Universitetet
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FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study programme/specialisation: Industrial Economics/ operations and maintenance	Autumn semester, 2019 Open/Confidential
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Title of master's thesis: *Assessing the impact of business model for predictive maintenance scenarios using multimethod simulation: a case study of centrifugal compressor.*

Credits: 30

Keywords: • Predictive maintenance • Simulation modelling • Business model • Opportunistic maintenance • Centrifugal compressor	Number of pages: ………………… + supplemental material/other: ………… Stavanger,………………………. date/year

abstract

The oil and gas industry are an industry with complex and expensive equipment. Downtime from equipment failures can cost companies millions of NOK each day and pose a significant risk to employee safety. Through maintenance and replacement of parts before they fail, companies can ensure that the operation of assets remains safe, efficient, and uninterrupted. This approach can have a decisive effect when it comes to preventing catastrophic failure, costly downtime, and damage to machinery.

The way operators monitor their assets today is by visualizing processed data to rate performance, track historical trends, monitor device health, and make operating system updates to increase overall equipment and the production window between required maintenance. Most assets today are equipped with sensors, but the question is how can companies exploit the endless amount of information from sensors located on platforms and equipment? There is a gap between how the industry operates today relative to the great opportunities that exist by digitizing maintenance systems. How can they be utilized to do a better job, or improve the safety of those working on the installations? The sensors which are already installed gathers data, but it is not used for more than just checking for anomalies and trends. The key lies in being able to utilize the data from the sensors to enrich and automate the decision-making.

If the sensors are used proactively, there is a lot to gain from predictive maintenance. This can make it possible to predict failures of assets before they fail. There is also a lot to save from not replacing equipment when the warranty or the OEM says so, but only when needed, based on sensors and historical data. There are cost implications associated with implementing a whole new system. Any capital equipment is purchased and installed to generate productive output for a defined period. The cost of implementing predictive maintenance contains of two parts – the fixed or acquisition cost, which includes the cost of the machine and systems itself and the commissioning cost. The second part is the cost of running the machine. Due to these cost of implementing new maintenance system, companies use simulations models to assess the impact of changing the business models or maintenance policies.

By using a simulation software, a generic business model for PDM services with different stakeholders can simulated. The case study in this thesis is a gas processing plant that export gas to Europa and the asset of interest is a centrifugal compressor. The model will assess the current condition monitoring and maintenance system and

The study revealed the potential for implementing a predictive maintenance where the predicted failures can be done at the same time as the scheduled maintenance. 8 out of 10 failures could be predicted resulting in over 90% availability for the equipment.

When the current check-based monitoring was compared to the alarm-based monitoring system, the time spent on checking went considerably down. Time spent on checking with the alarm-based monitoring system is just 12 hours compared to 182.5 hours a 93.5% decrease in checking time.

The traditional maintenance system that are used now needs to be redeveloped, and the stakeholders must be willing to implement new technology as implementation of new technology is far wider than just the technology.

ACKNOWLEDGEMENT

I would first like to thank my thesis advisor associate professor Idriss El Thalji of the Faculty of Science and Technology at the university of Stavanger. The door to Prof. El Thalji office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work but steered me in the right the direction whenever he thought I needed it.

I would also like to thank Helge Nordal which had the role of an experts involved in the validation of the model for this research project and : Without his passionate participation and input, the validation and verification of the model could not have been successfully conducted.

I would also thank my family for their continuous support and help throughout the semester. They have aided and backed me during the years of study and during the research and writing of this thesis. It would not have accomplished this without them.

Contents

List of figures

List of Tables

1. Introduction

This chapter describes the background of the studied field, problem description, scope, and objectives. It also presents the limitations and delimitations.

1.1 background and Problem description

Maintenance of equipment are crucial for all industries and is part of business models for all organizations. However, oil and gas industry should be given more priority sector because of the high operating cost and the complexity of equipment.

