probabilities and assessment of consequences. After the scope definition it is necessary to quantify and then evaluate the risk, in order to obtain a proper solution, to which is related a proper acceptability/tolerance.

A decision generally deals with three elements: alternatives, consequences, and preferences. The alternatives are the possible choices for consideration. Now it's clear that the amount of decision making procedures is considerable, but each method shows the alternatives in a different way, going to remark what it might be the eventual solution. The goal is to choose the best alternative with the proper consideration of uncertainty. Decision analysis provides methods for quantifying preferences tradeoffs for performance along multiple decision attributes while taking into account risk objectives.

In the following part we present the use of a proposed customised methods to identify valuable maintenance/repair overhaul options for ageing equipment through a risk based evaluation of different options.

4. Case studies from an Energy generation company: current methods new improved proposed solutions.

This paper aims to compare some technical risk assessments, to underline what needs to be improved, but mostly to describe the percentage of uncertainty and inaccuracy, which is derived from a calculation and a processional choice most often based on technical experience, which would require a greater theoretical basis. The following method is applied to the analysis of two case studies in an electricity generation company across multiple locations in the Republic of Ireland. As part of an on-going process of Process Safety improvement, the organisation highlighted the need to advance the identification, analysis and management of risks across the business, and to facilitate comparison and tracking of options in relation to corrective actions. A project team was therefore assembled, with representatives from different stations and specialism, to create a risk analysis process and template to meet the business' needs. The overall approach for risk evaluation of possible interventions of the company is reported in Fig 1.

The approach has been applied to two examples. The first example is about a Generator Rotor hub in a dam. The outer rim of the rotor had a series of stacked steel laminations onto which the rotor poles were attached. The defects that were identified appeared to be largely related to poor welding technique/procedure during construction. So the risk was around how to best address the potential defect, to avoid structural failures of rotor hub in service, an event that would have a noticeable impact such as damaging the generator poles/stator and possibly injuring personnel. To prevent this phenomena the company needs to decide when to replace the rotor and if do this replacement using a newly designed component. These questions are answered with a technical risk assessment achieved by focusing on technical/operational considerations, together with commercial ones around the possible applicable solutions and how they could be realised, identifying all the critical aspects through the support of a risk matrix and corresponding monetary and likelihood intervals to support the relevant scenarios severity and probability estimations

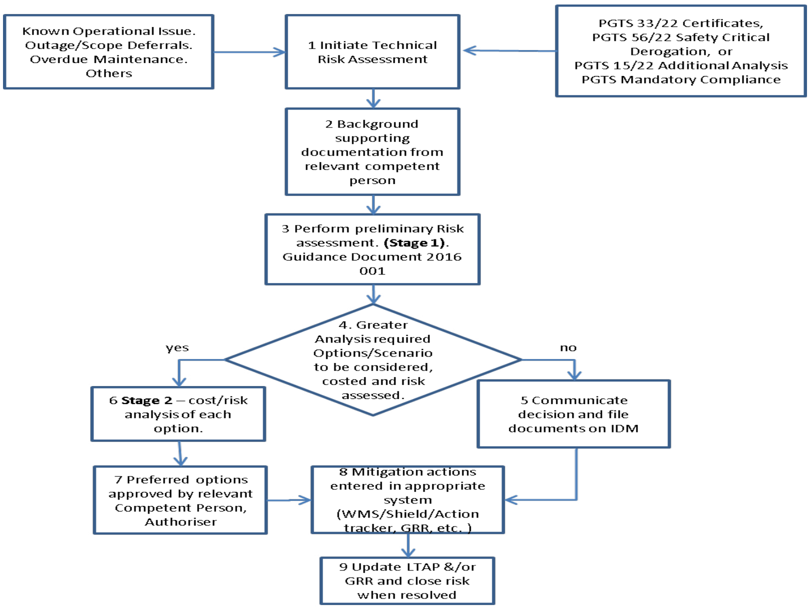

Fig. 1. Overall approach for risk evaluation of possible interventions.

The second example concerns the improvement that could be obtained by using a more specific and detailed method. This is demonstrated in a case study to evaluate options for revamping of the bypass valve unit of a HP turbine. The failure in this study was a result of Solid Particle Erosion (SPE). The origin of the solid particles is corrosion of the lining of the high-energy pipework, due to aging of the piping lines combined with an operating regime leading to greater thermal cycling. The increased duration between outage/repair opportunities also lead to an increased exposure to the effects of erosion.

Since the failure some work has been carried out to mitigate the risk of damage from SPE. For instance especially fundamental changes to the operations of hot and cold starts and monitoring for possible SPE damage. After an appropriate comparison between the various options, for each of which a risk analysis has been established, the best solution was obtained by identifying the impact rating, its probability and its risk using the categories supported by estimating a range of risks related to the options the company is facing for repair and the consequences related to the residual risk as well.

