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MAXIMIZE YOUR ASSETS OPERATIONAL VALUE BY FOCUSING MAINTENANCE ON RELIABILITY THROUGH UTILIZATION OF CONDITION ANALYSIS AND PREDICTIVE ANALYTICS

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Abstract

By analyzing the historical development of on-condition maintenance to date, Oil, Gas, and Petrochemical organizations can identify trends and understand their maturity and applicability to their organization. In particular the cross-industry emergence of reliability centered maintenance (RCM) enabling technologies and processes that deliver 'Expert Insight' can enable a transition to risk-based machinery management (RBMM), driving up production capacity and reducing maintenance costs.

RCM technology, including the application of failure mode effects analysis (FMEA), advanced condition monitoring and predictive analytics, from more mature business sectors, such as civil aerospace and nuclear power generation, can be leveraged in Oil, Gas, and Petrochemical to enhance current maintenance programs by allowing more time to plan and to increase the focus of maintenance activities. In this context organizations need to identify opportunities where on-condition maintenance is value-added for their equipment and processes in order to prioritize their RCM enablement programs.

In order to prioritize those programs each organization must face and overcome the challenges of quantitative validation of on-condition maintenance tasks and opportunities, in the process driving the transformation to risk based management of plant and reliability engineering processes.

RCM technology also provides additional benefits through the documentation of risk and failure modes, and furthermore capturing engineering feedback on analytical outcomes can improve the diagnostics and prognostics over time.

A further effect of the sharper focus on managing through lifecycle risks (costs) may be a change from the current focus on unit costs for machinery supply to a more holistic approach.

1.0 Introduction

All major independent and state-owned oil, gas, and petrochemical (OG&P) companies are facing a number of key challenges that are driving a renewed focus on risk based machinery management[i]:

- The ability to obtain consistently manufactured quality process equipment from suppliers worldwide.
- Process and technology applications are pushing proven design envelopes.
- Infrastructure and workforce are aging.
- Companies are operating equipment longer and with fewer resources.
- Major incidents have resulted in increased governmental regulation and industry self-regulation.
- Tighter health, safety, and environmental (HSE) regulations.
- The lack of information availability or sharing throughout the asset lifecycle.

In the face of these challenges, stakeholder expectations are ever rising for improved performance at lower cost.

Similar challenges have been overcome in other industries, and those successes can inform the strategic thinking and action planning of how oil and gas companies should meet them today.

This paper draws on experience from the civil aviation and nuclear industries to suggest how technology and process elements of Reliability Centered Maintenance can be applied to the oil and gas industry to drive down maintenance costs and improve production availability.

In particular this paper considers how a risk-informed application of predictive analytics empowered diagnostics and prognostics can deliver many of the business objectives of both maintenance and operations teams in three areas:

- Safer and more compliant operations;
- Reduced (optimal) maintenance costs; and,
- Increased asset availability, resulting in higher production yields.

It seems counter-intuitive that safety and compliance can be improved whilst reducing overall maintenance spend and out of service time, so the paper also presents brief examples of what can be achieved in the form of cross-market case studies.

The goal of the paper is to leave the reader with the knowledge that new levels of optimized performance can be attained, and the quickest and most reliable route to that performance is through use of proven technological and process developments from other industries.

One of the greatest scientists in history, Sir Isaac Newton, once said 'If I have seen further, it is by standing on the shoulders of giants'. The authors are in no way claiming to be giants ourselves, but would hope we can help you find a place to stand to have a more informed view.

2.0 A brief revisit of RCM from a risk standpoint

The RCM process described in the DOD/UAL report[ii] recognized three principal risks from equipment failures:

- Threats to safety;
- Impact on operations; and,
- Challenges to the maintenance budget.

Note that modern RCM principles give threats to compliance (environment or legislative) a separate classification, although most RCM processes manage them identically to threats to safety. For most purposes, extreme economic impacts may be dealt with similarly to compliance risks rather than as simple cost management issues where the permit to operate concept applies. The OG&P industry, through the draft API-691 RBMM standard, is considering economic, health, safety, environmental and compliance risks in the development of maintenance strategies which is a shift from the safety-centric focus.

RCM offers five principal risk management strategies:

1. Predictive maintenance through Condition Monitoring;
2. Preventive maintenance;
3. Detective maintenance through failure finding and operational tasks;
4. Run-to-Failure; and,
5. System/Design changes.

