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Abstract:

Introduction of integrated operation concepts in operation and maintenance of offshore oil and gas assets is expected to contribute to increased oil recovery, lower operating and maiantenance costs and reduced HSE risk.

Suppliers working on field development and modification projects are in need of a framework for assessing the impact of different CBM-strategies at the design stage. A cost-benefit analysis (CBA) framework will be a part of this.

Much of the unnecessary operational costs related to offshore process facilities can be associated with revenue losses in terms of unnecessary maintenance shut-downs and extended maintenance down-times due to failures, in which there has been limited time for preparation.

Condition Monitoring (CM) data will be an important input for maintenance and logistics planning and optimization. By being able to accurately monitor the condition of process equipment, together with trending and prediction of equipment conditions, one can expect a reduction of revenue losses. In order to do so it is necessary to have a complete picture of equipment condition from CM instrumentation and process data. Further it is crucial to validate this data and transform it into information and knowledge that can enable decision makers to take the right decisions with respect to logistics and maintenance.

Keyword:

Integrated Operations
Condition Based Maintenance
Cost-Benefit Analysis

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A framework for cost-benefit analysis on use of condition based maintenance in an IO perspective

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June 10, 2011

Preface

This thesis is the result of my M.Sc study at Norwegian University of Science and Technology (NTNU) in the department of Marine Technology. The title of the thesis is "A framework for cost-benefit analysis on use of condition based maintenance in an IO perspective".

The main focus of this thesis has been to put the spotlight on the different aspects that will influence a cost-benefit analysis when condition based maintenance is put into an Integrated Operations perspective. Originally, I intended to include a thorough cost-benefit analysis using real data, but sadly this proved impossible due to lack of access to data. The focus was shifted to forming an impression and an opinion of Integrated Operations, and to make the reader aware of the scope of implications IO can have, both financially and structural.

I would like to thank professor Magnus Rasmussen (NTNU) and Anders Valland (Marintek) for their support.

Trondheim June 10, 2011
Christian Steensland Børresen

Summary

The maintenance costs of an offshore production platform make up about 30 % of the daily costs, and this is not including the cost of shutdown caused by functional failure. Reducing the maintenance costs will have a great impact on the bottom line[18].

Condition based maintenance is defined as the most cost-effective means of maintaining critical equipment. The idea is that the failure modes an asset is vulnerable to, are monitored by human inspections, performance monitoring or condition monitoring. Based on the collected data, the user can decide when to perform a preventive maintenance action. The goal is to increase safety, reduce costs or both. By gaining knowledge on the current and past health of the asset, trending can predict when the ideal time for maintenance comes. This can be coupled with other opportunities, such as downtime for other reasons, which will reduce costs even further.

Integrated operations is the concept of cross-integrating personnel and work processes by means of modern communications technology. It includes video conferencing (offshore-onshore), real-time reservoir management and generally anything that requires transfer of data to somewhere it has previously not been utilized. The potential is said to be huge, and the concept fits very well with condition based maintenance. The data can be entered into a database, and utilized in ways it has never been before.

Cost-benefit analysis is very useful decision making tool, especially when numbers are large. It suits very well for a decision that involves changes to the reliability of a system. It is crucial when deciding on a specific condition based maintenance strategy. There are many parameters that have to be included in the analysis, and some of them could be hard (but important) to quantify, such as the value of reputation.

Problem Description

The following problem description is an edited version where the only difference is that the part about the case study has been removed, as this (as explained in the preface, and discussed with Rasmussen) proved impossible.

The M.Sc. thesis includes the following tasks:

1. Describe accepted CBA models that are applicable for the subject.
2. Discuss the input and output parameters of the CBA, how CBM can influence these and vice versa.
3. Describe how CBM is affected by IO with respects to identification of maintenance needs and execution of maintenance.
4. Describe a methodology for selection of an appropriate CBM strategy

The student will be able to influence the task and the problem definitions. The M.Sc. thesis must be written in English. The thesis must be written like a research report, with an abstract, conclusion, content list, reference list, etc. During preparations of the thesis it is important that the candidate emphasizes easily understood and well written text. For ease of reading, the thesis should contain adequate references at appropriate places to related text, tables and figures. On evaluation, a lot of weight is put on thorough preparation of results, their clear presentation in the form of tables and/or graphs, an on comprehensive discussion.

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List of acronyms

bbl Barrel

BCR Benefit-Cost Ratio

CBA Cost-Benefit Analysis

CBM Condition Based Maintenance

CM Condition Monitoring

DEI Development Engineering Inspector

ECAM Electronic Centralized Aircraft Monitoring

FMEA Failure Modes and Effects Analysis

HSE Health, Safety and Environment

ICT Information and Communication Technology

IO Integrated Operations

IR Infrared

JIT Just-in-time

KPI Key Performance Indicator

LCC Life Cycle Costs

NCS Norwegian Continental Shelf

NPV Net Present Value

OLF Norwegian Oil Industry Association

PA Passive acoustic

PM Preventive Maintenance

RCM Reliability-Centered Maintenance

TCI Technical Condition Indexing

UI User Interface

Chapter 1

Introduction

With rising costs and an unstable oil price, the future of the oil industry is all but certain. As the hydrocarbons get less accessible, the need to modernize, to stay ahead of both required technology and costs, arise.

Integrated Operations (IO) is being celebrated as the future of the offshore industry. It is a concept that utilizes Information and Communication Technology (ICT) to enhance the level of communication and data flow within the organization. IO is such a wide term that it has the potential to influence almost all aspects of an offshore company. The implications, benefits and challenges associated with IO are substantial, and this thesis seek to explore them.

A Condition Based Maintenance (CBM) strategy constitutes of maintenance tasks being carried out in response to the deterioration in the condition or performance of an asset or component as indicated by a condition monitoring process[5]. It goes very well with IO, as it might be the only way to increase the automation in the field of maintenance. An introduction to CBM along with the concepts relevant to IO, and the methodology for selection of CBM strategy will be explored.

Use of Cost-Benefit Analysis (CBA) is necessary to make informed decisions, taking both reliability and financial perspectives into account. The basic concepts surrounding the CBA will be included in this thesis.

Chapter 2

Condition Based Maintenance

CBM is a preventive maintenance strategy based on the technical condition of the assets, rather than a predetermined periodic interval decided by the age of asset or the time since last preventive maintenance action. The technical condition is determined by monitoring specific parameters that reveals the current health of the asset, such as temperature, corrosion or flow. This information can be used in predicting the future health development, and maintenance decisions can be taken to minimize costs.

Use of Condition Monitoring (CM) as a means of improving maintenance performance has been adopted to a great extent in the industry. The continuous improvement of techniques and diagnostic methods makes the strategy a viable alternative to traditional Preventive Maintenance (PM) on more and more types of equipment. In his Doctoral Thesis, Tom A. Thorstensen summarizes the following benefits of CBM[29]:

- Reduced repair time and costs
- Avoided revenue loss
- Maintenance cost savings
- Increased equipment lifetime
- Higher efficiency
- Sound basis for continuous improvement
- Improved safety assurance

2.1 Failure

In CBM, failure is not thought of as an event, but as a process. An asset is put into service, and at some point in its life, it starts to fail until it reaches the status of functional failure.

The philosophy is not to prevent the failure process to start in the first place, but to take action before the failure reduces the functionality of the asset below the desired level. There are three main categories of failure.

2.1.1 Age-related failure

With age-related failures, the failure process starts at the beginning of the assets life. Because of exposure to stress, the asset deteriorates, not necessarily at a linear rate, until it reaches functional failure. It may seem intuitive that because of their progressive nature, age-related failures are easy to accurately predict. This, however, is almost never the case. The fact that a failure mode is age-related only means that the odds of the asset failing increases with age. Assets with failure modes that are age-related should be monitored and given TCI's, and repaired when they dip below the desired level.

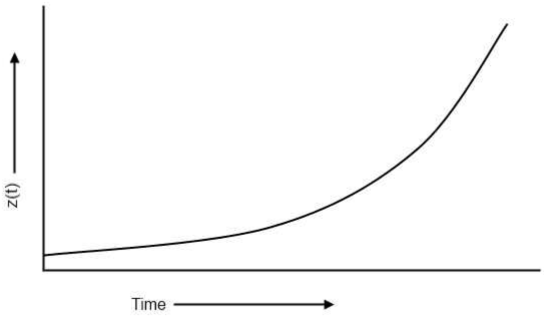


Figure 2.1: Failure rate of age-related failure

2.1.2 Non-age related failure

Deterioration is not always proportional to applied stress, and the relationship between the likelihood of failure and asset service time is almost non-existent. This is the case of many different types of assets, but especially with instruments and electronics. The failure process does not start at the beginning of the assets life, but at some point in its life where something goes wrong. From that point, the performance of the asset may or may not decrease, but it will in the end result in functional failure. The goal is to look for signs of such a failure process having started, and intercept it.

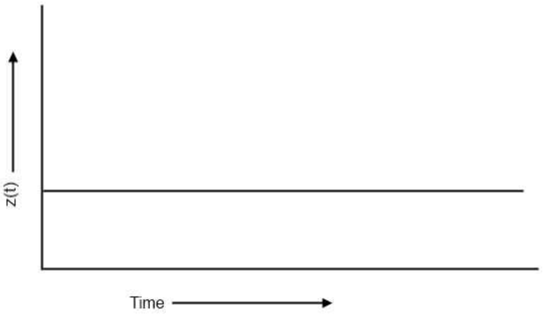


Figure 2.2: Failure rate of non-age related failure

2.1.3 Running-in failure

Some components fail shortly after being put into service, or after a maintenance action. This is because of a pre-existing error or some human error in the installation process.

