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A DIGITALIZED APPROACH FOR COMBINING DIAGNOSTIC CAPABILITIES AND MAINTENANCE RISK-BASED INSIGHTS TO IMPROVE MACHINE OPERATION

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ABSTRACT

The emergence of the Industrial Internet of Things (IIoT) and Big Data and the associated predictive analytics in industrial sectors where assets represent a high-value component, drives opportunity to increase profitability and leads to the Asset Performance Management (APM), a new integrate approach to run the assets at best, maximizing their operational and financial results.

This paper presents a case study which integrates the predictive capabilities of a Monitoring and Diagnostic (M&D) service with a risk analysis carried out on the asset and the information on maintenance activities performed on site, thus resulting in a new enhanced service.

The aim of traditional M&D is to process the field data using analytics, to deliver insights on equipment health and suggest actions. We support these recommendations with a quantitative assessment coming from the risk analysis, reporting the benefits associated to the suggested actions, expressed in risk reduction, and the effects may happen if no action is taken. Moreover, for certain failures, the recommendations are automatically retrieved from the risk analysis.

Maintenance strategy revision is also performed, having as objective to turn the initial time-based preventive plan into a risk-based predictive one. This is enabled by both the risk analysis outcomes and the availability of M&D. For example, for a not critical item whose functioning can be easily monitored remotely, time-based maintenance activities may be saved.

The other component of the extended M&D work process is the creation of some components for a dynamic maintenance strategy, enabled by analytics. Data on maintenance activities, e.g. failure frequencies, are used for suggesting that the maintenance plan or the risk analysis need a revision. It is also suggested when to implement a new M&D recommendation within the running maintenance plan.

We applied this strategy to an Oil&Gas plant and the results of the integrated service delivered have been observed for several months, providing feedback on the methodology as well as points of reflection for further enhancements.

INTRODUCTION

In industrial plant, Gas Turbines (GT) are used mainly either for power generation or mechanical drive, therefore becoming an essential portion of the plant and fulfilling a production-critical mission. Plant operators want to achieve the economic optimum, considering revenues and maintenance costs, during whole GT life-cycle, maximizing equipment availability and reliability (Allegorico, 2014). A well-performed maintenance is an essential component for this purpose and it may highly benefit from the support of M&D.

In BHGE we have developed M&D capabilities that we apply to a broad installed fleet of rotating equipment, GT in particular. The process for monitoring assets is consolidated and can be described as follows: data from on-board sensors is checked for quality, stored in databases/cloud, and feed a number of analytics, which monitor the GT health status, calculate the performances and detect incipient or occurred functional failures. If a potential issue is identified, a disposition process starts. Depending on the case severity, it may require extensive troubleshooting, e.g. a Root Cause Analysis, and it can involve Subject-Matter Experts (SME) and site personnel, such as operators and maintenance representatives. The outcome is a set of recommendations to be implemented, in order to prevent a failure scenario or perform discard/restore tasks on an occurred failure.

Looking from a site operator perspective, this process may help in increasing availability and solving the issues that the asset may encounter during its life-cycle. However, since it is not fully integrated with other processes taking place in site, maintenance in first place, the recommendations may be too generic or uncorrelated to the site evidences.

This paper presents a case study where we integrate the M&D process with the maintenance one, aiming to a dynamic maintenance strategy. In a changing environment where Industrial Internet of Things (IIoT) is offering a chance to drive productivity and growth, we use digitization as an enabler to integrate processes and approach a smart maintenance management (Iannitelli et al., 2018).

For the present study, we selected an Oil&Gas plant, operating in gas gathering application: natural gas from on-shore and off-shore wells is connected to a station where it is compressed up to the output pipeline pressure in three consecutive compression stages. One of the three stages has no redundancy, unlike the others, and its unscheduled outage may cause the downtime of the entire plant. Therefore, this compression train is considered the most critical for the application and we apply the methodology of the case study to it.

In-scope asset is composed of a gas turbine, a centrifugal compressor, a knock-out drum separator and a process air cooler. The assets are manufactured by BHGE as well as by other Original Equipment Manufacturers (OEM).