While there are no perceived risks to personnel safety a long term forced outage would have huge financial implications, mainly caused by the necessity to repair the unit, which has an additional time to manufacture a new module. The probability rating has been selected as a result of the fact that SPE is generally a known feature on those units, to which the awareness of the plant age must be added, but sometimes it could be merely caused by an incorrect inspection, that didn't report the damage observed. The potential mitigation action was refurbishing the spare HP module to reduce the duration and financial impact of a forced outage. This risk assessment considers the risks of damage to the impulse wheel. The availability of a spare HP module was also considered a factor able to positively affect outage duration.

The study was conducted using monetized risk considerations. The options available are outlined and assessed below:

- Option A: Replacement of valve station with design upgrade to mitigate known issues.
- Option B: Replacement with same design valve.

After the risk assessment for the current situation (see Fig. 2), each option was broke down into the actual costs of the planned interventions plus the monetized values of the risk connected to the intervention itself; the residual risk left after the intervention was also then evaluated. A sum of risk rated costs was then computed by considering for each options the loss of revenue directly proportional to the length of time needed to perform each intervention plan, the actual repair costs (evaluating all the components involved such as materials, equipment, labor etc.), the mitigation costs that refer to the options as for instance a replacement with the same design, could be obtained considering continuous maintenance regime. The evaluation also needs to take into account the performance penalties that could be connected with the options (such as inability to run at full speed power etc.) A risk rated cost

Station: and unit:	
Purpose of Project and brief Synopsis:	
Existing Condition (issue being assessed):	
Existing derogations and or attached documentation	
Brief summaries of possible solutions	

Risk assessment of current situation:

Categories		Description	rating	results
Loss of revenue	cost of 'GWHR loss' Link to Portfolio Income			
	Likelihood			
	Risk rated cost (€)			0
Plant damage cost (insert justification here)	Cost of repair/ replacement			
	Likelihood			
	Damage risk rated cost (€)			0
Safety (insert justification)	Safety cost			
	Likelihood			
	Safety risk rated cost (€)			0
External Stakeholders/ PR (justification)	PR cost			
				0
Environment	Environmental cost			
	Likelihood			
	Environmental risk rated cost (€)			0
Sum of risk rated cost for current status				0

Fig. 2.Part of the template used for risk evaluation of current situation

		Option A:		
Categories		Description	rating	results
Loss of revenue	Best estimate Availability loss (no. of days)			
	Likelihood			
	Risk rated cost (€)			
Repair cost 1	Best Estimate Cost of repair/ replacement			
	Likelihood			
	Risk rated cost (€)			
Mitigation cost	Best estimate for Mitigation cost			
Performance penalties	Best estimate for possible loss of performance			
Others	This may be performnace enhancement or reduction			
Safety exposure for work (insert justification)	Safety cost			
	Likelihood			
	Safety risk rated cost (€)			
Sum of option cost				€0
Residual risk of situation after option A		Description	rating	results
Loss of revenue	GWHR loss			
	Likelihood			
	Risk rated cost (€)			
Plant damage cost (insert justification here)	Cost of repair/ replacement			
	Likelihood			
	Damage risk rated cost (€)			
Safety (insert justification)	Safety cost			
	Likelihood			
	Safety risk rated cost (€)			
External Stakeholders/ PR (justification)	PR cost			
Environment	Environmental cost			
	Likelihood			
	Environmental risk rated cost (€)			
Sum of risk rated cost for residual risk				0
Total Risk Rated Benefit				€0

Fig 3 Template used for risk evaluation of various options

was also assessed in relation to health and safety incidents and/or the risk of process safety events connected with the intervention (such as working at height etc..). No simulation or iterative calculation is supporting this evaluation, as it simply requires expert judgment from the asset management team with an appropriate anchor point to justify the chosen estimates. Last but not least the method required to evaluate a monetized risk value of the residual risk left after the intervention through which a value of the risk rated benefits can be subsequently added to.
The risk rated benefit used for prioritizing the options is simply obtained by comparing the benefit given by the current risk exposure minus the residual risk exposure against the costs which is obtained by the evaluation of risk rated costs of the various mitigation plans as explained above. The higher the benefits the better the option (see Fig.3).

4.1. A new prospective for the risk assessment: the dynamic decision analysis

It is noticeable how useful, feasible could be the implementation of the decision trees able to define a solution for any kind of risk assessment. The method should be able to apply the best solution even in a new plant, with a different value of the risk, but companies can have a more accurate decision method using that one. Improving the management of ageing equipment should be obtained using these methods. Market demand obligates companies to make the ageing plant work harder, causing the most need to apply a proper risk assessment with its cause analysis.