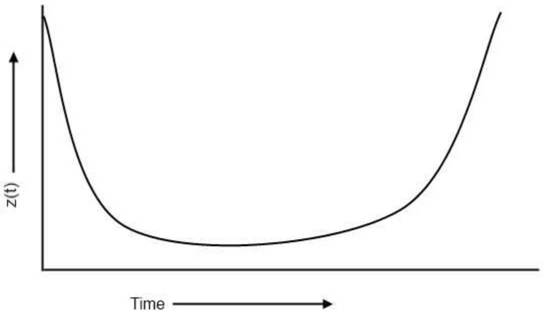


Figure 2.3: Failure rate of age-related failure with run-in failure

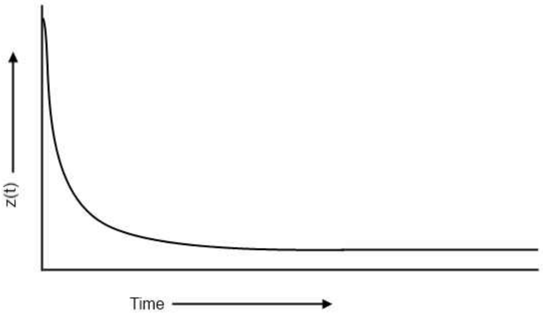


Figure 2.4: Failure rate of non-age related failure with run-in failure

Figure 2.3 is also popularly know as the bathtub curve. This is for a single part, and it is very important not to confuse this with a system of multiple parts. It is a very common mistake to think that a system will have a failure intensity rate that resembles the bathtub curve. The reason that this is a common misconception is that when the individual parts of a system is being maintained, the system bathtub curve is a side effect, and in reality is the average curve for all the parts. The raised ends are due to initial quality and training problems and wear-out of longer-lasting parts respectively. Unless the maintenance strategy is to treat the whole system as a single part, with no maintenance on individual parts, then there is no such thing as a system bathtub curve[25].

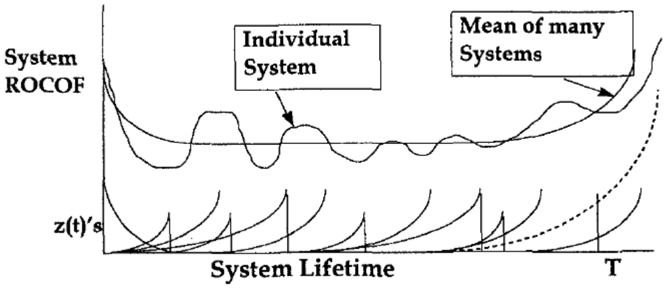


Figure 2.5: Bathtub curve for repairable system

2.2 Failure Modes and Effects Analysis

The most important thing when deciding on a CBM-strategy is to get a clear picture of as many of the failure modes as possible. Different failure modes may differ in consequences, deterioration speed, detectable warning signs and so on. One of the first steps is doing a thorough Failure Modes and Effects Analysis (FMEA).

The goal of an FMEA is to identify the failure modes that are reasonably likely, or less likely, but with severe consequences, to cause functional failure, and to establish the effects of said failure modes. A failure mode is an event that could cause functional failure, which is the asset losing function. In an FMEA, we first stipulate what is defined as functional failure, and then look at what might be the cause. Useful sources of information about failure modes are:

- The manufacturer or vendor of the equipment
- Generic lists of failure modes
- Other users of the same equipment
- Technical history records
- The people who operate and maintain the equipment

The people who operate and maintain the equipment, in most cases, are by far the most reliable sources of information. In a CBM setting, we do the FMEA to be able to decide on which failure modes are to be monitored.

2.3 P-F Interval

It has been discovered that very few failure modes are age-related, which means that there is little reason to trust young assets and distrust old assets. However, many failure modes give some sort of warning that they are impending. This is why CBM is interesting. It enables users to intercept failures before the point of functional failure. The P-F curve illustrates what happens in the final stages of failure.

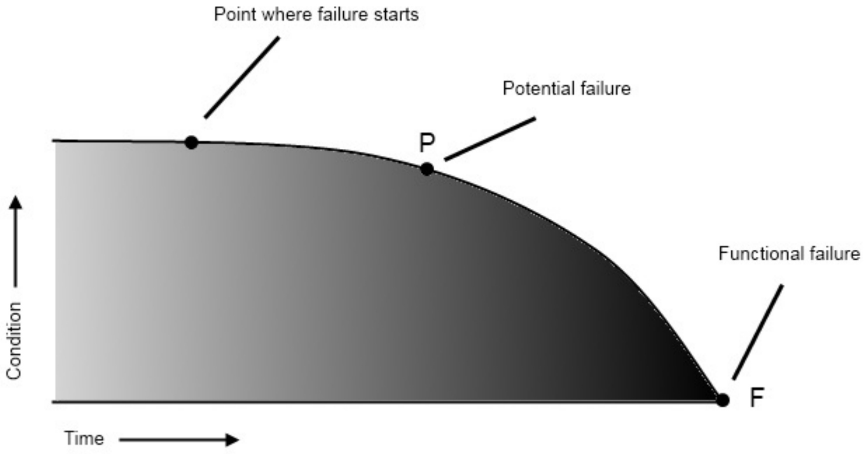


Figure 2.6: The P-F curve

Point ’P’ indicates the point in time, after a failure starts to occur, when the failure is detectable. Point ’F’ indicates when the asset has failed. The idea behind CBM is to detect the failure within the P-F interval. The actual length of the interval could be anywhere from seconds to years depending on the failure mode. For some types of equipment, even just a few seconds of warning could be valuable. Those seconds could for instance be used on a controlled shutdown to avoid secondary damages, or even avoid injuries and death.

The profile of the P-F curve may vary between the different failure modes, and it can even vary within the same failure mode i.e. inconsistency in regards to the P-F interval.

If the P-F curve resembles figure 2.7, then it is the shortest interval that is of importance. The desired inspection interval depends on on the length of the shortest P-F interval. If the goal of the monitoring is to intercept and repair failure modes before they become functional failures (and not just shut down to prevent damages and injuries) then the inspection interval must be small enough to allow time for planning and repair actions to be taken before the asset fails. If the P-F interval of a failure mode is 2 months, and inspection interval is 1 month, the potential failure will be discovered at the very least 1 month before functional failure[16].

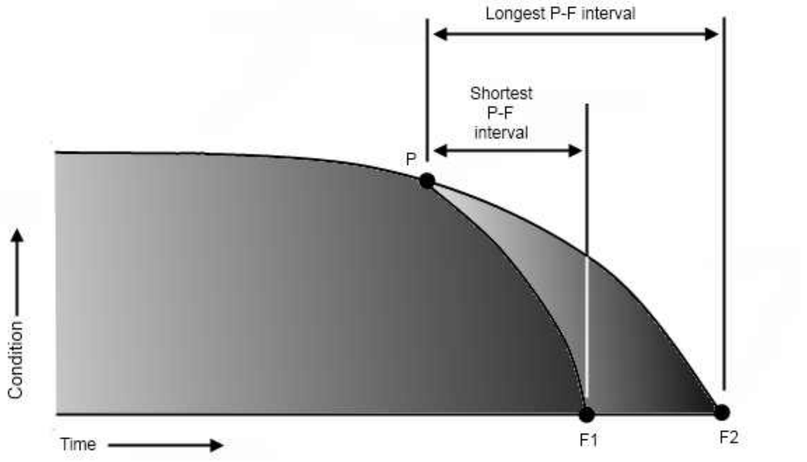


Figure 2.7: Inconsistency in the P-F curve

When we put this into an IO perspective with the possibility of online monitoring (very short inspection interval), many failure modes become candidates for CM.

2.4 Monitoring Techniques

A single failure mode can have multiple points of potential failure depending on which monitoring technique is used. The monitoring techniques that apply to the offshore industry are mainly condition monitoring, performance monitoring (or primary effects monitoring) and human inspection. First of all, the chosen monitoring technique must allow for a sufficiently long P-F interval for intervening actions to be made. Second, the monitoring technique must pass the CBA. It is worth noting that in many cases, human inspection may be sufficient. However, as this thesis aims to put CBM in an IO perspective, the amount of equipment that could potentially be monitored may render the human inspection alternative practically impossible based on the limited amount of available man-hours on an offshore installation.

2.4.1 Human Inspection

This is the most basic monitoring technique. It is based on the human senses, and it is therefore very versatile. However, the human senses are not very sensitive, which means that the point of potential failure (the point in the failure process when the failure is detectable) may be late in the failure process, and may give a very short P-F interval. In any case; if human inspection is one of the chosen techniques, the data must be manually put in to the IO system.

2.4.2 Performance Monitoring

Performance monitoring refers to monitoring of the primary effects of the equipment in question, such as flow or temperature. These effects are already monitored, and to be able to put the CBM in a IO perspective, the values must either be manually read of e.g. gauges and put into the IO system, or modified to automatically send the data onshore. The strength of this technique is the generally small costs. In many cases, the deterioration caused by the failure process will affect the performance of the asset which, in many cases, will be detected by the existing instruments. Since the instruments and gauges are already in place, the capital costs involved are smaller than condition monitoring. The drawback is that users are limited to monitoring the effects that are chosen by the supplier of the asset, and more sensitive instruments that monitor other effects are off the table. Another drawback is that in most cases, performance monitoring requires additional modifications to constitute as CBM in an IO perspective.

2.4.3 Condition Monitoring

Condition monitoring is using equipment to monitor other equipment. The technique can be viewed as a highly sensitive version of the human senses. Since the instruments used for condition monitoring are so sensitive, they often allow for a long P-F interval. Unlike the human senses, a CM-instrument is very specialized, and will only detect specific symptoms of failure. The failure mode, along with a CBA, determines the type of CM-instrument. Most monitoring instruments can be put into one of the following six categories.

Dynamic Monitoring

Moving parts vibrates at different frequencies. These frequencies can vary across a very wide spectrum, and by monitoring the asset as a whole, it is possible to home in on the vibration of individual components and look for variations and changes. Amplitude sensors are used for the lower range frequencies, velocity sensors are used for the middle range frequencies and accelerometers for the higher frequencies.

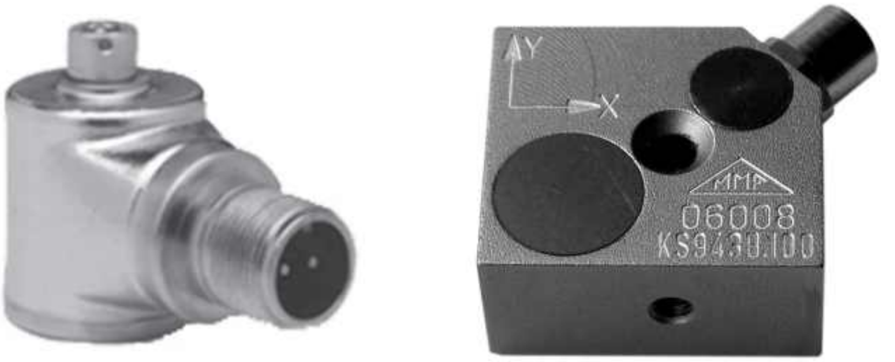


Figure 2.8: Velocity sensor and Accelerometer

As for analysis, Fourier transform allows for conversion of data into frequency spectra. Artificially intelligent systems have been developed for vibration analysis. However, they have been developed for a particular machine component. An expert system that truly incorporates the techniques used by maintenance engineers for high accuracy fault detection of vibration data has not yet been developed [9]. There will still be a need for maintenance engineers onshore to analyze the data, unless the software have been specifically tailored to the asset in question.