In today’s industry with complex infrastructure poor maintenance strategies can reduce a plant's overall production capacity by between 5 and 20 percent.

Chris Coleman Satish Damodaran Mahesh Chandramouli (Coleman, satish, Mahesh , & Ed , 2017)Ed Deuel

Key findings from a research conducted by Baker Hughes showed that

- “Offshore oil and gas organizations experience on average $38 million annually in financial impacts due to unplanned downtime. For the worst performers, the negative financial impact can be upwards of $88 million.
- Fewer than 24% of operators describe their maintenance approach as a predictive one based on data and analytics. Over three-quarters either take a reactive or time-based approach.
- Operators using a predictive, data-based approach experience 36% less unplanned downtime than those with a reactive approach. This can result in, on average, $34 million dropping to the bottom line annually” (hughes, 2017)

Most of these unplanned downtimes is caused by difficulties in determining when and how often an asset fails and when it should be taken offline to be repaired. The oil industry has traditionally used old-fashioned types of maintenance systems, where the most widely used maintenance methodologies have been reactive or preventive maintenance. (Coleman, satish, Mahesh , & Ed , 2017)

One of the maintenance system that have gained increased attention is Predictive maintenance, both from the industry and in academia.

The goal of a predictive maintenance strategy is to extend the effective life of the equipment and prevent failure. Deviation detection is a common approach because it detects when an equipment behaves differently than expected. Non-conformance detection solutions are often more accurate than simple rule-based methods of failure detection and are useful in preventing costly failures and downtime.

The oil and gas industry were initially reluctant to adopt new technologies with particularly no long-term track record in the industry. It was either too expensive or they were happy with the existing maintenance systems. This has however changed in the few past years with O&G industry digitalising more of their maintenance programs. (Boman, 2017)

There are two main reasons why new maintenance systems and technologies are becoming more and more accepted by the oil and gas industry. The first reason is the decline in oil and gas prices that in the industry which have caused significant operating deficits for owners and stakeholders. The oil and gas companies realised it was important to reduce operating costs. The second reason is that many of the equipment that are currently being used is getting old. To let them fail before fixing them, will eventually become very expensive as failures of the equipment increases with age. These two factors, awareness of expenditure related to outdated maintenance management and aging equipment, can push new technologies to be more accepted in the oil and gas industry. The benefits of the new technologies are reduced cost of maintenance and the ability to monitor old equipment that. This, together with the new wave of digitalization around the globe in general, means that the potential for new ways of doing maintenance have great potential. The maintenance of companies' assets cost large amount of money but also creates enormous revenue by reducing the downtime. The way of doing maintenance has changed a lot over the years and demands of the end-users have increased concerning functionality, content, and price. As a result, the costs related to development and operation of these system are very high. To justify the price, it is essential that the system become successful, easy for in-house personnel to use and it contributes to increased availability of the equipment.

Developing a business case for predictive maintenance is something that is important for companies. The most important question that all companies need to be able to answer before they even start predictive maintenance is, how will I generate revenue from this?

If this question cannot be answered, all efforts to build an elaborate, predictive maintenance solution will quickly stop. Knowing the business case of the company and having a strategy for making money on predictive maintenance will help to convince the company's management and stakeholders to justify the investment in implementing a predictive maintenance system. (Wallner, 2019)

Although equipment operators know the fact that their equipment is less likely to fail during operation typically justifies the investment, the case for owners and other is a bit more challenging.

This is some of the reason why oil and gas companies has not yet fully embraced the Predictive maintenance(PDM). Many PDM programs that have been implemented across the oil and gas industry has failed to generate measurable benefits in terms of decrease in maintenance cost or given any measurable plant performance improvements.