In the following sections will be described: the dynamic Asset Performance Management process, the deployed analytics for performing Monitoring & Diagnostic, the risk analysis developed on the maintainable items, an asset strategy management, analytics for maintenance optimization, a quantitative method to evaluate the enhanced work process (and related service BHGE can offer) and the outcomes after few months of project.

NOMENCLATURE

ACA – Asset Criticality Analysis
APM – Asset Performance Management
BHGE – Baker Hughes, a GE company
CECO – Centrifugal Compressor
CMMS – Computerized Maintenance Management System
DE – Diagnostic Engineer
FMEA – Failure Modes and Effects Analysis
GE – General Electric
GT – Gas Turbines
IIoT – Industrial Internet of Things
LOP – Loss Of Production
HSE – Health, Safety and Environment
M&D – Monitoring & Diagnostic
OEM – Original Equipment Manufacturers
RCM – Reliability Centered Maintenance
ROI – Return Of Investment
SME – Subject-Matter Experts
TTR – Time To Repair
UCP – Unit Control Panel
WO – Work Orders

ASSET PERFORMANCE MANAGEMENT

A maintenance department is responsible for keeping the equipment under their management in the best operating conditions and to ensure that it can deliver according to the specification. A well-performed maintenance enables key factors such as sustainability, availability, profitability.

Different maintainable assets require different maintenance strategy, depending on the failure modes and the consequences they might cause. In other words, the entire maintenance strategy depends on the result of a risk analysis performed on the maintainable asset. From a maintenance standpoint, whatever impacts Health, Safety and Environment (HSE) is a must-do. All the other activities offer the chance for optimization, finding the best compromise between maintenance costs and production loss. Therefore, maintenance strategy selection has been studied extensively and various decision-making approaches were proposed (Gandhare & Akarte, 2012).

Recently we are witnessing the “servitisation” of maintenance (Meier et al., 2010). OEM are looking for opportunities to provide the maintenance service within the in-service phase of the product life cycle, to generate additional revenue and profit. GT operators are expecting to pay for the usage of the product rather than the full ownership. Hence, the concept of continuous maintenance as-a-service, strongly characterized by the predictive on-condition component, has been introduced (Roy et al., 2016).

Maintenance management can be a complex activity, especially for huge industrial plants with thousands of assets. To help maintenance representatives and operators, Computerized Maintenance Management System (CMMS) is commonly adopted. It supports the management in decision making, planners in organizing the activity, workers for carrying out the executions.

If CMMS is used as a practice for each step of maintenance management, the amount of data produced and collected represents a valuable source for the continuous maintenance named above. Among this information, work orders (WO) must be mentioned: they contain details on activities performed at site, including the needed spare parts, men hours and results of inspections.

The transition from a time-based preventive strategy to a condition-driven predictive one, fundamental to enable the continuous maintenance as-a-service, requires knowledge and modeling of items degradation, along with availability of data and related insights coming out from analytics. In this ecosystem, the Monitoring and Diagnostic (M&D) capability can be considered a complementary essential component.

The benefits that M&D systems can bring to operators and manufacturers alike are common knowledge and include operating cost reduction, improved knowledge base for OEM, life extension of components, improved safety, reduced downtime, lower fuel consumption (Bechini, 2007). However, as mentioned in the introduction, M&D process may be uncorrelated to other processes taking place in site, first of all maintenance, and the scope in our case study is to integrate them.

Linking together M&D and continuous maintenance as-a-service represents a big opportunity to support at best anomalies resolution and prevention, suggesting integrated meaningful recommended actions, based on an optimized maintenance strategy and controlled risk.

There is an ongoing effort in the development of process and tools enabling the integration of M&D, CMMS and beyond. These efforts fall under the Asset Performance Management (APM) strategy (Jooste, 2003). Figure 1 shows the typical APM process used in BHGE. The grey box at right represents the in-scope asset, where the operations & maintenance activities take place. A connection infrastructure allows data to be stored in databases and processed by analytics, the blue block in the bottom, which are delivering actionable insights back to the site.