Particle Monitoring

Some failures cause particles of different sizes and shapes to be released. Particle monitoring will be able to detect these failures. Among the detectable failures are wear, fatigue, corrosion and contaminants.

Chemical Monitoring

With chemical monitoring, one is able to detect elements in fluids, usually the lubrication oil. The chemical elements that are detected can reveal information about where they come from. An example is if boron is found; that would indicate that there are coolant leaks in oil. Chemical monitoring can detect wear, leaks and corrosion.

Physical Monitoring

Physical failures are the ones that cause a physical change to the appearance of the asset such as cracks, fractures or other types of deformation to the asset.

Temperature Monitoring

Temperature monitoring is to monitor the temperature of an asset, rather than the processed material. The technique mainly involves some sort of infrared camera, though there are more "analog" methods, such as paint that changes color on different temperatures.

Electrical Monitoring

Electric monitoring look for changes in resistande, conductivity, dielectric strength and potential. It is able to detect a number of different failure modes such as corrosion and loss of insulation.

2.5 Technical Condition Index

Technical Condition Indexing (TCI) is defined as the degree of degradation relative to the design condition. It is a Key Performance Indicator (KPI) used to abstractly represent the condition of a component. A comprehensive CBM strategy will produce a very large amount of data which would require a significant amount of analysis to be able to use it as a basis for making decisions. By combining CBM with certain automatic TCI rules, the resources required for analysis will be reduced, and allows for faster decision making. An example is assigning the TCI on a separator wall as a function of the loss of wall thickness due to corrosion.

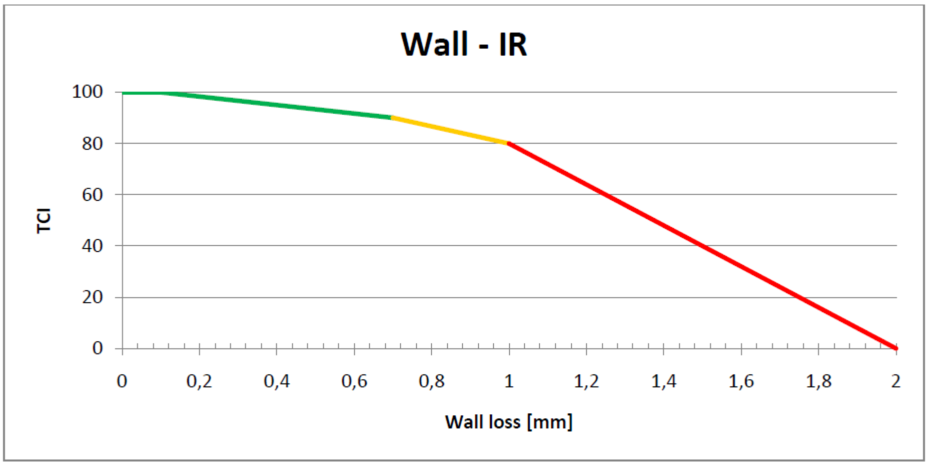


Figure 2.9: TCI as a function of wall corrosion

It is difficult, if not impossible, to determine the technical condition of a component or system based on a single parameter. That is why the TCI is calculated using the aggregation methodology. The aggregation methodology consists of establishing a hierarchy of objects to represent the system, assign a weight to each object based on the criticality, and assign input variables that reflect the technical condition of the objects. The TCI values are aggregated upwards in the hierarchy to enable users to view the technical condition of a system at any given level.

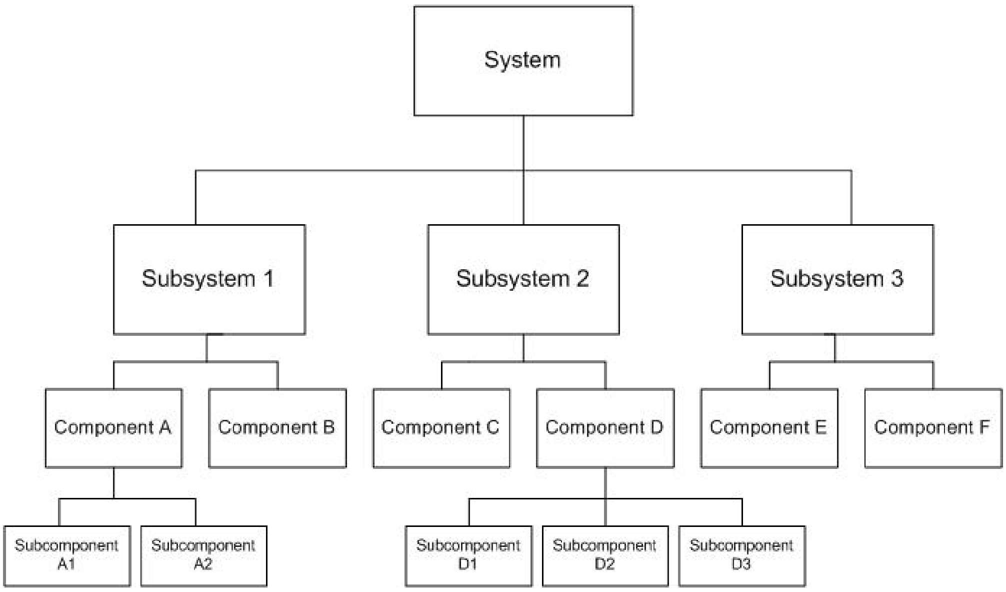


Figure 2.10: TCI hierarchy

Chapter 3

Integrated Operations

IO is an operation philosophy enabled by modern advances in ICT. The core of the philosophy is to open up communication channels to enable many of the different aspects of running an offshore installation to integrate. This has many benefits such as having part of the drilling team onshore, or keeping the logistics team informed of the likelihood of imminent repair actions requiring logistic actions. IO tries to remove divides between disciplines, professional groups and companies. The whole concept revolves around making faster and better decisions.

One of the most commonly illustrated examples of IO in the offshore industry today is the use of always-on video conference rooms. This concept may have a big impact on the communication between the people who are working offshore, and the people who are working onshore. Furthermore, it has the potential to not only influence the communication itself, but it could replace the need for certain personnel to physically be offshore. However, video communication is not the only potential of IO, and it is probably not in the video conference room the big money is going to be made or saved.

Norwegian Oil Industry Association (OLF) concluded in their 2006 report "Potential value of Integrated Operations on the Norwegian Shelf" that IO represented a potential value of 250-300 BNOK on the Norwegian Continental Shelf (NCS). The basis for this estimate was not provided in the report, and was not released by the project. This number is so huge and abstract that it bears no real value to the actual companies in their decision process. To be of real value, more specific analysis must be made so that the results are tangible and of practical use in further calculations[17].

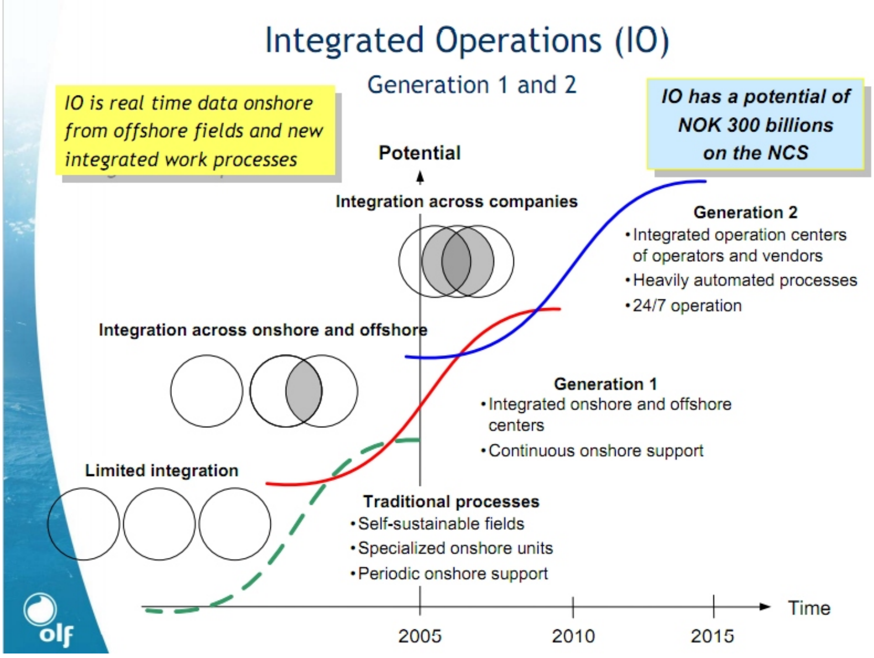


Figure 3.1: The potential of IO on the NCS[15]

There are a few serious challenges regarding IO. The concept is quite new, and so many different parties have their own definition of IO. Everything in IO is expensive to implement, and there is little benefit from trying IO on a small scale, since it can be argued that IO, by definition, is a large scale corporate integration.

3.1 IO & Maintenance

As stated, IO requires some level of shared data or information. For maintenance to be viewed in an IO perspective, a logical strategy is CBM. However, just because a system is subject to CBM, does not mean that it can be defined as a part of the IO strategy. The gathered data must be available, and utilized, by others than just the offshore workers.

As a practical minimum requirement for CBM to constitute as IO, I postulate that the data must be entered, automatically or otherwise, into a database of some kind. This database should be accessible both offshore and onshore, though not necessarily as raw data. In many cases, simple TCI values may be favorable as deep analysis of raw data may be counterproductive as to making fast decisions.