RCM provides criteria to use when selecting a risk management strategy for a system that presents a specific risk when it fails.

RCM-based equipment maintenance strategies involve selecting a combination of tasks to mitigate the risk from a FMEA. The following table conveys the Maintenance Tasks types identified in the API-691 standard that should be prioritized when creating a maintenance plan.

Condition Monitoring	Surveillance tasks	Monitoring indications, or other parameters or conditions to compare to established acceptance criteria
	Predictive maintenance tasks	Collection of condition data from indicators, portable or permanent monitoring equipment, or other parameters for use in analysis and trending
	Advanced Condition Monitoring tasks	The collection of Surveillance and/or Predictive data in combination using model based approaches for the purpose of Prognostic analysis
Preventative Maintenance (PM)	Non-Intrusive PM tasks	Time based tasks which typically reduce the likelihood of failure, but which do not require replacement of parts, disassembly or otherwise cause re-introduction of infant mortality failure risk
	Intrusive PM tasks	Time based tasks which require replacement of

		parts, or disassembly to perform refurbishment or detailed inspection
Functional tests	Failure finding tasks	Testing of equipment or protective device functionality whose failure would otherwise be hidden during normal operations
Operational tests	Operational tasks	Start-up and running of equipment to verify both initial ability to operate, and long-term ability to continue to perform its function over a desired mission time (includes routine equipment swapping

Table 1 - RCM Maintenance task types

Tasks should be prioritized as follows when formulating a risk mitigation strategy:

1. Condition Monitoring and Predictive Maintenance;
2. Time Based Non-Intrusive Maintenance or Failure Finding Tasks;
3. Time Based Intrusive Inspection; and,
4. Time Based Refurbishment or Replacement.

Strategy planning requires an assessment of the potential impact and failure detection time frame or P-F interval (e.g., the time interval between earliest detection of the issue to the point of functional failure). For simplicity in this paper we have grouped the impacts into three areas:

1. Safety;
2. Economic (operational and maintenance budget impact); and,
3. Insignificant or no impact.

We would characterize the mitigation selection strategy using Figure 1 below:

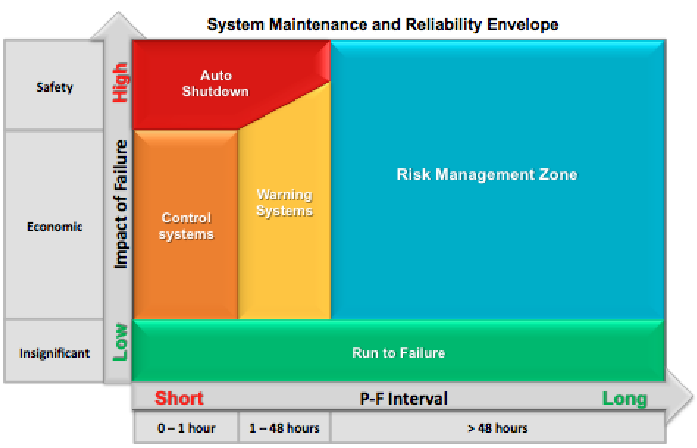


Figure 1 – The Risk Management Zone

The Y axis of the diagram is divided into the three impact zones. The X axis represents the P-F interval.

As can be seen from the diagram, where impact is insignificant the strategy is typically run to failure but could utilize intrusive PM though time-based refurbishment or replacement tasks.

The divide between the other zones is dependent on the relevant mitigation strategy's ability to respond. For failures with a P-F interval faster than the ability of a maintenance regime's response time, automated systems are required; auto-shutdown in the case of safety issues or the control system or warning systems for economic risk.

For longer P-F intervals, in this particular example above a somewhat arbitrary period of 48 hours, Predictive maintenance, Preventive maintenance, or Detective maintenance should be selected as a risk management strategy. The choice of RCM strategy can have a significant impact on maintenance costs, and in turn also effect safety, compliance and operational availability. The success of the chosen strategy can be governed by selection and application of RCM tools, processes and tasks.

2.1 Where RCM programs fail

What is less obvious is why the RCM approach so often fails. Machines still break unexpectedly, and not only do they fail on a unit basis, the industry occasionally suffers catastrophic machinery-centric events with impacts way beyond the levels foreseen by the RCM program. Common causes of RCM failure include:

- Unit rather than system focus;
- Insufficient reliability data for adequate planning;
- Unsuccessful RCM tool deployment;
- Inadequate equipment management processes;
- Shortage of skilled resources; and,
- Uneconomically viable maintenance plans.