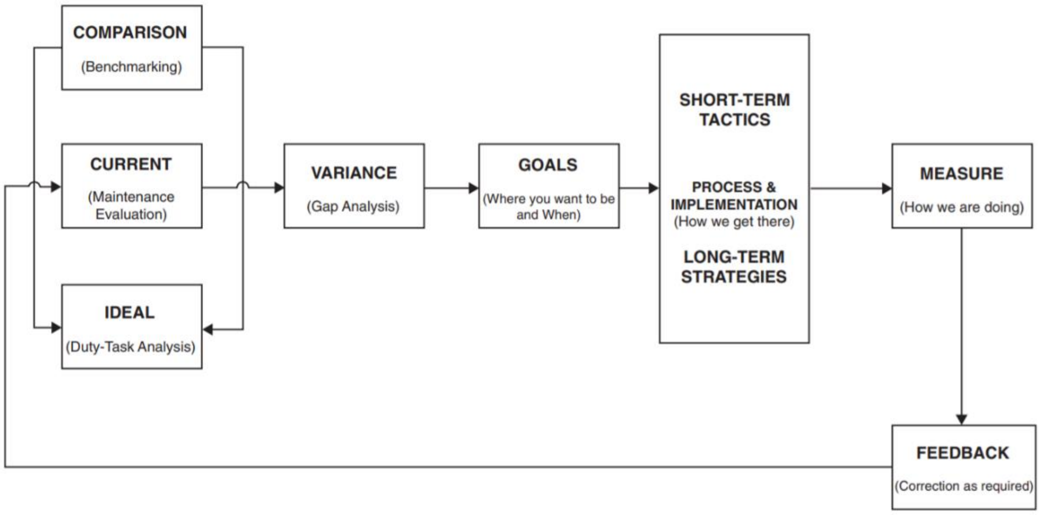

Figure 1: business improvement process. (Mobley, 2002)

One approach to this challenge is a business improvement process to convince reluctant stakeholders. A maintenance organization should start by measuring its own performance. For example, by reviewing the current maintenance systems and policies. Benchmark comparisons with similar organizations provide a basis for analysing performance on both metrics and processes. The third step in goal setting is to identify realistic ideal performance levels. These objectives should have the following characteristics:

- written
- measurable
- understandable
- achievable

The stakeholders who will be challenged to reach the goal should be part of the process. Failure to secure the right kind of involvement from the people affected by the decision can lead to some unpleasant consequences during implementation. Once the goals are set, one can identify any gaps between where performance is now and where it should be. Then both short-term plans and long-term strategies can be implemented to achieve these defined goals. Frequent measures and feedback will revise the performance to achieve the desired levels. (Mobley, 2002)

1.2 Scope and Objectives

The scope of this thesis is to develop a simulation model, that will assess the current maintenance and monitoring system in a centrifugal compressor. The base for this study is a case study from a gas exporting plant. The thesis presents the development of a model in order to understand the system chosen and how. The main objectives of the developed model is to simulate a generic business model for predictive maintenance service.

The research question is formulated as follows:

Assessing the impact of business model for predictive maintenance scenarios using multimethod simulation: a case study of centrifugal compressor.

1.3 Research methodology

The research methodology in this thesis is going to be a theoretical part and practical part where the main objective is to simulate maintenance system in a gas plant. The theoretical part is based on academic literature, industry standards, journals, and interview with an expert.

The main objectives of this Research:

1. A literature review in the field of maintenance strategies and maintenance management.
2. An insight in challenges faced by the industry.
3. Model development using multimethod simulation modelling tool.
4. Evaluation of the developed models.

1.4 Limitations/delimitations

There was time limit on this thesis set by the rules and regulations of the university of Stavanger. The given time frame for working on and finishing the thesis during the fall is from 1st of September to 2nd of January.

Delimitation of this thesis:

- This thesis is not going into technical details of the asset.
- There were no companies involved providing with information, assumptions hade to be made.
- Some uncertainties with the program, there are aleatory uncertainties meaning that the model with, and uncertainty related to the software itself.