3.2 Optimizing the Logistics

The Council of Logistics Management defined logistics as "The process of planning, implementing, and controlling the efficient, cost-effective flow and storage of raw materials, in-process inventory, finished goods, and related information from point of origin to point of consumption for the purpose of conforming to customer requirements."[7]

The efficiency of the logistics can only be as good as the quality of the relevant, available information. Efficient logistics aims to reduce logistic actions as much as possible without disrupting the operational progress. In other words, it is always seeking to remove waste from the logistics chain. An IO-directed CBM strategy opens up the possibility to remove even more waste from the logistics chain. Little expenses are spared when a critical component has a breakdown which causes a halt in rig production, as the costs of a non-operative rig are huge. Spare parts will be flown in by helicopter if need be, which could cost as much as 50-100 kNOK. The cost of logistic delay is unnecessary, and it is well worth it to put a lot of effort in avoiding it.

As a very large portion of maintenance actions can be anticipated, the amount of spare parts and tools necessary in offshore storage could be reduced. A conscious analysis of how much is needed is important, but it should be possible to approximate a Just-in-time (JIT) spare part strategy. However, JIT logistics is a very risky and vulnerable strategy. As the supply chain gets slimmed down, the vulnerability from minor disruptions increases. An example is the small fire on March 17, 2000 inside a Philips semiconductor fabrication plant that in the end caused the downfall of the Swedish company Ericsson's phone handset production, and they had to create a joint venture with Sony[22]. The slimming of the supply chain must be balanced against the value of being prepared for opportunities of joint maintenance, should they arise, as well as the risks involved.

3.3 Opportunity Maintenance

With CBM in an IO-setting, an overall more perspicuous overview of the installation is possible. As the degree of integration increases, more opportunities will arise for performing maintenance without further productive loss. This is made possible by an integrated combination of:

- Maintenance foresight from trending the deterioration of failures, expert judgment and statistic analysis.
- Logistic foresight where anticipated logistic delays are used as opportunities. The integration between the logistics and other aspects must be tightly woven to allow for

logistic preparations to facilitate opportunities.

- Managerial foresight and oversight with two-way integration with maintenance and logistics will uncover opportunities.

If enough critical systems are subject to CBM and IO, with a sufficiently long P-F interval, then it may be possible to perform joint maintenance. If two critical systems, that require the platform to shut down, are in need of maintenance within e.g. the next six months, then maintenance could be scheduled in such a way that they both share the same downtime. In effect, the downtime cost would only apply to the system with the longest downtime. The other system would get its downtime for "free". This is a huge cost saver, as downtime is immensely expensive in the order of 100.000 [USD/hr], or more, for a production platform.

However, if a maintenance task is postponed, there is an increased risk of having functional failure. This will result in both downtime and the added cost of corrective maintenance, in addition to possible safety issues[2].

This concept applies to all critical systems, and is reason enough to *consider* having an IO-based CBM strategy on all critical equipment. It is important to note that this requires much more manpower, as the maintenance actions on all the systems has to be carried out at the same time. It is probably worth it to fly out extra personnel for joint maintenance events if they arise.

Opportunity maintenance may prove to be the biggest benefit from IO.

Chapter 4

Cost-Benefit Analysis

A CBA is done to determine whether a planned action is profitable or not[14]. A CBA weighs the total expected costs against the total expected benefits to determine the best option. The goal is to measure the efficiency of the intervention relative to the status quo. Traditionally, a CBA uses a discount rate to give all costs and benefits, future and present, a common value. This decision making tool has been widely used in both private companies and social, governmental decisions such as whether to build a power plant or not.

CBA is a very useful tool in maintenance. There seems to be a basic error within the maintenance philosophy. The error is to suppose that maintenance is a question of reliability; it is really an economic problem, in which reliability is a factor[25].

There are two ways to look at the results that are relevant to this thesis:

1. Net benefit, which is the present value of costs subtracted from the present value of benefits
2. Benefit-cost ratio, which is the present value of benefits divided by the present value of costs

Both indicators should be examined before a decision is made. It all depends on the nature of the different alternatives and the funds available. If funds are limited, there may be better ways to spend resources, even though the net benefit indicator shows a positive result.

Example: Lets say that there are \$100 available to invest in any combination of the following five alternatives:

Table 4.1: Example of CBA

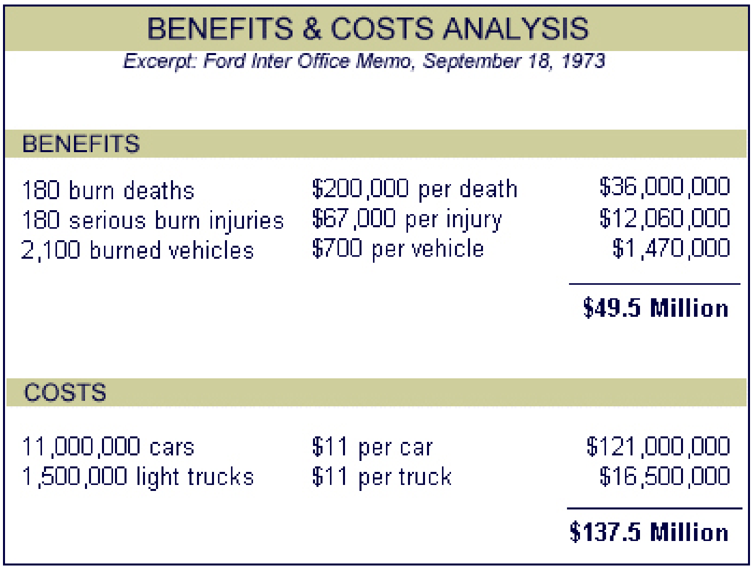
Alternative	Cost [$]	Benefit [$]	Net benefit [$]	BCR
A	100	200	100	2
B	51	120	69	2,35
C	30	65	35	2,17
D	20	43	23	2,15
E	50	105	55	2,1

In this example, option A is the one with the highest net benefit while option B has the highest Benefit-Cost Ratio (BCR), so lets look at the different alternatives. We can invest in option A, which leaves us with \$200. Option B only costs \$51, so we can add option C, which yields \$204 when the \$19 we saved are added. Our last option is to combine option C,D and E that yield \$213. This is meant to illustrate that there are more to a CBA, if you are the decision maker, than choosing the option with the highest net benefit or BCR.

The quality of the CBA is entirely dependent on the accuracy of the estimated costs and benefits. The chosen discount rate will not be the subject of great discussion, as a conservative value will be used, most often taken from the financial market.

In the case of IO, finding estimates for all the significant cost drivers will be less of a challenge than finding and quantifying all the benefits. There will be clear benefits resulting from less frequent shutdowns, as well as less tangible benefits such as increased safety. How much is less injuries, deaths or environmental damages worth? This has to be part of the CBA.

Perhaps the most famous failed CBA comes from the American multinational automaker Ford Motor Company. In 1970, the engineers of Ford were urging in an internal memo that "technology should be developed to provide rupture protection for the fuel tank for 30 mph side and rear impacts." It was apparent that there was a particular problem with the Ford Pinto, and that the company knew about it. The problem could be fixed at the cost of $11 per car.



BENEFITS & COSTS ANALYSIS

Excerpt: Ford Inter Office Memo, September 18, 1973

BENEFITS

180 burn deaths	$200,000 per death	$36,000,000
180 serious burn injuries	$67,000 per injury	$12,060,000
2,100 burned vehicles	$700 per vehicle	$1,470,000
		$49.5 Million

COSTS

11,000,000 cars	$11 per car	$121,000,000
1,500,000 light trucks	$11 per truck	$16,500,000
		$137.5 Million

Figure 4.1: The CBA of fixing the problem with the Ford vehicles

After the CBA, it became apparent that paying for the legal fees resulting from the death and injuries of their customers were cheaper than paying to prevent them. A ghastly sense of ethics set aside, the Ford environmental and safety engineers made a big mistake in their CBA. They failed to include all the costs and all the benefits. The huge loss of reputation is absolutely something that need to be included in the analysis[19].

Chapter 5

Input Output

In a simple CBA we only have to establish all the costs and benefits. However, this thesis encompass the theory of CBA of CBM and will also explore the impact of IO on the CBA. The benefits from the changes made to the systems will primarily be less downtime, maintenance and so forth, so the input to the CBA will not only be the costs and benefits, but also the change in failure rate, active repair hours etc.

5.1 Pricing the priceless

Some of the factors that need to be quantified are the less tangible values such as loss of reputation, injury to personnel and benefit from increased communication, if at all possible. When it comes to the first two points, every operator should be well within the regulations. However, it is impossible to remove 100 % of the risk involved in the offshore industry. This means that accidents can happen even when regulations are followed. There are costs related to accidents, and conversely, there are benefits related to avoiding accidents. Quantifying these are important when developing a cost-benefit analysis of a decission that may influence the frequency and severity of accidents and incidents. It may seem unethical to discuss the cost of death or environmental damage, but it is important to note that it is done in a context where we calculate the benefit of avoiding such incidents.

David J. Sherwin states that safety is best incorporated as very high failure costs. Furthermore he says, "There is a price for human life in safety economics and it is sentimental nonsense to deny it. It is a high one, of course, in a civilized society, but it is nowhere near infinite. It embraces both actual and estimated sums, including compensation, fines, loss of production, loss of reputation and community goodwill, increase in insurance premiums, and internal morale factors e.g. risk of strike".

5.1.1 Value of avoiding loss of reputation

According to a 2006 Weber Shandwick's Safeguarding Reputation survey, 66 % of global executives believe that it is harder to recover from reputation failure than it is to build and maintain reputation[21]. Charles J. Fombrun, chairman of Reputation Institute, claims in an article published in Forbes that "a 1 % increase in reputation produces a 1 % increase in stakeholder support and a 1 % increase in market value"[10]. The challenge lies in estimating the percentual loss of reputation. If an incident occurs that affects the reputation, it will not only be the incident itself that influence the reputation, but also the way it is treated both by the company and the media.