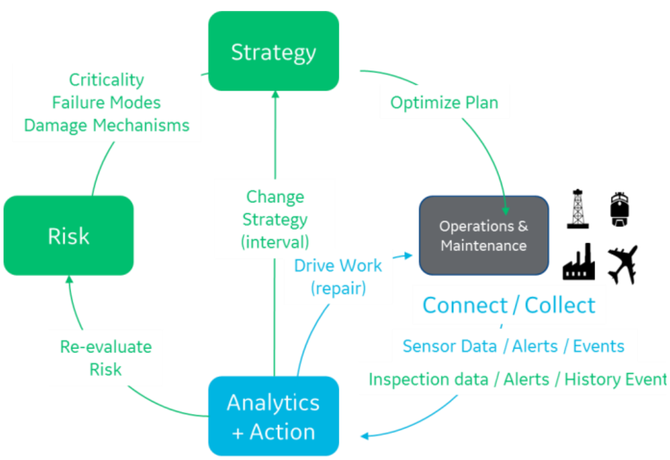

Figure 1 - Asset Performance Management process

In the M&D framework, analytics process the data coming from on-board sensors, along with alerts and events from the Unit Control Panel (UCP), whose control logics may provide important diagnostic indications. On the other hand, analytics can also process maintenance data coming from site, e.g. inspections reports, history events, spare parts details, costs. This data is complete and automatically available if CMMS is used as a normal practice and is connected online to the APM process.

In the green upper box is represented the maintenance strategy, which drives the activities at site. Strategy is conditioned by the risk analysis performed on the asset and the indications from analytics regarding strategy update.

This framework is more valuable if its components are integrated and exchange information among them automatically. This is possible thanks to availability of data and insightful analytics.

The expected outcome of an APM process is an extended capability giving actionable answers in a risk-cost frame and using an optimized predictive maintenance strategy, which can be used by OEM for delivering an advanced dynamic maintenance to serve their assets.

THE MONITORING & DIAGNOSTIC PILLAR

The remotization of asset data gathered online during operation is foundation to the dynamic maintenance strategy of an APM we want to implement. As described by Ray, 2016, multiple data infrastructure architecture for IIoT applications have been used by the companies.

In general, when implementing a remote connection, critical aspects to consider are: completeness of the data set, quality, continuous transfer of the data and compliance to cyber-security. For the case study, we acquire data from all the on-board sensors, sampled at one second rate, as well as signals calculated by UCP and the booleans (alerts and events) generated by the control logic. These datasets, once proven in quality, are the inputs of the M&D analytics, scanning for anomalies and incipient failures. They are also used for troubleshooting purposes once issues arise.

Moreover, we have availability of vibration monitoring information, coming from high scan rate acquisitions processed on premises. For more references, Bently & Hatch, 2003. This data is used on regular basis for checking the vibrational status of the equipment, or when an event is suspected to be linked to a rotodynamic issue.

As described in the previous section, another source of data necessary for the case study is the CMMS, containing the information on maintenance activities. For the present case study, we do not connect CMMS on-line, but use sampled extraction of data for proving the methodology.

Case study analytics

Monitoring analytics process the acquired data, in order to calculate performances and detect functional failures, as well as check for deviations from the normal behavior. Whenever a potential issue is detected, a diagnostic alert is raised. These alerts have then to be processed by an operator, e.g. a Diagnostic Engineer: a technical assessment is performed, eventually leading to the opening of a technical case. A disposition process starts, involving subject-matter expert and/or site personnel, up to the resolution of the case.

For the case study presented in this paper, we apply existing sets of analytics already used in the standard M&D service, and develop new ones, for covering specifically the assets under the monitoring scope of work.

Two categories of analytics are used: physics based and data-driven. The first type leverage on the physical knowledge of the monitored asset and check for anomalies using traditional programming techniques, such as threshold crossing, logical operators, time delays. Sometimes, a physics model implementing the governing equations of the phenomenon may be incorporated. On the other side, data driven analytics are based on availability of large quantities of data and implement machine learning techniques. For more details, Dawn et al., 2015.