A good starting point for the development of the logical-probabilistic model can be a functional analysis of the system, exploiting also, where available, the information contained in the analysis already carried on with traditional methodologies. The last case study was about a common procedure for LP rotor gas turbines risk assessment in which the decision was divided in:

- Option 0: LP Module cover lift for inspection, without new blade stored,
- Option A: 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 B: LP Module cover lift and replacement of all the blades.
- Option C: LP inner block replacement (rotors & carriers)

Each option has a different workscope and cost, associated to a risk rating based on the risk matrix, gained through a possible value of the impact and the likehood of the solution adopted. In this study a dynamic event tree method was used to calculate the probability of the gas turbine blade rupture. It was based on a structural reliability analysis in order to quantify the behavior of several critical components of structures subject to uncertain loadings, boundary and geometrical conditions and material parameters.[7] Turbine failure modes are generally described by frequency, stress corrosion and erosion, creep fatigue; the computation of the probability of failure requires the selection of a particular stress condition, fuction of time.

The Integrated Dynamic Decision Analysis (IDDA) - described by Remo Galvagni [8] [9] - allows to carry on the risk analysis in a dynamic way, taking into account process time dependant occurrences, optimisation of procedures for LPG tanks maintenance and testing [10] IDDA method is based on a logical-probabilistic modelling of the system, integrated with its phenomenological modelling. The IDDA analysis was applied in Baldissone et al. [11] to formaldehyde plant production, in Baldissone et al. [12], [13] to a VOCs treatment plant and Demichela [14] to the risk-based design on an allyl-chloride production plant. The interaction between logical–probabilistic and phenomenological model could be easily shown in Fig.4.
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 the run time of the model, to fit it to the current knowledge status.

The elaboration of the logical – probabilistic model, described in the input file through the IDDA software, returns all the possible sequences of events that the system could undergo, depending on the knowledge disclosed in the input model, together with their probabilities of occurrence.

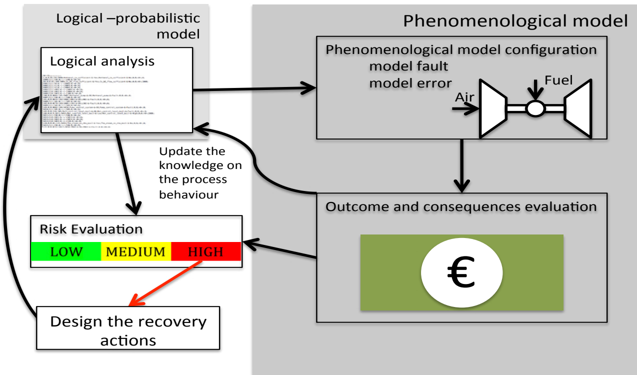

Fig 4 The interaction between logical–probabilistic and phenomenological model

In the logical modelling of the different options, it has been considered how the maintenance procedures are carried on depending on the number of damaged blades.

The Event Tree representation for the option A is reported in Fig.5 [7].

A phenomenological model, together with the logical modelling, must be prepared in order 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 in order 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.

The phenomenological model allows calculating the costs for the different maintenance options for each scenario described by the logical model. The basic costs have been supplied by the plant management.

Through this model the following results have been obtained: Option 0 (no spare parts stored) has a risk of 2023k€, that decreases to 1845k€ for Option A (7 blades stored), since the spare parts are available and no plant trip is required longer than the planned one. Option A modelling 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 B shows a risk of 3399k€ and Option C of 5799k€, since in both cases the substitution of all the blades (Option B) and also of the rotors and carriers (Option C) involve higher costs.

On the other hand, these two last options have as a consequence an extension of the maintenance period: 8 years

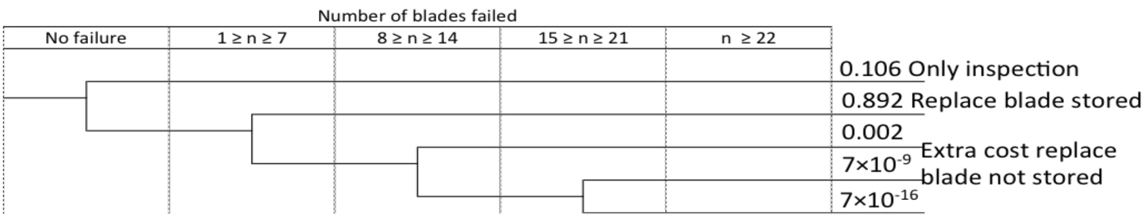

Fig 5 Event tree developed for option A

for the B and C Options against 4 years for 0 and A Options. Thus actualising the risk values to the yearly maintenance risk, the following figures are obtained:

Option B with a risk value of 425k€/y appears to be the most convenient, against the 461 k€/y for Option A, 506k€/y for Option 0 and 725 k€/y for Option C.

Option C 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 take into account at the moment this aspect.

5. Conclusions and Way Forward

As discussed above, most of industrial equipment is nowadays used beyond the useful life foreseen at the design stage. To maintain the requested productivity level and the operational safety the equipment thus need a more frequent maintenance. The extra-maintenance requires extra-costs that need to be optimised, in terms of frequency and effectiveness, against the chance of renewing the equipment itself.

This paper has described three case studies where this issue has been addressed through qualitative and quantitative methodologies able to support the operational optimisation in the industrial domain.

The methods and approaches here described have been tested on the energy sector, but they are of wider application and their extension to other domains will be the way forward.

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