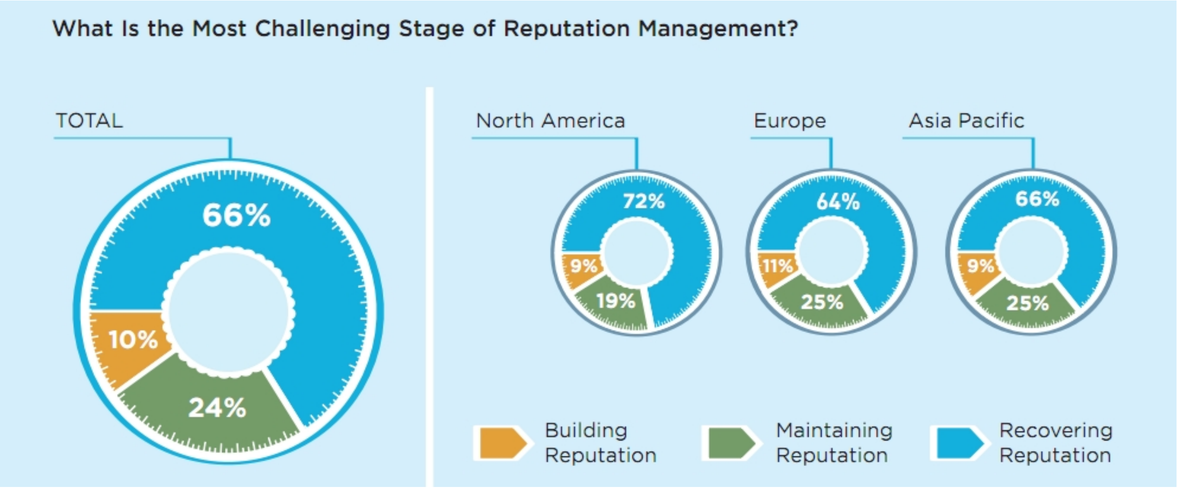


Figure 5.1: Reputation Management. Reprinted from WeberShandwick.com

Loss of reputation for a company can, and often will, cause actual loss of revenue. The offshore industry is subject to strict regulations whose primary function is to ensure ethical and safe conduct in relation to both personnel and the environment. A sub-par reputation could result in loss of contracts, loss of suppliers or even "brain drain" where technically qualified persons leave the company. Brain drain is considered an economic cost since the workers take with them the training sponsored by the company. Difficulties in getting new expertise will also impact the overall strength of the company.

5.1.2 Value of avoiding damage to the environment

John Moubray states that "A failure mode has environmental consequences if it causes a loss of function or other damage which could lead to the breach of any known environmental standard or regulation".

In the offshore industry there is always a risk of damaging the environment, in some cases

Figure 5.2: Deepwater Horizon

on a large scale, such as in the case of the Deepwater Horizon oil spill in the Gulf of Mexico in 2010. The environment is precious, and some would argue fragile, so there is no doubt that an oil spill on a grand scale is a catastrophe. However, when it comes to quantifying the benefit of avoiding an oil spill, the regulations indirectly gives us the answer of what the intangible value is. As far as a CBA goes, the cost of an environmental accident is the direct costs following it, in addition to the cost of the loss of reputation. According to the coastal administration, the variations in the severity of oil spills are so great that it becomes meaningless to use mean values (the cost can lie between 0-3 BNOK), so it should be assessed in each individual instance[30]. However, to be able to produce a meaningful analysis on future oil spills, a fixed cost per cubic meter of oil spill will give the best approximation. Even though the consequence of two separate, equally large, spills may be differ greatly depending on geography, wind, etc.

5.1.3 Value of avoiding death or injury

The coastal administration has valued a statistical life at 20.15 MNOK and injury at 2.4 MNOK[30]. That is to say, if a project costs 20.15 MNOK and on average will save one human life, then it is worth doing. This number varies greatly depending on whom is inquired. W. Kip Viscusi, a professor of law and economics at Harvard, has estimated the value to be $6.3 million (1998) based on the "wage premium" that is paid to workers who accept riskier jobs. Some governmental regulations indicate a much higher value of a statistical life. Regulation of workers' exposure to formaldehyde supposedly costs $72 billion per life saved, other health issues not counted[1]. It is reasonable to believe that a lot of the regulations have not been subject to a CBA, and that they are more a question of policy and politics.

In the practical terms of a CBA, the value of a statistical life must be set sufficiently high to cover the actual costs of a death, along with any other values the company places on their workers. As this is such a sensitive issue, the number provided by the coastal administration, 20.15 MNOK, can be used in a CBA.. This means that if a company is able to save one life by implementing a policy, such as CBM, during its life time, they will have earned 20.15 MNOK, all else being equal.

5.2 Costs

To perform a CBA it is important to have as accurate estimates of the costs as possible. Some of the costs are one-time initial costs, while others are annual costs. Costs such as operation personnel and hardware onshore may be shared across multiple systems or pieces of equipment, meaning that there is an effect of economies of scale. To monitor one system will have one cost associated with it, and subsequent systems will only increase the operating cost with a relative small percentage.

As a CBA compares one or multiple new investments to the status quo, the only costs and benefits worth looking at are the ones that differ from those that are already in place. Determining the status quo must be done in each individual case, so this thesis will assume both non-CBM and non-IO, with main focus on costs and benefits related to IO.

5.2.1 Onshore

One scenario of relevance is building some sort of control room. This will require a significant investment in planning, building, hardware and software. In any case there is a need to connect the offshore installation to the onshore office with a high speed digital connection. According to Rune Folstad, Aker Solutions, the existing bandwidth of most offshore installations are sufficient for a typical IO-connection.

Hardware

Some of the hardware may be moved from other parts of the company where they would be rendered redundant as the CBM gets implemented. Trained personnel will also have to work in this control room, so the size of the room depends on the amount of hardware and personnel.

Epsis.no delivers a range of control rooms partially equipped. They have a size capacity of 4-14 people and cost in the range of 15.000 USD to 85.000 USD.

The hardware will have to be updated from time to time and it will also need to be maintained. It is therefore logical to assign an annual operation cost to the hardware itself.

Figure 5.3: Large team room delivered by Epsis

Software

Whatever the current software in use are, it is reasonable to assume that the "old ways" of doing maintenance from onshore will persist for a significant amount of time. Therefore it is assumed that any initial and annual costs of the new software will be in addition to the old software, and will not replace it. There is likely an annual licensing fee associated with the software. A certain amount of tailoring of the software to fit the maintenance strategy will probably be necessary, and could be quite expensive.

Onshore Personnel

As mentioned, personnel will have to be trained to operate the new system. Some of the personnel may be moved from other parts of the company, either working 100 % on the CBM team or just partially. Some new postitions may need to be filled with new employees. However, IO is at its core a culture of cooperation, and training will take care of most of the new needs of the IO strategy. IO in its most extensive form will inolve a company-wide restructure that should include third party consultants. This could be quite expensive.

5.2.2 Offshore

To implement a successful CBM strategy, we need some sort of monitoring of the condition of the equipment or system in question. This can be achieved by lubricant analysis, performance monitoring, electrical health monitoring or acoustic emission monitoring, among others. This data could be collected by a Development Engineering Inspector (DEI) on a regular basis, however this thesis aims to put CBM in an IO perspective, so the transfer of data is preferably an autonomous task where the data is transferred from the equipment offshore, to a company-wide accessible database. This is not strictly a requirement for CBM to constitute as IO, but an extensive IO-policy is practically impossible if the chain of information gets disrupted by human intervention in too many links.

Hardware

In some cases, it may be desirable to mount external equipment such as a Neutron backscatter or IR thermometry. There are many other types of monitoring equipment, and they vary greatly in cost as well as their function. The decision on what instruments are needed will be based on costs, the value of the gathered data, target failure mode and P-F interval. The idea is that the instruments will send data to the onshore teams where it will be analyzed. The offshore hardware will also have to be maintained, which will involve an annual cost.

Installation

The monitoring equipment must be mounted to the components that are to be a part of the CBM-plan. This will either be done by the existing offshore team, or by external personnel. This may or may not involve downtime for the offshore installation, depending on how invasive mounting the equipment is. It is possible to make use of a downtime opportunity to remove additional downtime. One of the main goals of monitoring the equipment is to reduce downtime since it is so expensive. Downtime for installing monitoring equipment can be so expensive that the costs surpasses the benefit of having them. It is strongly advised to avoid this by implementing it in the design phase, use an existing opportunity or use equipment that does not require downtime to mount.

5.3 Benefits

The traditional way of doing maintenance has been to perform periodic maintenance based on the recommendations of the supplier. On some types of equipment, the supplier performs the maintenance themselves. The problem with this method of organizing maintenance is that it generates a lot of waste in terms of unnecessary resource expenditure. Maintenance will be performed either too early or too late.

There is also the issue of supplier incentives. As suppliers in many cases both set the interval for PM, and either performs the maintenance and/or supplies the spare parts themselves, they are effectively on both sides of the table. It is hard to imagine why they would want to optimize the maintenance interval. Chances are that they prefer to set a shorter interval than the economically optimum both because it lowers functional failures, which looks good on their statistics, and because it gives them a good second income.

With CBM, however, maintenance can be performed when it is needed, and the equipment is left untouched as long as it is performing adequately. It has been shown that on some types of systems, breakdown occurs more often shortly after the periodic inspection. This suggests that the act of "opening up" the system may induce problems that would otherwise not occur. For many years, the late Igor Karrasik, arguably the most prominent and widely read pump engineer, responded to enquiries about pump overhauls by saying that a pump should not be opened for inspection unless either factual or circumstantial evidence indicated that overhaul is necessary[6]. By adopting a CBM-policy, these kinds of failures would happen less often simply because the system would be exposed less.

In some cases, there is a need to perform a shutdown to be able to perform the maintenance. The cost related to this is substantial, and should be avoided if possible. A CBM-policy would reduce the number, and potentially the length, of these shutdowns. The number of physical inspections would also be reduced, which is a good thing as they in many cases involves risks for the inspectors.

To perform a CBA, benefits, as well as costs, must be quantified on common ground. As mentioned, some of the potential benefits from CBM does not have dollars as their immediate denomination, but rather less tangible values such as increased safety and communication.

5.3.1 Increased Reliability

By having information of the monitored equipment, one hopes to catch failures before they happen. This is achieved by making decisions based on trending of parameters and prediction of lead time to failure or residual life distribution. The assumption is that the component will give off some kind of warning of impending failure[6]. This will lead to increased reliability.

Maintenance and Inspection

When a component or system is subject to CM, the need for physical inspection will be diminished. The benefit of this is that physical inspections take time for the personnel that carries out the inspections, which is a resource they could spend on other tasks. As mentioned, inspections may in fact have a negative impact on the condition of the equipment if the inspection is performed unnecessary.

Users may also be able to eliminate secondary damage which would be caused by unanticipated failures.

Analysis of maintenance costs have shown that a repair made after failure, normally costs at least a few times more than the same maintenance activity when it is coupled with CM[20].