2.1.1 Unit rather than system focus

Many RCM programs focus on individual units rather than interdependent systems. Each system is made up of several components or subcomponents from a variety of suppliers. Often, the components rather than the system are faulty and can lead to systemic issues. These system level issues may not be seen if the program only identifies and addresses unit component failures. Further, interdependent unit risks such as reduction in layers of protection through planned maintenance may not be accounted for unless the system risk is also examined holistically and continuously monitored.

2.1.2 Insufficient reliability data for adequate planning

An operator that has a relatively low number of units from an original equipment manufacturer (OEM) often will not have experienced the full set of failures a particular asset is vulnerable to. Moreover, the OEM may not provide an adequate and up to date set of reliability data and FMEA, particularly once a unit is outside a warranty period or service agreement. Without knowledge of what may occur and how to detect it any RCM program is limited.

2.1.3 Unsuccessful RCM tool deployment

With an industry trend of on-condition maintenance to drive out costs, condition monitoring tools are often used as a substitute for detective or preventive maintenance tasks. Whilst sometimes successful, there is a risk that a tool deployment may prove inadequate. There are many potential causes of tool deployment failure, but many tools inherently lack specificity of diagnosis to enable planning. Also, in some cases the P-F interval may be very short due to limited analytical capability. In the worst of all cases condition monitoring systems over alert and end up as ignored noisy or nuisance systems which are untrusted; effectively eliminating the potential RCM benefits.

2.1.4 Inadequate equipment management processes

Inadequate management of change (MOC), is the most common cause of RCM program failure. The as-designed / as-built risk for a system may have been well understood at commissioning, but unless an effective MOC process is used to manage the asset over then service life, the risks that were originally assessed may differ significantly as the asset matures. This leads to unforeseen asset risks and higher cumulative system risks which are effectively unmitigated.
Other processes commonly implemented with some degree of shortfall include continuous improvement knowledge capture, incident investigation, root cause analysis, audits of process adherence, and continuous updates of risk assessment and level of protection analysis.

2.1.5 Shortage of skilled resources

The execution of each strategy for risk mitigation is dependent to a greater or lesser degree on skilled resources playing a role. However, it is a common industry challenge that skilled engineering resources are in increasingly short supply. From the early 1980s to 2000, very few engineers and mechanics entered into the oil and gas industry which has resulted in a large percentage of their workforce retiring and being replaced by inexperienced workers in recent years. Without adequate resource and skill levels, plans that are heavily dependent on human involvement are challenged.

2.1.6 Uneconomically Viable Maintenance Plans

Organizations where some or all of the above issues have occurred often attempt to mitigate potential risks with excessive maintenance activity, increasing downtime and increasing the level of lost production, raising maintenance cost significantly, and even causing an increase in levels of maintenance induced failure. Escaping the “Catch-22” situation of inadequate predictive maintenance versus excessively expensive preventive or detective maintenance is the focus of the remainder of this paper.

3.0 Learning from the experience of others

In industries where catastrophic failure cannot be tolerated due to the immediate and obvious wide-scale impacts, approaches have matured which overcome these potential RCM program pitfalls. The civil aviation and nuclear power generation industries have addressed the RCM pitfalls in different ways with a similar outcome; the industries operate and plan maintenance with risk-informed decision making.

3.1 The Nuclear transformation story – A case study

In the 1980s following the Three Mile Island incident, the US nuclear industry faced serious challenges not dissimilar to those facing the oil and gas industry today[iii]. From 1980 to 1987, production costs increased by 40% largely due to new regulatory mandated safety upgrades and retrofits.