The physics-based analytics for monitoring the in-scope asset can be divided in the following sub-categories:

- signals anomaly recognition, i.e. algorithms applicable to one or more signals in order to identify deviations, such as exceeded threshold, noisy/erratic signal behavior, which can be a symptom of incipient instrument failure, detection of a step up/down or a slowly increasing/decreasing trend;
- functional system monitoring, i.e. analytics working at system level, for both the gas turbine and centrifugal compressor (CECO);
- model-based analytics, strongly leveraging on a physical modeling of the equipment, such as performances assessment.

The analytics are coded in Matlab/Simulink and in Python languages and deployed in BHGE analytics framework which automatically and continuously apply them to the incoming data flow.

For data-driven analytics, we apply a commercial suite, GE SmartSignal, which gives the possibility to train a model with embedded machine learning techniques on multiple type of asset, at equipment or system level. Training data representing the normal behavior of the equipment/level must be selected and inputted to the system, in order to create a baseline and train a model. Therefore, the monitoring consists of comparing the actual measurements on the monitored asset with the outputs of the model. If deviations are detected, a diagnostic alert is raised.

Since the machine degrades over time, the model needs recurrent re-training with failures-free data. The need of a model retraining is usually advised by the increment of False Positive alerts, e.g. normal conditions predicted as unhealthy. With respect to the physics-based approach, the data-driven analytics have the advantage to have easier tuning of the parameters and to be agnostic, because the monitoring can be performed without implementing and even knowing the inner physics of the phenomenon (Hines et al., 2008).

RISK ANALYSIS

The first step of the risk analysis is the Asset Criticality Analysis (ACA), which defines the highest criticality of each single item, by exploring its worst failure condition (Norsok Standard, 2001). Only on the items considered "critical", a more detailed Failure Modes and Effects Analysis (FMEA) is performed. In FMEA, the risk associated to each failure of the critical items is analyzed and when is too high with respect to predefined parameters, it is mitigated by specific recommendations. Hence, the outcome of the analysis is represented by a set of recommendations. For more references on the methods see Moubray, 1997.

In this case study, the objective of the risk analysis is to challenge the actual time-based maintenance plan of the site, focusing on on-condition tasks that can orient maintenance towards a predictive approach. Moreover, within an APM process, FMEA recommendations can be used by Diagnostic Engineers to perform the troubleshooting once an issue is detected, as well as to quantitatively support the insights delivered to site team.

The development of a risk analysis requires the engagement of multiple professional profiles, such as equipment SME, mechanical and instrument experts, working in close collaboration. Beside the design documentation, e.g. Piping & Instruments Diagrams, control and mechanical drawings, a joint review of the way maintenance is performed in site needs to be conducted, so to have a more accurate estimation of the maintenance activities cost. We consider, for example, the warehouse availability with spare parts list, the activities that are normally conducted on site versus off-site, the available tools and resources, so on and so forth.

The risk analysis could be performed at different levels: at equipment level (GT, CECO), at system level (lube oil, fuel gas system, …), sub-system level (metering valve for the fuel gas system). For this study, the last analyzed component is the actual maintainable item. Since one of the objectives is to challenge the existing maintenance plan, an analysis carried over a deeper level would not add any value. As an example, in case of a small valve failure due to an issue on the trim, the whole valve is being replaced, allowing the plant to get back in operation as soon as possible. The valve will be then overhauled in the shop. Overall, a total of round 450 assets is identified.

Asset Criticality Analysis

Asset Criticality Analysis is performed on the whole scope of work (Norsok Standard, 2001) and estimates the total risk associated to each item by analyzing its worst failure scenario. Total risk is composed of four risk estimations, with respect to as many categories: safety, environment, operation and financial. If any category has an estimated risk above a certain threshold, the item is labelled as "critical" and a FMEA needs to be performed on it.