1.5 Outline of the thesis

- Chapter 1 an introductory chapter describes the background of the studied field, problem description, scope, and objectives. It also presents the limitations and delimitations.
- Chapter 2 presents the theoretical framework related to the maintenance of assets. This includes preventive maintenance, preventive maintenance, and predictive maintenance. This chapter also outlines the asset management and the consequences of poor maintenance.
- Chapter 3 present the steps that the author followed when developing the model and executing the simulation.
- Chapter 4 presents system analysis of the chosen system. It presents the stakeholders, their requirements and needs.
- Chapter 5 describes the maintenance systems and the monitoring system of the asset studied, this described helped to develop the model. This chapter also deals with data collection.
- Chapter 6 presents the development of the model and descriptions of variables, parameters and functions.
- Chapter 7 is all about the outputs of the model. How predictive maintenance and alarm-based maintenance can be used is explained in this chapter.
- Chapter 8 presents discussion about the simulation conducted and the thesis. Finally, a conclusion drawn on regards to the thesis objectives and the formulated research question in chapter 1.

2.0 Theoretical framework

2.1 Maintenance

This presents the theoretical framework related to the maintenance of assets. This includes preventive maintenance, preventive maintenance, and predictive maintenance. This chapter also outlines the asset management and the consequences of poor maintenance.

Maintenance is the work performed to preserve an asset (such as a compressor or a turbine), to enable continued use and function, over a minimum acceptable level of performance, over its designated lifetime, without unforeseen renewal or major repair activities. (Albrice , 2016)

Maintenance is a combination of everything technical, administrative, and managerial actions during life cycle of an item intended to hold it or restore it to one condition where it can perform the required function. In the past, maintenance was intended as an expense account which managers did not care for except when it was absolute necessary. Fortunately, this perception is changing. Nowadays, Maintenance is recognized as an essential contributor to performance and profitability for business organizations. Maintenance managers, therefore, explore all possibilities to boost profitability and performance, as well as achieve cost savings for the organization. Figure 2 identifies the different type of maintenance managements. The maintenance organization is tasked with a broad number of challenges including quality improvement, set up time, reduced lead times, cost reductions, capacity expansion, management of complex technology and innovation, improve the reliability of systems, and related environmental issues. (Wan hazrulnizzzam, mohd nizzam, Mazli, & Deros, 2009)

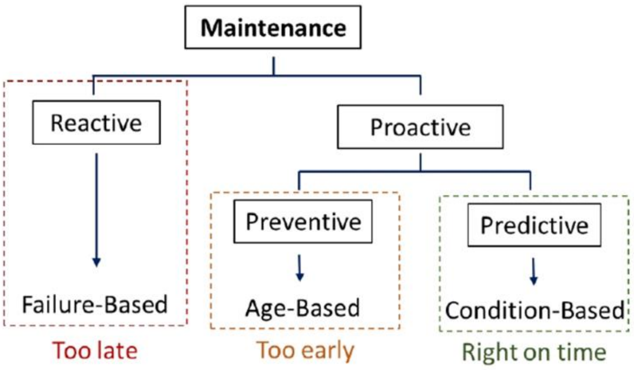

Figure 2: different maintenance managements (BREE, 2019)

Reasons for maintenance

- Physical integrity: to keep the asset in a good working condition and minimize the downtimes and disruptions.

- Risk management: to keep the asset in good in a state of good repair for the operator's own safety and health
- Responsible ownership: to keep the asset in good state so it can achieve its full potential life service.
- Duty to mitigate: to keep the asset from unnecessary damage that can result in the assets premature failure. (Albrice , 2016)