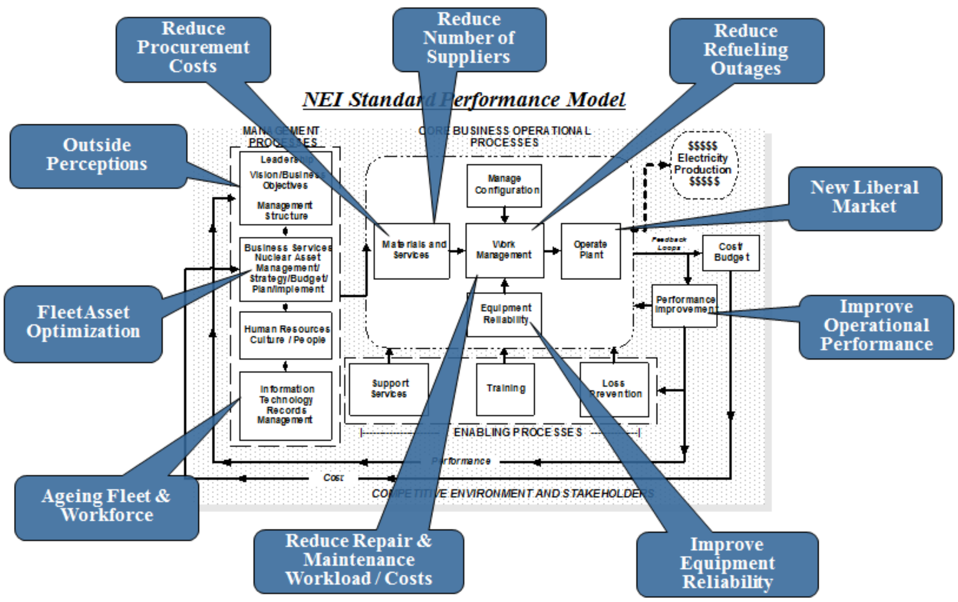


Figure 2 - The Challenges Facing the Nuclear Industry in the 1980s

In particular outside perceptions of the industry risks were at an all-time low, whilst an aging fleet and workforce combined with a new liberal market left the industry having to reduce costs and improve performance if it was going to survive. Improving equipment reliability and driving down repair and maintenance costs whilst increasing availability by shortening turnarounds was a similar seemingly paradoxical requirement to that in oil and gas today.

The key improvement factors that enabled the transformation of the industry into the predictable business it is currently were:

- Establishment of sound operational and safety fundamentals;
- Setting safety and operational objectives;
- Increased focus on equipment and activities that have safety and reliability implications;
- Advances and adoption of new technologies;
- Adoption of process management concepts; and,

- Mergers and acquisitions that consolidate work practices.

One of the key tools and processes used in the transformation was Probabilistic Risk Assessment (PRA)[iv]. US Nuclear Regulatory Commission (NRC) issued Generic Letter 88-20 in 1988 which mandated US nuclear plants to perform PRA.

PRA combines operational, reliability, and maintenance data at the system level to reveal risk insight into the consequences of individual activities. This allows operational and maintenance planners to gain an understanding of risk combinations and to make decisions informed by the impact to risk of those decisions.

The Nuclear Energy Institute (NEI) was formed in 1994 when several nuclear energy industry organizations merged, providing a unified industry voice to federal regulators.

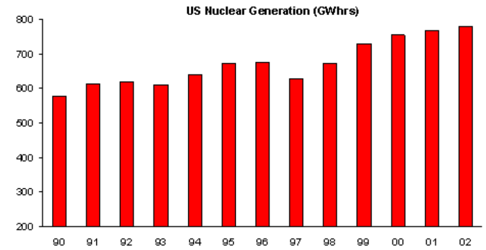
PRA became the basis for the "Risk-informed" Regulatory Process[v] which established:

- Industry collaboration, oversight processes, and Working Groups;
- More efficient and effective regulatory process;
- Blend of PRA, combining operating experience and design enhancements based on advances in technology;
- PRA technical adequacy assessment;
- Improved safety performance by focusing on matters that have safety significance; and,
- Greater interest in gaining a better understanding of design margins.

Today, Risk-Informed Applications are widely applied and form the basis of operations across the US nuclear industry, and increasingly worldwide and include[vi]:

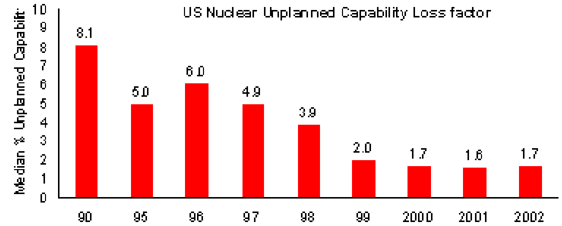
- PRA Quality Standards;
- Maintenance Rule;
- Integrated Safety Management Specifications (Tech Specs);
- In-Service Inspection and Testing Programs; and,
- Graded Quality Assurance Programs.

What has been achieved in nuclear is staggering. The nuclear industry has tracked metrics which show that in the ten years between 1991 and 2001 the relative cost of maintenance and operations was reduced by almost 45%, the production capacity was increased by approximately 22%, and relative risk was reduced by almost 80%. Any one of those improvement factors alone would be a phenomenal achievement, but to have delivered all three seems little short of miraculous.