For each category, risk is expressed with the formula:

$$risk = consequence \cdot occurrence$$

where *consequence* is an integer number representing the impact of the failure (usually, an exponential scale is used) and *occurrence* is the failure occurrence calculated as failure numbers per year. The analysis is performed in a semi-quantitative mode: consequence and occurrence levels are defined in a risk matrix (Moubray, 1997).

Risk matrix setup is a crucial step in risk analysis. Typically, each plant operator has defined its own criticality matrix, tailoring consequence and occurrence levels on the peculiarities of the plant. When not available, as in the case of this study, the risk matrix can be setup and discussed with SME, starting from a standard one and customizing it on the production needs and experience. The general limitation in using a risk matrix can be a poor resolution, since it uses discrete levels. For more details, Cox, 2008.

Regarding consequence levels definition, safety and environmental levels are quite standardized and agreed within the industry; in Table 1 we report an example of the safety risk category. On the other hand, the operational and financial consequence levels should be defined considering the specific mission of the site and the relative business segment. As an example, a unit downtime of two hours occurring every month may be ranked as acceptable for a gas compression station, while can be detrimental for a Liquefied Natural Gas plant, due to the much higher overall financial impact.

Consequence	Level	Description
Very Low	1	Minor first-aid without Lost Time Injury
Low	10	Lost Time Injury
Medium	100	Hospitalization and/or temporary disability
High	500	Permanent disability and possible litigation
Very High	1000	Fatality, litigation, and business jeopardize

Table 1 - Consequence levels for the safety risk category.

Operational consequence directly depends on the unit downtime. Financial consequence *fc* is calculated using a model function and is expressed in \$/year. In particular, it is the sum of two main contributes, Loss Of Production (LOP) and maintenance costs:

$$fc = LOP + maint\_costs$$

Maintenance costs account for Time To Repair (TTR), influenced by the activities to be performed as well as the number of workers and shifts, spare parts costs, need of special tools and the involvement of SME.

LOP, for the site under investigation, can be modeled as a linear function of downtime which depends, in turn, on the cited *TTR* and *Tdel*, the time required for delivery of parts which are essential to restart operations. As an example, some spare parts may be not available in the warehouse, others (like pressure relief valves) can need special test benches which may be not available on site, forcing to send the part to specialized shops. Hence, a general expression for the *LOP*, expressed in \$/hour, is:

$$LOP = k \cdot f(TTR, Tdel)$$

The accuracy of the financial model depends on the availability of information on actual maintenance policies and practices as well as manhour and spare parts costs. For the case study, this data comes from CMMS work orders analysis and a site survey performed with maintenance representatives.

As required by the risk analysis protocol, the occurrence of a described scenario is estimated considering that no maintenance is performed at all on the asset under analysis (SAE JA1012, 2011). Therefore, the failures occurrence is mainly calculated considering the failure rates reported in reliability handbooks (SINTEF, 2015) and the experience of SME. Analysis of CMMS work orders also provides insightful information: comparing the reported failures and maintenance activities performed, it is possible to estimate a failure occurrence as no maintenance was applied at all.

ACA is performed on the 450 in-scope assets and gives us a database of the worst failure per each item. The analysis leads to identify around 20% of the items as critical.

Failure Modes and Effects Analysis

On the critical items resulting from ACA, the FMEA is performed. This methodology derives from Reliability Centered Maintenance and is used to evaluate risk in a semi-quantitative method and to identify the proper mitigation actions for reducing the risk. The main FMEA steps are: failure modes identification, failure effects description and unmitigated risk calculation, choice of the mitigation actions and calculation of mitigated risk.

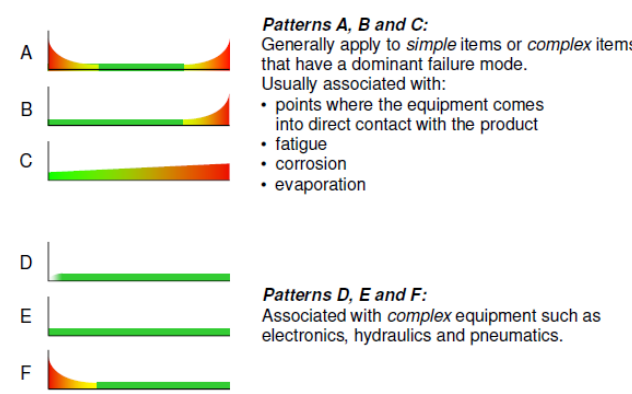

Figure 2 - Typical failure patterns.