2.2 Reactive maintenance (Corrective)

Reactive maintenance also called corrective follows a simple logic which is 'drive it until it breaks.' No efforts or efforts are made to maintain the equipment initially designed by the designer to ensure the design's service life. Recent studies indicate that this is still the dominant mode of maintenance. The advantages of collapse maintenance be a two-sided sword. If we are dealing with new equipment, we can expect minimal incidents of failure. If our maintenance program is purely reactive, we will not use labour or incur capital costs until something breaks. Since we do not see any associated maintenance costs, we can see this period as saving money. During the time we think we are saving maintenance and capital costs; we spend more money than we would have had under any other maintenance approach. We spend more money on capital costs because, while we wait for the equipment to break, we shorten the life of the equipment and result in more frequent replacement. We may incur costs of failure of the primary device associated with the fault and causing the failure of a secondary device. It is an increased cost we would not have experienced if our maintenance program were more proactive. Our labour costs associated with repairs are likely to be higher than usual because the failure is likely to require more extensive maintenance than it would require had the equipment not been run to failure. The chances are that the equipment will fail within hours or near the end of the typical working day. If it is a critical device that must be back online quickly, we will have to pay overtime costs for maintenance. Since we expect to run equipment to failure, we will require a large inventory of repair parts. This is a cost that we can minimize under another maintenance strategy. (Singhal, 2018)

2.3 Preventive Maintenance

What is meant by preventive maintenance?

According to the professional's guide to maintenance and reliability terminology preventive maintenance is *"an equipment maintenance strategy based on replacing, or restoring, an asset at a fixed interval regardless of its condition.* Scheduled restoration tasks and replacement tasks are examples of preventive maintenance tasks. » (Gulati, Kahn , & Baldwin, 2010) retrieved from (Ramesh Gulati, 2019)

Preventive maintenance is a type of maintenance done at regular intervals while the equipment is still functioning to prevent failure or reduce the likelihood of failure. Preventative maintenance can be time-based, ie, every week, every month, or every three months. However, preventative maintenance is often based on use e.g., every 150 cycles, every 10,000 hours or like cars: service every 10,000 km.
This type of maintenance is a means of increasing the reliability of their equipment. By using only, the resources necessary to perform maintenance activities designed by the equipment designer, the life of the equipment is extended, and reliability is increased. (Hupjé, 2018)

2.4 Predictive maintenance

Predictive maintenance has been given many definitions. Some say that predictive maintenance is monitoring the vibration of rotating machinery to detect initial failures and to prevent that detected problems into catastrophic failure. Others say it is to detect developing failures in motors, electrical switchgear by monitoring the infrared image of the components. So, what is predictive maintenance? Predictive maintenance (PdM) is a concept, which is applied to optimize asset maintenance plans through the prediction of asset failures with data-driven techniques. instead of relying on statistics from industrial or in plant average life like mean-time-to-failure to schedule maintenance activities, predictive uses direct monitoring of the asset's condition, system efficiency and other indicators to tell the actual mean time to failure for the asset.

Basically, predictive maintenance differs from preventive maintenance by basing maintenance on the actual state of the machine rather than on any present schedule. Preventive maintenance is time-based. Activities such as changing lubricants are based on time, such as calendar time or equipment run time. For example, most of the oil in the vehicles changes every 3,000 to 5,000 miles. This effectively bases the oil change requirement on the equipment running time. No concern is given to the actual condition and performance of the oil. It is changed because it is time to change. This methodology will be analogous to a preventative maintenance task. If, on the other hand, the driver discounted the vehicle's running time and had analysed the oil for a certain period to determine its actual condition and lubrication characteristics, it may be possible to extend the oil change until the vehicle had run 10,000 miles. This is the fundamental difference between predictive maintenance and preventive maintenance, where predictive maintenance is used to define the required maintenance task based on quantified material/equipment conditions. There are many benefits to predictive maintenance. A well-orchestrated predictive maintenance program will eliminate catastrophic equipment failures. A plan for maintenance activities can be made to minimize or erase overtime costs. It is possible to minimize inventory and order parts as needed well in advance of downstream maintenance needs and optimize equipment operation, save energy costs, and increase plant reliability. (Singhal, 2018)

2.5 Maintenance mix

There is great difference in maintenance strategies in different industries. Some of them have equipment that cannot be repaired so often, or their equipment runs into failure without being costly for organizations. While some other organizations have equipment's that that is too important for their operations and business to fail. Consequently, these organizations spend large amount of money on predictive and preventive maintenance. The majority organizations have mixture of the all three maintenance strategies.