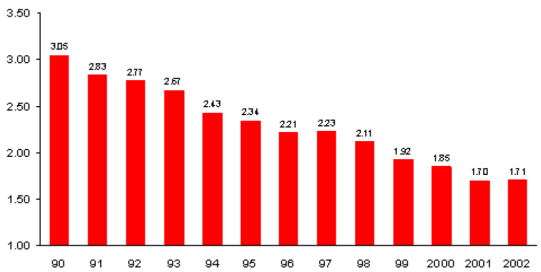
Source: NEI/EUCG

Figure 3 – Power Generation Increase +25%



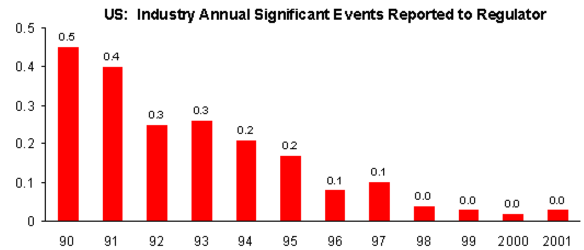
Source: WANO

Figure 4 - US Nuclear Capacity Factor



Source: NEI/EUCG

Figure 5 – Increased Production through reduced outage time



Source: US NRC

Figure 5 - Threats to safety

3.2 Civil aviation case study – Rolls-Royce and Total Care

Until the early 1990s, the civil aviation market had operated like many others as an original sale then parts and maintenance supply chain model. The operations and maintenance risk sat with the airline operators. Until 1987 Rolls-Royce was a government owned business, rescued from bankruptcy in the 1971. Its market share of the key large engine market for long haul airliners was in the region of 5%, with the market dominated by Pratt & Whitney and GE.

In the 1990s Rolls-Royce created a new sales model where it persuaded customers to pay for its engines by the flying hour rather than purchasing the asset directly. This “Total Care” model transfers the maintenance risk to Rolls-Royce; a customer simply has a contract for power availability. The engines in turn remain owned by Rolls-Royce and may cycle through not only several aircraft in their service lifetime, but even multiple operators.

In order to make this business model successful, Rolls-Royce must be able to maintain or improve engine reliability whilst delivering a maintenance program at lower cost than the operators could themselves. In short for Total Care to be successful it must deliver higher reliability at lower cost, again a similar challenge to that the oil and gas industry. To lower costs, Rolls-Royce had moved maintenance scope from the preventive or detective strategies to predictive, enabling risk-informed decisions like the nuclear industry.

Rolls-Royce approached this challenge with two primary tools: design modifications to eliminate the cause of failure and advanced predictive analytics to detect the earliest possible onset of defined failure diagnoses.

Designs are modified based on collected reliability data from the large fleets of units. Because of the standardization of the fleet, this data can successfully inform design decisions based on service drivers, and Rolls-Royce has created an ‘Engineering For Service’ group to underpin this service.

As an OEM the most effective way to eliminate a failure is to modify the design, but in some cases this is either not practical or economically viable.

Of the other four RCM risk management strategies run to failure is rarely a viable option on an aircraft. Redundancy implies additional weight or reduced operational efficiency. As the commercial aircraft industry has matured, the focus has been to reduce the opportunity for failures. One of the approaches has been to reduce the number of components that have moving parts. Reduction of number of moving parts reduces overall risk of failure, but increases the event severity when failures occur.

Preventive maintenance to a schedule provides little or no economic gain for the OEM or operator since it can impact flight planning and can result in maintenance induced failures.

FMEA analysis and reliability block diagrams reveal that aviation gas turbines have a number of failure modes that can manifest themselves in a low number of flights. An aircraft fitted with Rolls-Royce engines takes off on average every three seconds making detective maintenance a potentially extremely expensive strategy. Rolls-Royce had to get better at Predictive Maintenance in order to be successful.

By developing a solution to detect, diagnose, and predict specific failures, Rolls-Royce was able to move many maintenance items to an on-condition basis. This in turn reduces the burden for detective or preventive maintenance actions and corresponding maintenance cost. This solution uses advanced predictive analytic techniques to analyze data streamed to the service center in the UK after every flight and successfully identify specific failures. Through delivery of specific diagnoses, planners are able to make risk informed decisions on which maintenance actions need to be:

1. executed now;
2. deferred to the next overhaul; or,
3. monitored for further development.