For each critical item, all the relevant failure modes have to be traced. The possible failures that an item may suffer can be retrieved from literature (e.g. SINTEF, 2015), OEM or plant operators' reliability databases and the experience of SME involved in the FMEA development.

To the applicable failure modes, two important attributes are associated: the failure pattern, selected among a set of typical ones shown in Figure 2, and an estimation of P-F interval (SAE JA1012, 2011). Failure pattern helps to identify the proper mitigation strategy: for example, the preventive replacement of a maintainable item may be effective for preventing a failure with typical wear-out pattern (type C), while brings no benefit if applied to a failure with pattern modeled by the random type E.

P-F interval, reported in Figure 3, is the time between the point P where a potential failure can be somehow identified and the point F at which deteriorates into a functional failure (SAE JA1012, 2011) and is an important indicator in the risk analysis because it represents the available time to recognize a failure before it might have a functional impact on the production process.

After the failure mode identification, must be analyzed the effects that each failure has on the whole asset. This is performed qualitative, describing the failure scenario, the potential secondary damages and the main activities and costs for restoring the original operating conditions. It is also done quantitative, using the same risk matrix, assumptions and methodology adopted for the ACA described in the previous section, thus resulting in the estimation of the unmitigated risk for the categories safety, environment, operations and financial.

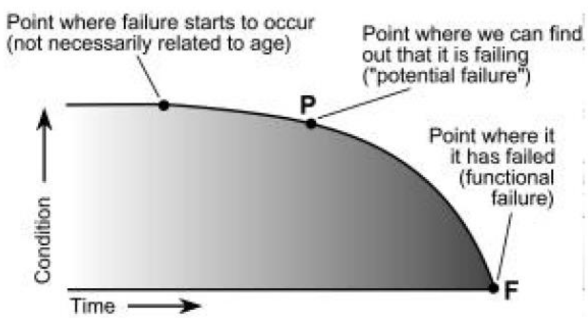

Figure 3 - P-F interval in failure modes occurrences.

Total risk is a combination of the ones calculated for each category: for the risk analysis in object, we select the maximum value. If total risk is above a certain threshold, some recommendations need to be identified in order to reduce the risk down to an acceptable level. Mitigation tasks are usually decreases the risk acting on the occurrence factor (*risk* = *consequence* · *occurrence*). A detailed analysis of the action cost is also added, considering spare parts, TTR, LOP, man-hours and the need of special tools.

The recommendations applied in the FMEA belong to the following categories:

- on condition / monitoring type: if a failure is detectable (P-F interval long enough), it is possible to use the M&D data for condition monitoring, triggering maintenance tasks only when needed.
- discard/restoration tasks: typical of time-based maintenance approach, the item can be subject to change-over (discard) or overhaul (restoration). Such tasks are effective only if is possible to define an age at which there is an increase of the failure mode probability (failure patterns A, B, C in Figure 1).
- failure finding: tasks commonly used for protective devices. The conditions that sensor should detect are simulated and it is checked if protective device is correctly responding.
- redesign: this represents the "last chance" when all the previous tasks are not effective.
- corrective actions: we add this kind of tasks, commonly not included in a FMEA, in order to support troubleshooting and identification of the maintenance actions to be performed as a failure occurred.

Applying a recommendation, the failure effects decreases its associated risk to a lower mitigated one. A recommendation is more or less effective depending on the amount of risk it reduces and the cost for performing it. Therefore, a good indicator is the ROI (Return Of Investment) variable, described by the equation:

$$ROI = \frac{benefit}{cost} = \frac{K_{fe} \cdot (p_u - p_m)}{cost}$$

where *cost* is the cost of the action, and benefit is the amount of reduced risk after the implementation. If the reduction is performed only by acting on the occurrence level, as usually happens, it corresponds to the cost of the failure effects K_{fe}, multiplied by the difference between p_u and p_m, the occurrence of the unmitigated and mitigated failure scenario respectively. The higher the ROI, more convenient is to perform the task in terms of achieved risk reduction.