It is clear that for maximum revenue to be generated by the installation, critical equipment downtime must be minimized, hence any intrusive maintenance performed should be as short as possible and timed to coincide with other outages[5].

Maintenance will only be performed when it is needed, rather than when it is scheduled based on some predetermined maintenance plan. In some cases, operation may be suspended to allow for a shutdown to be able to perform the maintenance. By knowing which components are in need of maintenance, this can be coordinated so that multiple interventions may be carried out during the same shutdown, and thus saving a substantial amount of money.

Reliability and Availability

Since CBM is better in terms of effectiveness of maintenance, the reliability becomes higher. If done right, it will reduce the amount of functional failures. Functional failures can have costly consequences such as increased maintenance cost, secondary failure, operational downtime or even reduced safety.

At the same time, the average interval between maintenance operations will increase. Prescheduled maintenance strategies will most of the time be performed a lot more often than is necessary over the lifetime of the system. This means the maintenance costs is decreased.

Chapter 6

Selection of CBM-strategy

In theory, the decision to implement a CBM-strategy should be on a failure mode basis, and not a component basis. If we were to monitor the temperature of a component, we would only detect failure modes that gives off warnings in terms of temperature. According to OREDA-2009, a pump has 16 different failure modes categorized as critical. If the pump itself is of critical importance e.g. safety, it would be insufficient to monitor only half of these failure modes, and disregard the rest.

However, when the user is in the process of making a decision for, or against, CBM on a component, in many cases it *will* be on a component by component basis. If that is the case, it is very important to either cover all failures, or be very aware of the failure modes that are not covered by the CBM, and develop another preventive maintenance strategy for these.

The first step in the process of selecting a CBM-strategy is to establish whether CBM really is the best option or not. One must consider the implications of using the much less complicated strategy of corrective maintenance, also known as on-failure maintenance. When corrective maintenance is employed, no action has been taken to predict or prevent failures, and the asset is repaired at functional failure. If the consequence of failure is small, then this might be a viable option. This is almost never the best strategy for critical equipment. In most cases, the accepted maintenance strategy has already been established, meaning similar equipment is either subject to corrective, or (non-CBM) preventive maintenance.

The general view has been that equipment with huge failure consequences for either safety or costs are the only real candidates for online CM, but this is a narrow view without thought for the added benefit of IO. If the consequence of *maintenance* is costly, online monitoring could still be the best option with the reduction of maintenance actions and the possibility of joint maintenance and other forms of opportunity maintenance.

6.1 Selection Process

The methodology for selection of an appropriate CBM strategy does not differ a great deal whether it is performed in the design process, or at a later date with retrofitting of monitoring equipment. The main difference is the costs, whereas if the decision is made in the design phase, it will be a lot cheaper and the outcome of a CBA could be different. Here follows a multi step process for selection of appropriate CBM strategy for a single asset:

1. Find all failure modes that should be subject to a maintenance strategy. This can be done by the methodology of an FMEA.
2. Find the necessary P-F interval for each failure mode that allows sufficient time for intervention.
3. Find all monitoring techniques for each failure mode that comply with the P-F interval. Human inspection, performance and condition monitoring are all valid candidates.
4. Perform a CBA on the resulting monitoring techniques. If there are none, a preventive or corrective maintenance must be considered.

A flowchart of the selection process is included in Appendix B.

Chapter 7

Case: Offshore O&G Separator

This case study will build upon the findings of former student Jørgen Houmstuen in his M.Sc.Thesis named "Condition Monitoring of Offshore O&G Separator - Cost-Benefit Evaluations and Presentation of Information". The separator is a first stage production separator located at the Draugen platform on the NCS. The thesis explores a number of different methods of CM solutions, and found that a combination of Infrared (IR) thermometry and Passive acoustic (PA) monitoring would have a net lifetime benefit of 76.305.000 [NOK]. This included benefits from reduced environmental risk, increased safety, company reputation and increased reliability and availability.

Figure 7.1: Separator

The case study of this thesis will explore the benefits of equipping the right people with the knowledge of any upcoming maintenance actions. The goal is to give them enough time to make the proper preparations to minimize the downtime and other costs.

7.1 Downtime

Downtime is a huge cost driver on a production platform. In this case study, downtime costs are limited to loss of revenue due to reduced production. It is important to note that the lost production will be regained either at the end of the plateau period, or gradually each year. Because of the effects of net present value, the monetary loss is real, even though the total volume of produced hydrocarbons is the same.

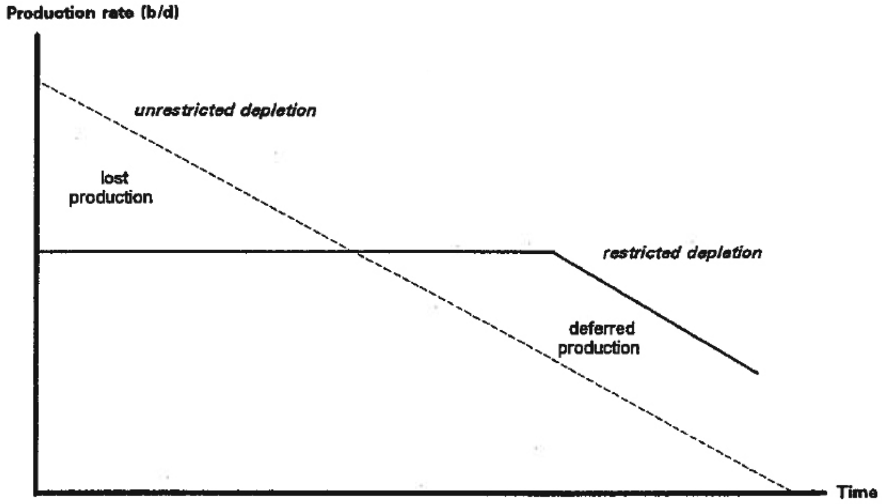


Figure 7.2: Production Profile

The lost revenue can be calculated from the following formula where F(i) probability of production loss in year i, V(i) is volume, PR(i) is the oil price, r is the discount rate and a(j) is the volume recovered in the following years.

$$\mathrm{REVLOSS} = \sum_{i=1}^{n} \frac{F(i).V(i).PR(i)}{(1+r)^{i}} - \sum_{i=1}^{n} F(i)\ .\sum_{j=i+1}^{n} \frac{a(j).PR(j)}{(1+r)^{j}}$$

Figure 7.3: Expected Revenue Losses

Houmstuen calculated that present downtime costs amounted to 662.500 [NOK/hr.] with an oil price of 50 [USD/bbl] for the Draugen platform. Standard & Poor's, in their March 2011 analysis of Statoil ASA, stated that their "long-term pricing assumption of $60 per barrel" was conservative. The $50 used in these examples can thus be argued to be too conservative, though a higher oil price will only influence the results positively.

7.1.1 OREDA

OREDA is a project organization sponsored by oil and gas companies with world-wide operations. The purpose is to create a compilation of reliability and maintenance data for a wide variety of offshore assets. The OREDA handbook contains data on failure modes in the form of failure rate, active rep. hrs and man hours. The chosen failure modes for the separator is listed in the handbook with the following mean failure rates:

Failure Mode	Mean Failure Rate (per 10^6 hours)	Failures (per year)
Critical	-	-
Abnormal instrument reading	14,03	0,1229028
External leakage process medium	9,55	0,083658
Plugged / Choked	4,05	0,035478
Degraded	-	-
Abnormal instrument reading	24,96	0,2186496
External leakage process medium	15,61	0,1367436
Plugged / Choked	29,68	0,2599968
Total failure rate	**97,88**	**0,8574288**

Table 7.1: OREDA failure rates

7.1.2 Repair Times

When the separator fails, a number of actions influence the downtime. The process is illustrated in the figure below.

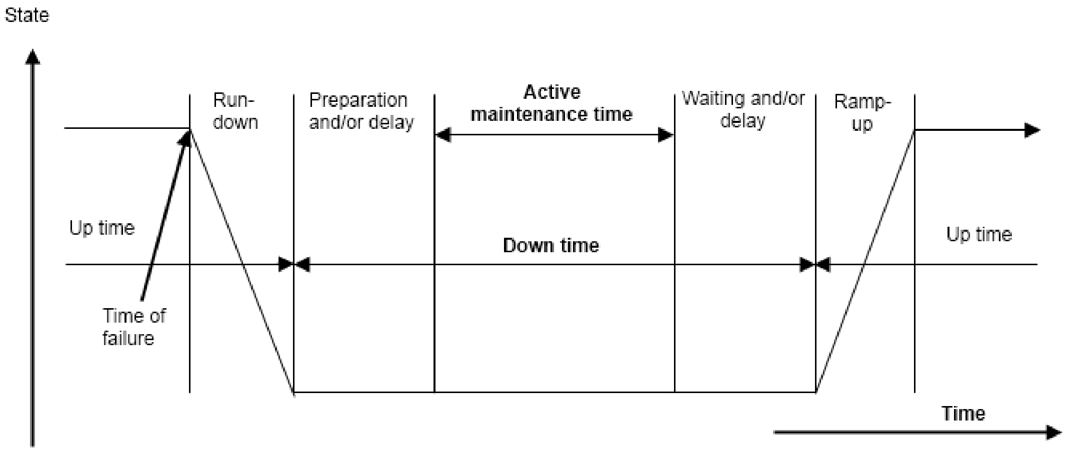


Figure 7.4: The Repair process

By being aware of the maintenance task in advance, some of the elements in the downtime category can be moved to an earlier point, and thus decreasing the total downtime. The elements that can be moved on a separator are mainly construction of scaffolding, preparation of "blinding case", maintenance planning and waiting for spare parts or tools.

With an IR+PA scheme, Houmstuen found that we would be able to intercept 84,92 % of the potential failures before they turn into functional failures.

Failure Mode	IR+PA
Critical	
Abnormal instrument reading	0,102870
External leakage process medium	0,066926
Plugged / Choked	0,031930
Degraded	
Abnormal instrument reading	0,183010
External leakage process medium	0,109395
Plugged / Choked	0,233997
Total intercepted failures/year	**0,728128**

Table 7.2: Yearly intercepted failures, found by Houmstuen

According to the OREDA database, maintenance actions that can possibly be moved outside the downtime section require the following amount of time:

Action	Time Consumption [hrs]
Construction of scaffolding	5
Preparation of "blinding case"	6
Maintenance planning	2
Sum	**13**

Table 7.3: Time consumption of different maintenance actions

In a CBM IO-setting, all of these actions can be done while the separator is still running. By multiplying total intercepted failure/year with saved downtime/failure, we get **9,466 hours saved downtime/year**. With a net present downtime cost of 662.500 [NOK/hr], this amounts to 6.271.000 [NOK/year].