Only by achieving a diagnosis with a very high percentage success rate can these risks be appropriately balanced.

Actual numbers are managed confidentially within the Rolls-Royce Group, but the success indicators for this strategy are evidenced their economic. Rolls-Royce now has in excess of 50% of the civil aviation large engine market, and Rolls-Royce Group is the best performing share on the FTSE 100 over the last 15 years with a share price increase of over 2000%.

4.0 Avoiding the RCM traps by learning from success – A recommended RCM strategy

The above lessons from both failure and success can inform the future approach to RCM strategy for OG&P organizations. The first lesson is that there is no golden bullet for reliability, in fact quite the opposite. RCM programs which are successful adopt a holistic approach to the problem, combining the right people, processes, technology, and knowledge into a structured and organized program. Failure to recognize the value of any individual aspect can lead to a suboptimal program and potentially to failure.

Oil and Gas facilities however do not fly (hopefully!), nor do they radiate large portions of populace if they fail. So what actual practical lessons can be taken from the case studies above which are relevant to oil and gas organizations?

Both the Nuclear Industry and the Rolls-Royce models shared a common aspect – Risk Informed Decision Making. On a daily basis operators and maintainers dealing with issues on the plant are making decisions on whether to defer, execute or avoid maintenance. Studies have shown that one of the major causes of high value incidents in the oil and gas industry is the poor awareness and understanding of risk and consequences in that decision making. The required strategy must enable risk informed decisions.

Figure 7 - Preventative Maintenance and Risks

Figure 7 above shows a traditional approach to risk mitigation in oil and gas organizations. A set of risks created at design time inform and approach to preventative maintenance and an associated detective maintenance inspection plan. This combination dictates the maintenance work scope on the units.

This approach is vulnerable to change. New risks of failure emerge as the assets mature. Operational context creates different driving factors which may accelerate or exacerbate failure or drive occurrences at a faster P-F interval than it is economic to carry out inspections. This leads to blind awareness of how risks propagate when combined.

A revised and idealized model which accounts for the learning from aerospace and nuclear looks more like Figure 8 below.

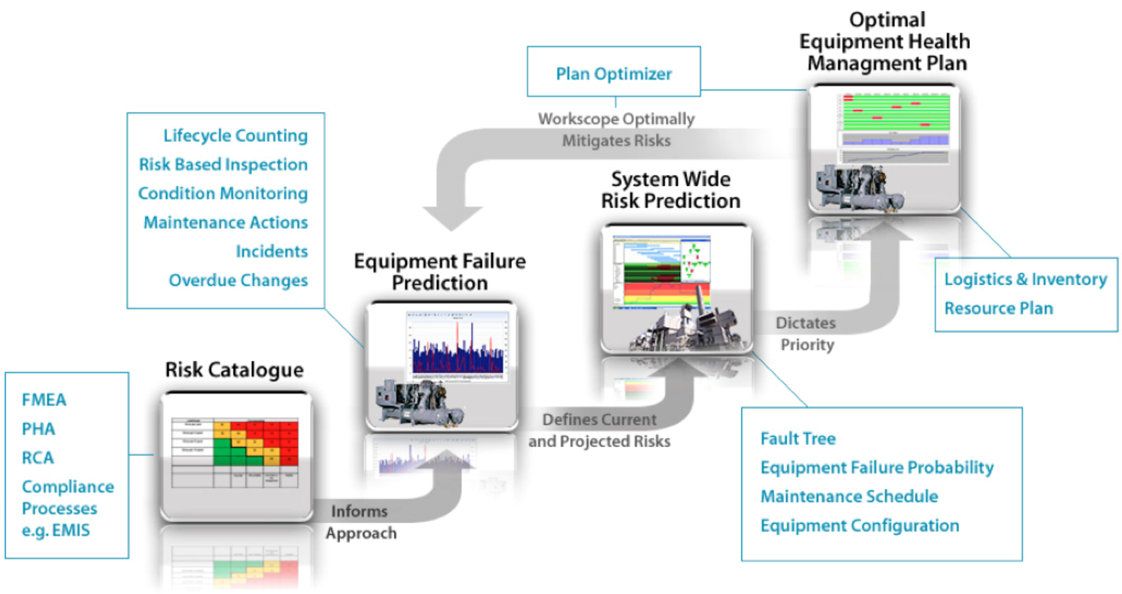


Figure 8 - Integrated Risk Based Maintenance Decisions

The risk catalog in the bottom left box is maintained throughout the asset life-cycle. Periodic risk assessment updates are carried out informed by reliability databases, and in particular an up-to-date FMEA is created and maintained to inform operators and maintainers not only what the risks are but what effects may be observed to signify their onset. Processes like Root Cause Analysis continuously update the FMEA, and Process Hazard Analysis style risk assessments offer a criticality insight to the operating context.