ASSET STRATEGY MANAGEMENT

As stated in the Risk Analysis section, one of the objectives of the risk analysis is to challenge the preventive time-based maintenance plan adopted by the site, building the basis for a predictive on-condition approach.

In general, a scheduled maintenance plan is based on recommendations from OEM and experience accumulated through the years. Not always the choice of the tasks to be performed, their frequency and the required resources take in account the real risk of an asset failure, its typical age, its failure pattern, the P-F interval and, in general, the considerations coming out from a risk analysis.

For the above considerations, we make a comparative analysis between the existing maintenance plan and the maintenance mitigation actions coming out from the FMEA, in order to design a new optimized risk-oriented maintenance plan. The result shows three different optimization opportunities: extra maintenance activities over low-risk asset, giving the opportunity for rationalization and cost reduction; under-performed actions on higher risk items, as these are not being perceived as critical, resulting in additional specific recommendations along with significative overall risk level reduction; planned actions on equipment whose degradation can be measured and monitored, offering the chance to adopt on-condition maintenance, optimizing costs.

This activity has been performed using an Asset Strategy Management tool which allows to simulate different maintenance plans, by selecting the activities on each asset, and to compare them in a risk-cost frame. Final outcome is a new optimized plan, characterized by a lower maintenance cost and overall risk reduction. For example, the new plan for GT lube oil system, showed -12% of maintenance costs and -40% of risk reduction.

Maintenance Focused Analytics

The dynamic maintenance strategy is realized thanks to the so-called maintenance focused analytics. Their scope is to integrate the M&D pillar (blue lower box in Figure 1) with risk analysis and maintenance strategy segments.

The analytics we develop fulfill the different needs: deliver automatic recommendations retrieving the actions from the risk analysis, suggest that maintenance strategy and/or the risk analysis need a revision, suggest when to perform a new M&D recommendation within the adopted maintenance plan. The development is done in a commercial APM software, using block diagram programming and integrated scripts in R language.

The first application associates automatically a potential anomaly detected by M&D to all the relevant information retrieved from the risk analysis, such as failure modes and effect, risk estimations, mitigation actions. For example, an analytic we implemented is monitoring the GT lube oil air cooler performance and identifies two different functional failures. One of them is a decreasing trend of the heat exchange coefficient. In such case, the analytic retrieves the possible failure modes, i.e. dust accumulation on cooler bundle and tubes fouling, the related failure effects, and the recommendations to perform a visual inspection on the cooler and to schedule, if needed, a bundle cleaning with compression air or chemical tubes cleaning.

The other failure mode is an abrupt drop of air cooler performance; this can be associated to a failure of electric motor or fan blades. In this case, FMEA recommendations include inspection of motor and blades as corrective actions and the on-condition tasks, to be integrated in the maintenance plan, of checking the grounding connections and cables of the electric motor and inspect for abnormal noise possibly due to vibrations, for the transmission and blades.

The second application fulfilled by maintenance analytics is used to highlight to maintenance responsible the necessity of a risk analysis or maintenance strategy update. In particular, on a recurrent basis, the analytic processes CMMS work orders and calculates the failures occurrences. These frequencies are compared with the ones estimated in the risk analysis. If a high discrepancy is detected, risk analysis assumptions and/or maintenance practices should be reviewed.

For example, the instrument failure of Resistance Temperature Detector installed on the bearing pads is estimated with an occurrence of once every 5 years in the risk analysis. Instead, CMMS data revealed that during the latest months these items had multiple failures. Causes of such inconsistency have been investigated, finding out that a wrong installation practice was in place. Hence, in the risk analysis and in the maintenance plan, we insert a mitigation action implementing a different installation procedure.