The maintenance manager must consider the cost when they are choosing the best strategy. Figure 3 illustrates how the cost for the different strategies is connected. It shows that predictive maintenance has the highest maintenance cost, but the repair cost is lower. Corrective maintenance has lower cost; however, the repairs cost is much higher compared to the preventive maintenance. (Albrice , 2016)

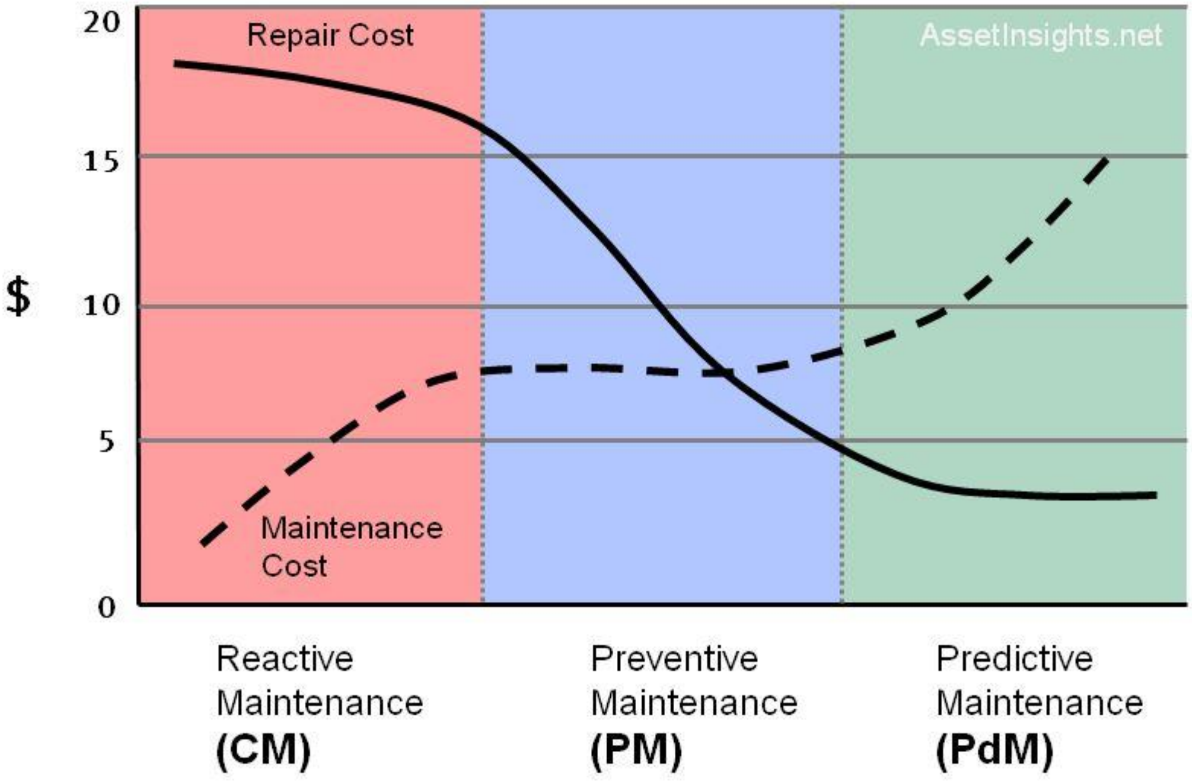

Figure 3: comparison the cost of different maintenance systems (Albrice , 2016)

2.6 Maintenance Cost

Maintenance costs are a large part of the total operating expenses for all production or production plant. Depending on the specific industry, maintenance costs can be between 15 and 60 percent of the cost of manufactured goods. For example, in food-related industries, average maintenance costs account for about 15 percent of cost goods produced, while maintenance costs for iron and steel, pulp and paper, and other heavy industries represent up to 60 percent of total production costs. These percentages can be misleading. In most US plants, maintenance reported includes expenses for many non-maintenance related fees. For example, many plants include modifications to existing capital-driven capital systems factors, such as new products. These expenses are not maintained and should be allocated at non-maintenance costs.