The risk catalog (first box) informs the approach for equipment failure prediction (second box). How are the specific risks from the risk catalog detected? The risks are not detected by one method alone. As the diagram suggests, multiple methods will provide a higher level of confidence in the failure prediction including:

- Risks to components which are life-limited may be observed increasing through the use of life cycle counters;
- Inspection results may give insight into current equipment condition;
- Executing maintenance actions can increase some risks whilst minimizing others;
- Human processes such as operator errors, incidents and overdue changes can be a contributing factor; and,
- Successful application of condition monitoring can also provide detailed and specific information on some equipment condition risks, the most advanced techniques able to make predictive diagnoses and forecasts for Remaining Useful Life (RUL).

The combined state of current and projected risks for individual equipment items informs a system-wide risk prediction model as seen in box three. By adopting a probabilistic approach to system-wide risk based on the states of collective individual item risks, and combining the planned maintenance and operational schedules into the risk view, a play forward projection of risk states can be created. This plant or facility level risk view can be oriented towards the three objectives of the RCM program, namely Safety/Compliance, Operational, and Budgetary.

By having a holistic live risk model feed by the current and predicted state of the plant, an optimal equipment health management plan can be created to minimize risk. Planners will take into account resources, parts availability, logistics, and other operational goals when creating the optimal operations and maintenance profile. In an ideal world, business simulations and scenario models could goal-seek based on business objectives, iterating on plans to create a truly optimized business.

The whole process is governed under a change regime, where equipment configuration, maintenance processes, improvement opportunities and any other impactful change is managed through a robust MOC process with proper engineering approval incorporated. The MOC process will ensure that new risks are not introduced inadvertently without proper mitigation planning and changes to the assets are captured in the risk catalog.

4.1 Eating the elephant of change

That ideal model is quite an elephant to eat for most organizations. Adoption of that approach will take time and perseverance; the degree of change involved requiring long term strategic planning and strong leadership to achieve. However this elephant can be eaten like any other elephant, one bite at a time.

The biggest question is which bite to take first?

4.2 A value- based approach to risk

Carrying the ‘bite’ analogy on for a moment, the first bite to take would be the one that delivers the most value. Figure 9 below suggests an approach to identifying where to start.

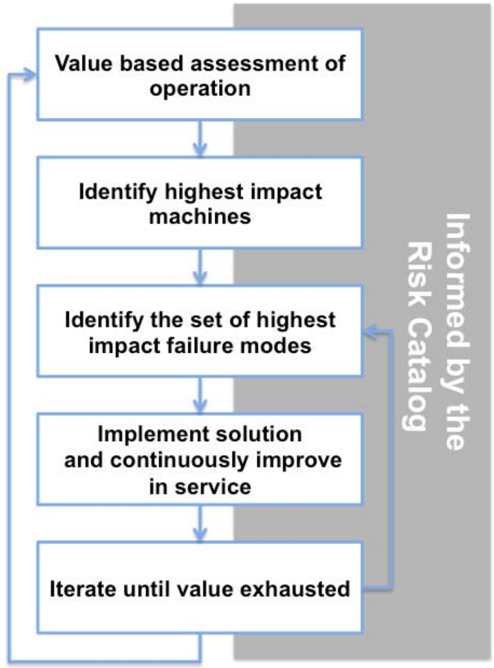


Figure 9 - Value Based Risk Action Selection

For many it seems counter-intuitive to be selective about risks, but studies have frequently shown that certain critical machines in an organization can have a disproportionate effect on the RCM objectives. In many oil and gas organizations the gas turbine and associated driven equipment can be responsible for more than 80% of lost volume production, whilst often representing less than 20% of the hardware estate.

The lessons from aerospace can be applied here, not least because of the similar nature of the equipment. The ideal may be to have more robust designs from the OEMs with higher overall availability metrics. Buying behaviors have often driven down unit cost without proper consideration for total cost of ownership versus total production volume capacity. A better way to select units may be to choose those which can generate the most corporate profit during their service life rather than those that cost the least.