7.1.3 Logistic Delay

If an asset suddenly gets the status of functional failure, spare parts and/or tools may be required to perform maintenance. Functional failure is rare, but it will happen from time to time, even with a CBM strategy. In fact, it will happen with 15,08 % with the listed failure modes, according to the calculations by Houmstuen. If spare parts and tools are not present on the platform, they must be procured from either an onshore base, or from the suppliers themselves. Depending on the size and weight of the items, they may be rushed by air, which costs something like 50.000 to 100.000 [NOK]. This is miniscule compared to the downtime costs. At best, the helicopter can be mobilized within a few hours. At worst, it may be days. With downtime costs running at the rate of 662.500 [NOK/hr], the potential loss from not having the necessary items to perform the maintenance as fast as possible is monumental.

If we assume that CBM in an IO-setting could predict 80 % of all critical maintenance tasks, then there is probably some available optimizing in the logistics departement in regards to warehousing of spares and tools. Storage space for spares and tools is limited on an offshore installation, and can be viewed as a limited resource.

7.1.4 Corrective Maintenance

When an asset reach the status of functional failure, corrective maintenance is required to restore the function. Since there will be no time for planning the maintenance operation, the cost of corrective maintenance will be high if the asset is of critical economic or safety value. Assuming functional failure of the separator results in down time, the corrective costs will be the following, disregarding the cost of tools and spare parts:

Event	**Downtime [hrs]**	**Man hours [hrs]**	**Cost**
Construction of scaffolding	5	10	3.332.500
Preparation Of blinding case	6	6	3.987.000
Maintenance Planning	2	2	1.329.000
Actual repair	12	36	8.022.000
Total corrective costs			**16.670.500**

Table 7.4: Corrective Maintenance Costs

This is the corrective maintenance cost of a *single corrective maintenance action* assuming there is no logistical delay, meaning that spare parts and tools are readily available offshore. The reason that this is a fair assumption is that the example seeks to explore the possibility of joint maintenance, thus the logistic planning, and corresponding actions, is assumed to have been made for a preventive maintenance that reaches functional failure before the maintenance action takes place.

7.1.5 Preventive Maintenance

PM is in its very nature always planned. The cost of PM is much lower than that of corrective maintenance as it allows for some preparation, though the active repair time is almost the same. In this example the actual repair time is the same as for the corrective maintenance, though it in reality is somewhat lower since the failure mode might not be perfectly clear from the start of the maintenance action.

Event	**Downtime [hrs]**	**Man hours [hrs]**	**Cost**
Construction of scaffolding	0	10	20.000
Preparation Of blinding case	0	6	12.000
Maintenance Planning	0	2	4.000
Actual repair	12	36	8.022.000
Total preventive costs			**8.058.000**

Table 7.5: Preventive Maintenance Costs

This is the preventive maintenance cost of a *single preventive maintenance action*. The cost is about half of that of a corrective maintenance action.

7.1.6 Residual life

Residual life can be defined as the time from τ_0 (today) until a failure occurs[3]. It is used to determine the optimal time to preventive maintenance by combining it with a cost-time function. The residual life for an asset with age t_0 with exponentially distributed probability density function is:

$$MRL(t_0) = \frac{1}{\lambda} \tag{7.1}$$

If the asset's initial probability density function is Weibull distributed, then the residual life of the asset is:

$$MRL(t_0) = \int_0^\infty t\alpha\lambda(t+t_0)^{\alpha-1}e^{-((\lambda(t+t_0))^\alpha-(\lambda t_0))^\alpha}\,\mathrm{d}t. \tag{7.2}$$

Based on the condition parameters of an asset, it is possible to establish the probability density function f(t), and thus calculate the mean residual life using this function:

$$MRL(t_0) = \int_0^\infty tf(t)\,\mathrm{dt} \tag{7.3}$$

Cost of operation and minor maintenance will increase as the asset continues to deteriorate. Cost elements related to loss of function can be an increase in minor maintenance activities such as lubrication and small repairs, increased in need of inspection and condition monitoring, increased administration costs, insurance costs or efficiency losses. It is given by the increasing function of:

$$co(t) = a \cdot t^b \tag{7.4}$$

The expected cost as a function of time to maintenance can be expressed as:

$$C(t_r) = CC + e^{-\lambda t_r}(CP - CC) + \frac{\lambda \cdot a \cdot \int_0^{t_r} e^{-\lambda x} x^{b+1}\,\mathrm{dx}}{b+1} \tag{7.5}$$

When the increasing cost of operation and minor maintenance (when b=1), equation 7.5 may be simplified to:

$$C(t_r) = e^{-\lambda t_r}(CP - CC) + CC + \frac{a}{\lambda^2}\left[1 - \frac{e^{-\lambda t_r} \cdot (\lambda^2 t_r^2 + 2\lambda t_r + 2)}{2}\right] \tag{7.6}$$

Example:

An offshore O&G separator with the following properties and an upcoming opportunity where the offshore installation is going into downtime in 300 hours for a duration of 50 hours:

- Exponential distributed MRL(t_0) = 1000 days (λ=0,001)
- Constant corrective costs CC = 16.670.500 NOK
- Preventive costs CP = 108.000 (only man hours) when $300 \leq t_r < 350$, and CP = 8.058.000 NOK otherwise
- Cost of operation and minor maintenance following equation 7.4 with a = 0,01 and b = 1

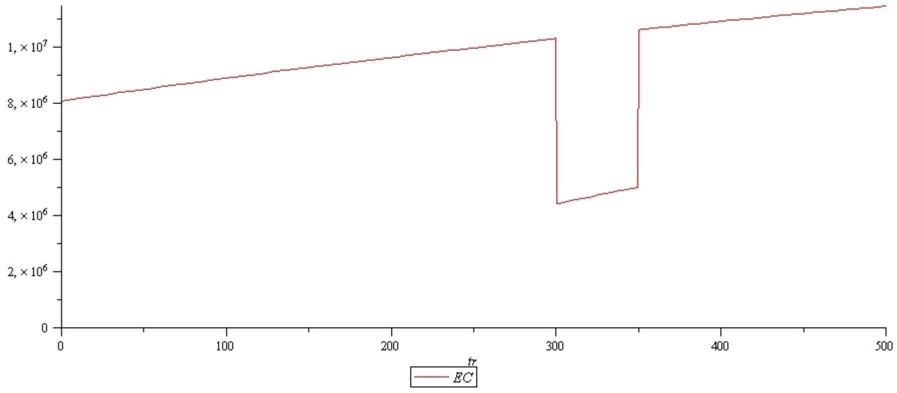


Figure 7.5: Expected cost of a maintenance event with upcoming downtime opportunity

It is very important to note that this is without taking the Life Cycle Costs (LCC) into account as this is an example of a single maintenance event. The savings from utilizing the upcoming opportunity far outweighs the risk of functional failure, and the best time to do the preventive maintenance action is when $t_r = 300$. Maple input can be viewed in Appendix A.

For this example to be realistic, the LCC would have to be factored in. As it stands, unless there is an upcoming opportunity, the best choice is always to perform a preventive maintenance action immediately. This is of course absurd, as there would be no uptime, only downtime. The model should include $G_r(t, L)$ which is the value of utilizing the useful life of an item with respect to the LCC within the time horizon for postponement of a maintenance activity.

When a joint maintenance task seems appropriate, one or more of the target asset's maintenance actions is likely moved either forward or backward from the optimum timing of maintenance, given the condition. This will influence the lifetime maintenance cost of the asset negatively, as the residual life is not utilized as it otherwise would. If the maintenance is moved to an earlier date, we run the risk of having to perform an extra maintenance task before the end of life, and our gain from the joint maintenance is lost. If the maintenance is moved to a later date, we run the risk of the asset reaching the state of functional failure.

7.1.7 Simplified example of Joint Maintenance

Let us assume that there are two systems similar to the described separator with the same properties. Maintenance on either of the systems requires downtime at the cost of 662.500 [NOK/hr]. They are both subject to CBM, and the P-F interval is more than two months. To be able to perform joint maintenance, they must both be due for maintenance within the same time period. All maintenance tasks require 12 hours of downtime. On each of the systems there are 0,728128 intercepted failure/year. The two systems will require maintenance within the same month 0,06068 times each year, or a total of 0,91016 times over the course of the lifetime of 15 years. We assume that 100 % of the downtime costs are saved on one of the systems. Discounted to NPV, this amounts to a lifetime saving of 4.306.867 [NOK].

Note that this is for just two systems subject to CBM, with just six failure modes each. It also assumes completely random failure.

Chapter 8

Discussion

This thesis has explored some of the concepts and possibilities found in modern maintenance philosophies. Some of them are very new, like Integrated Operations, and some are just the modern version of old concepts. As with many other things in this world, maintenance is in practice an inexact science. As a result, the different theories are targets of subjective opinions. To make matters worse, a good maintenance strategy is defined as a low-cost absence of events. As all things are relative, the absence of reliability events is difficult to satisfactorily document as there, by definition, is nothing to document except costs and production rate, or some other measure of reliability. The potential for improvements are largely hidden. This chapter will discuss this, and other problems related to the concepts presented in this thesis.

8.1 RCM

Reliability-Centered Maintenance (RCM) was developed in the 1960's and 70's in the American aviation industry. It corrected some very serious misconceptions about the very nature of reliability such as the concept that all complex systems have a *right* age where a complete overhaul is necessary. As we now know, this is not at all correct. Most complex systems does not fail at "scheduled times".

As stated, maintenance is a question of economics, where reliability is a decisive factor, while RCM is focused on reliability alone. Almost all modern maintenance strategies are built upon the concepts of RCM. Since RCM is focused on reliability and not economics, it will inevitably influence the quality of the strategies as economically maintenance tools. A user will either strictly follow the concepts, and possibly miss out on potential financial gain, or they will deviate from them and find themselves in the dark.