The third analytics group is part of a future development and aims to suggest when to perform a new M&D recommendation within the actual maintenance plan. Each recommendation is characterized by priority, depending on the risk of failure effect scenario, time duration, spare parts, costs and if requires the asset shutdown to be performed. On the other side, we have visibility of the maintenance plan, hence when planned shutdowns are scheduled, their duration, SME involved, spare parts, the activities to be performed. The analytic should calculate a new optimized maintenance plan including the incoming maintenance actions in a dynamic pattern, optimizing a risk-cost base. For this purpose, stochastic simulations are used in literature, as in Chootinan, 2006 or in Bohlin, 2009.

For example, if we have to perform a medium priority activity whose duration is higher than the following planned maintenance one, we expect that the analytic is able to quantitatively evaluate the opportunity to extend the maintenance or to schedule the activity at a later opportunity.

SERVICE OUTCOME

After applying the enhanced M&D work process, characterized by recommendations with risk analysis insights and elements of dynamic strategy, we are able to evaluate the main advantages and drawbacks.

The presence of a quantitative risk assessment attached to the recommendations helps to prioritize the activities and to have a better feeling of the benefits coming from their implementation. However, building a full risk analysis is time consuming, as well as retrieving information from it as a functional failure is detected by M&D analytics. For this reason, the maintenance analytics automatically linking a potential failure with the risk analysis information are essential and need to be increased. Moreover, while running the service, is possible to notice that some failure modes or mitigation actions are missing in the risk analysis. Therefore, the risk analysis should be object of a continuous improvement process.

An additional outcome is the risk-driven maintenance plan, resulting from the combination of diagnostic capabilities and risk assessment. The Asset Strategy Management simulation shows a reduction in cost and asset risk. However, a real measure of the benefits from the new plan must be evaluated in a multi-year timeframe, which includes the major inspection of the higher-values equipment, in this case the GT.

We also put the basis for a dynamic maintenance strategy, designing and implementing analytics for this scope. However, an online connection to CMMS might enable a wider scope, as well as online usage of reliability data coming from an installed fleet, hence achieving wider statistical significance.

For each recommendation delivered to plant operators, we calculate the benefit in terms of risk reduction, expressed in $ per year. This method is retrieved from the RCM theory, adopted to the case stud in analysis. The benefit of an action is expressed by the below formula:

$$bn = K_{fe} \cdot (p_u - p_m) - K_{ma}/N_{ma}$$

where the first term represents the risk reduction expressed in financial terms, since K_{fe} is the failure effect cost and p_u the occurrence of the unmitigated and mitigated failure scenario respectively, while the second term is the cost of the action itself K_{ma}, divided by the average number of years N_{ma} that the maintenance action can be considered valid for.

In the case that the failure scenario is being mitigated also by planned maintenance activities, their effect should be included in terms of added cost. Hence, the second term of the equation above becomes the summation $\sum_{i=1}^{n} K_{ma}^{i}/N_{ma}^{i}$, for all the actions mitigating the same failure scenario, even if applied to different maintainable items.

During the first 6 months of service, 10+ technical cases have been opened, with 30+ recommendations associated. The benefit calculated with the above methodology have brought to around 75 hours of equivalent production per year as risk reduction.

CONCLUSIONS

Case study allowed to prove the methodology of an integrated M&D work-flow. For this purpose, we performed a risk analysis on the asset and included the maintenance process in the scope-of-work, approaching it as a continuous maintenance as-a-service, hence strongly oriented to an on-condition strategy and supported by analytics.

Applying the integrated service, the important feedback we get is that CMMS data and its quality are crucial to enable a meaningful dynamic strategy. An other point of reflection is the risk analysis scalability: ACA and FMEA development can be time consuming, also considering that it must be well-tailored on the plant application in order to be effective. This arises the need of scalability tools in order to create a new risk analysis with reasonable resources.

Further developments are mainly regarding maintenance focused analytics, with the scope of using at best CMMS data, also working with Natural Language Processing for managing text resources, connecting to reliability databases for retrieving failure modes and their occurrences, applying algorithms for maintenance optimization.

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