For units already in operation, gaining insight into their failure risks should follow the paths in Figure 9.

Solution selection for the highest impact failure modes should be based on the P-F curve for those failures. However there are opportunities to improve the insight that can be gained during failure to affect the maintenance plan. Consider the two P-F diagrams below:

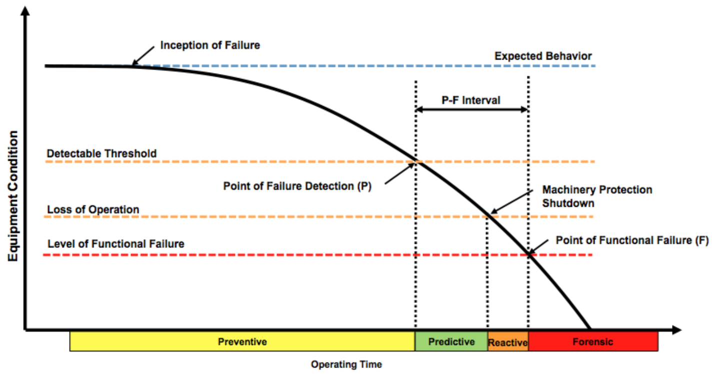


Figure 10 - Standard Condition Monitoring Solution

The curve in Figure 10 represents a common approach where the predictive space is limited as basic condition monitoring techniques do not allow much more time than the reactive protection systems. Whilst some value can be achieved, the impact on maintenance budget spend is limited, a great deal has to still be spent on preventative maintenance as the point where automated predictive techniques can accurately and reliably diagnose a fault is too late in the failure loci.

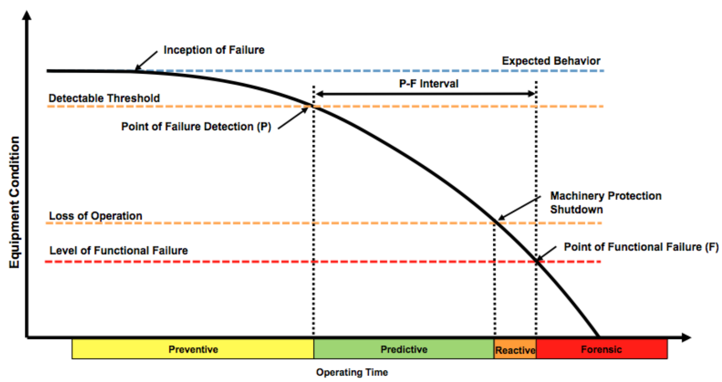


Figure 11 - P-F curve with advanced Predictive Analytics

The curve in Figure 11 however expands the predictive space into the preventive domain. Through application of advanced techniques focused on specific failure modes an earlier point of failure detection can be achieved. Driving this point of failure detection back up the failure loci enables choices, and as we have seen time to make risk informed decisions leads to value.

The only way to achieve this level of predictive diagnosis is through the application of sophisticated techniques driven through continuous improvement informed by a risk catalog. Simple anomaly detection systems require significant manual intervention in order to even approach similar levels of value, and ultimately are limited by the uncertainty they produce. Further, anomaly detection systems by their design are a "catch-all" type of approach which can lead to an extremely high number of nuisance alerts which in turn can result in user frustration and increased spend on detective maintenance.

Whilst a system that is based on an FMEA approach may not catch all possible events, focusing the effort on the most valuable returns can release significant value from an RCM program at an early stage of adoption. Through control of the overall program and clear strategic objectives aligned with the ‘four box’ Integrated Risk-Based Decision model, organizations can reach new levels of performance.

5.0 Conclusion

By looking at the risk-based machinery management programs and tools developed by the aviation and nuclear industries, OG&P companies can develop strategies which improve performance while managing costs. Operations and maintenance teams can safely increase equipment availability by applying a risk-informed approach of predictive analytics, diagnostics and prognostics in their planning. Introducing risk into operational decisions requires leadership, process changes, supporting tools, training and a change management program. By implementing an integrated risk-based decision model to underpin an RCM program, the OG&P industry will be able to realize significant advantages to their facilities from both economic and safety perspectives. Early adopters of RCM have the potential to achieve a market advantage over their competitors, similar to Roll-Royce in the aviation industry, by increasing equipment availably and ultimately production.

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