8.1.1 The ultimate contradiction

One of the biggest problems with RCM is that we know almost nothing about the true properties of expensive and critical equipment, as there are no documentation of them being left running without maintenance[25]. J.Moubray summarizes what he calls "The ultimate contradiction": *Successful preventive maintenance entails preventing the collection of the historical data which we think we need in order to decide what preventive maintenance we ought to be doing.*

The only way to learn about the true properties of equipment is to let them be subject to a corrective maintenance strategy for a long time. Neither users nor supplier are willing to do this because of safety and the high costs that are involved. In practical terms, it is quite easy to know if you are not performing enough preventive maintenance, but it is very difficult to know if you are spending too much time and money.

We are using probability models that are practically impossible to optimize because they require a statistical significant amount of data that simply does not exist. The data that does exist, e.g. the OREDA database, can not be defined as statistically significant for three main reasons:

- The databases does not differentiate between new and old technology.
- The databases generalize equipment too much, in such a way that the differences between variety of different models of the same category is not shown.
- The data comes from equipment that are subject to undefined maintenance strategies.

8.1.2 CBM

Condition based maintenance fixes the weaknesses of periodic and corrective maintenance, while at the same time keeping the strengths. The strength of corrective maintenance is that equipment are allowed to run as long as they perform adequately, and maintenance is only performed after the failure has occurred. The weakness of this is obviously that the equipment *will fail* at some point, which could be both dangerous and costly. CBM does the same thing, except it moves the maintenance to a point in time *before* the specific failure. The weakness of periodic maintenance is that it is based on time and not on failure, which means that it is practically impossible to minimize costs because the maintenance must be performed quite often. Even with a frequent periodic preventive maintenance strategy, functional failures will occur because of the unpredictable nature of failure.

Even though CBM fixes the major issues associated with corrective and periodic preventive maintenance, it has some problems in its own. For one; CBM requires, in most cases, additional equipment, which is costly. In addition, technological problems fixed with technology often creates more problems, and CBM is no exception. The most obvious technical issue is that not all failures will be detected. Not all failures are possible to detect, and of the ones that are detectable, not all *will* be detected. Even though most of the detectable failures will get caught, the 10-20 % that are not could cause a problem. Especially if there is a safety issue. Finally, the undetectable failure modes have to be subject to either corrective or periodic preventive maintenance. This includes failure modes that the user do not know about.

As explained, CBM is a fix to the current problems of maintenance, but it is not a complete fix. In many cases there will be an economical benefit of implementing CBM, including the issues that follows. However, the safety issues could, in many cases, be too steep a price to pay, or at the very least keep users skeptical of CBM.

To remedy the problems related to CBM, it is important to both raise the reliability of the CBM strategy itself, and raise the confidence in the concept.

CBM requires a significant amount of infrastructure in addition to the monitoring hardware itself. The core of the CBM would be a database that requires analysis of data and a user friendly User Interface (UI). All this makes a serious decision to implement CBM, a major investment.

8.1.3 TCI

TCI is a great decision making tool. The amount of data collected in an extensive CBM strategy is very large, and would render the data less usable as the amount increases. This is where TCI shines; it simplifies the data to an extent where decisions are almost pre made based on specific pre-designed rules. However, there are some issues with the TCI concept.

TCI is best suited for components and systems that has a gradual degradation either from the beginning of the asset's life, or from the beginning a failure. Let us imagine a system that includes a critical electronic component. The electronic component is subject to CBM and has a TCI assigned, along with the other components that make up the system. The most common probability property of electronic equipment is that the failures are random. It either works, or it does not. The aggregated TCI of the system could indicate that it is in perfect condition right up to the second the electronic component fails. This does not mean that it holds no value to assign TCI on systems with electronics, the TCI works very well on the gradually deteriorating components of the system. However, it does illustrate how important it is to have knowledge of the systems, and not blindly trust them to last long because the TCI says so. By relying on TCI's, we run the risk of oversimplifying the data and the state of the assets.

Also, T.A. Thorstensen points out the difficulties of interpreting TCI levels: *TCI methodology has revealed difficulties in stating the consequences of a specific index level. This is due to the fact that a single TCI value on a specific level normally consists of several measurements, and is based on rules that have converted the measurements to TCI and aggregated these to the level of interest. The solution has been to focus on trends rather than the absolute figures, and to compare different TCI levels with the real situation on the plant.*

8.2 Integrated Operations

Integrated Operations has been celebrated in the industry as the future of offshore operation. OLF caught the attention of many operators by their promise of an added benefit of 250-300 BNOK, most of which comes from an increase in production of 5-6 %[17]. This number has been brought up, with a slight chuckle, in almost every conversation about IO that the author has had. The report does not satisfactorily provide the data necessary to asses their report, and thus should be put to rest. There is little doubt that there are benefits from IO in production, maintenance and other areas. However, to go from a non-IO to an IO approach is a huge task that requires restructuring on a corporate level. This is an undertaking on such a massive scale that few, if any, companies are willing to "retrofit" IO into their structure.

IO can be implemented step by step, as can be seen from the live video/audio conference rooms that are already in place on some offshore installations. However, as the real benefit of IO is the integration of people and work processes, small scale IO will not reap the benefits that large scale IO offer. It is still uncertain how far into the IO concept operators are willing to go. The offshore industry is, in many ways, a conservative industry, and new ideas take a long time to get accepted.

The main problem with IO, as this thesis has previously indicated, is that the costs associated with IO are significant, while the benefits are somewhat intangible. The concept, Integrated Operations, is frequently mentioned in post 2003 literature while empirical reports on benefits are so close to non-existent that the author of this thesis has failed to find them.

The whole IO concept, in all practical terms, revolves around new technology that only recently has been a realistic part of the offshore industry. IO is a collection of uses of this new technology with cooperation and integration as a common denominator. Many, if not all, of these concepts are good for the industry, but the problem arises when the community tries to overreach itself. To successfully implement IO on the NCS, it is important to do it gradually, or else run the risk of spending money on something that will not get used. An example is to implement a CBM strategy in an IO setting while still holding to the old periodic preventive maintenance and not using the new CBM strategy. This has all the costs and none of the benefits, which is an unnecessary expense.

The biggest risk with IO is that the industry try too hard to utilize the technology without being deliberate about maximizing the level of safety an profit. Leonardo da Vinci said "Simplicity is the ultimate sophistication", and Albert Einstein said "Everything should be made as simple as possible, but not simpler". Extracting hydrocarbons on depths surpassing 2000 metres is no simple task in itself, and the operators should carefully consider how much technology is needed to do this as safely and profitably as possible.

The great thing about IO is that, even though it remains somewhat intangible, it takes an active stance on driving the offshore industry forward, which is necessary as the difficulty in claiming hydrocarbons is, and will continue to be, increasing with both depths and harsh environment.

Chapter 9

Conclusion

It is of the author's opinion that even though Integrated Operations holds significant value, the hype is to some extent a product of the value of IO as a publicity tool. The community should be aware that this is a pitfall, as it could corrupt the cause, which is to further the safety, environmental conscience and profitability of the offshore industry. Publicity is still important as it both communicates the confidence the industry has in its own operation, and it keeps the industry honest. However, the publicity must remain a by-product of the true goals of IO, and not the goal itself.

The following is the author's recommendation to successfully implement IO: An operator that is interested in Integrated Operations should not seek to revise their whole organization, but rather do it one step at the time. Let us assume the company feels like time is ripe for changing the maintenance strategy to a more IO oriented strategy. They should do just that, while ignoring the possibility of real time reservoir management and the other aspects of IO, for the time being. The reason for this is that IO implementation is such a huge transition, that it is important to keep focus. The new strategy should be implemented in such a way that it is ready for future transitions to IO. The new strategy will mature within the company and when the time is right, more IO aspects can be added.

Chapter 10

Further Work

For further work, I suggest performing analyses using real data, with focus on uncovering the value of opportunity maintenance in an IO perspective. I also recommend to look into the consequence, and possibly improvement, of the unreliability of the techniques themselves. This would incorporate logistics, reliability and production management, and could be very interesting.

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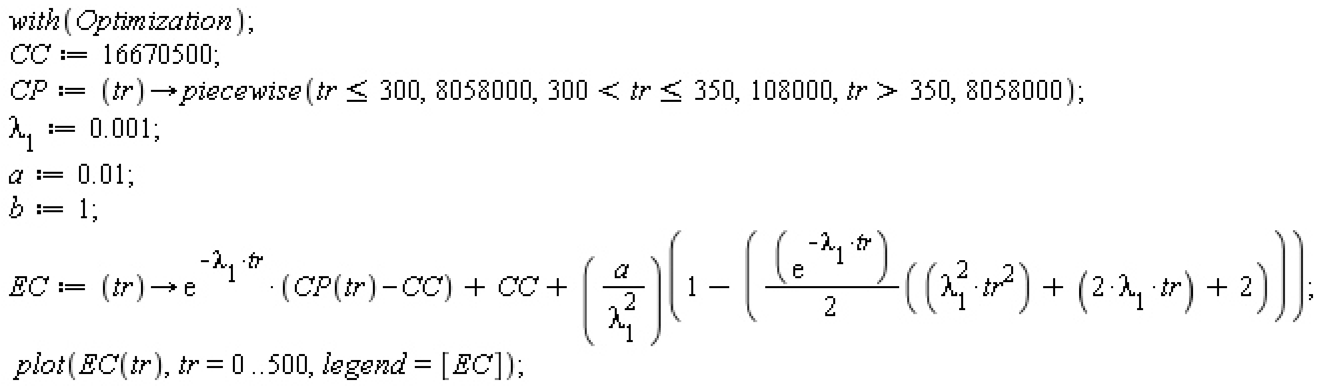
Appendices

Appendix A - Maple Input



$with(Optimization);$

$CC := 16670500;$

$CP := (tr) \rightarrow piecewise(tr \leq 300, 8058000, 300 < tr \leq 350, 108000, tr > 350, 8058000);$

$\lambda_1 := 0.001;$

$a := 0.01;$

$b := 1;$

$$EC := (tr) \rightarrow e^{-\lambda_1 \cdot tr} \cdot (CP(tr) - CC) + CC + \left(\frac{a}{\lambda_1^2}\right)\left(1 - \left(\frac{\left(e^{-\lambda_1 \cdot tr}\right)}{2}\left(\left(\lambda_1^2 \cdot tr^2\right) + \left(2 \cdot \lambda_1 \cdot tr\right) + 2\right)\right)\right);$$

$plot(EC(tr), tr = 0..500, legend = [EC]);$

Appendix B - Selection of CBM strategy