However, correct maintenance costs are significantly and represents a short-term improvement that can directly affect the plant profitability. Recent studies on the effectiveness of maintenance management indicate that a third – 33 cents out of every dollar - of all maintenance costs are wasted because of unnecessary or improper maintenance. When considering the US industry spending more than $ 200 billion each year on plant and plant maintenance, the effect of productivity and profit represented by the maintenance operation becomes evident. The result of ineffective maintenance management represents a loss of more than $ 60 billion every year. Perhaps more important is the fact that inefficient maintenance management significantly affects the ability to produce quality products that are competitive in the world market. Losses of production time and product quality as a result of poor or inadequate maintenance management dramatic impact on US industries' ability to compete with Japan and other countries. (Mobley, 2002, s. 1)

2.7 Asset management

In the developed countries there is broad agreement that the essential service is preserved, environment is protected, and the safety of the people is safeguarded. This has led to wide range of regulations and laws to be enacted by governments in these countries. In addition to these factors some equipment cannot fail due to its importance for the production process for the organization. The compressor examined in this case, is of this art, if it fails it will result in shutdown of the entire plant. Defects, scrap, and inefficient use of material will lead to sources of pollution and failures.

These thing are often the result of plants operating under less than optimal conditions. Breakdown of mission-critical equipment will interrupt production. In chemical production processes, a common cause of contamination is the waste material produced during the start-up period after the interruptions of production. Apart from providing waste material, catastrophic faults in plant and machinery operations are also a significant cause of not reaching the essential service level, industrial accidents, and health hazards. Asset management is all about keeping facilities in optimal conditions while at the same time preventing critical failures. This will promote effective means of managing service interruptions, pollutions risk and accidents.

The way to meet the issues raised above, is to focus on the importance of asset management. This can be achieved if there are clear strategy, the right system and people are used and controlled work through planning, scheduling process, process engineering and optimization. (Jardine & Albert Tsang, 2006)

2.8 Maintenance Excellence

Plant engineering & maintenance magazine conducted a survey where it was suggested that the maintenance budgets ranged from 2 to 90 % for the total plant operating budget with the average maintenance budget being 20.8. It can be justified that operations and maintenance represent an important cost expense in equipment-intensive industrial operations. But by making the right and opportune maintenance decisions these operations can achieve serious cost savings in operations and maintenance (O&M). Maintenance management excellence is when many things are done well. These things are:

- The plant is working and performing to the designated standards and the equipment is operating smoothly when it is functioning.
- The cost of maintenance of equipment are within budget and the investment of new asset is seen as economically reasonable
- The service levels of equipment and plant are high.
- The Turnover of maintenance, repair and operation materials is fast

The most essential part of Asset management is to focus on balancing risk, performance and the resources that are put in to achieve optimal asset management. (Jardine & Albert Tsang, 2006, ss. 3-4)

3.1 Modelling and simulation methodology.

The goal of this chapter is to present the steps that the author followed in building the model and simulate the dynamic behavior.

Modelling and simulation (M&S) are the use of models (e.g., physical, mathematical, or logical representation of a system, entity, phenomenon, or process) as a basis for simulations to develop data utilized for managerial or technical decision making.

Several modelling methods are described in order to ask which tasks are expected and the input / sources and resources to target. It should lead to the end of a simple project plan. According to john harts there are to rules for good modelling:

- "Clearly define the question to be answered with the model,
- and make the model no more complex than necessary to answer the question" (El-Thalji, 2019)

The simulation software used in this thesis is Anylogic. It supports agent-based, discrete event, and system dynamics simulation methodologies. Figure 4 displays the difference between the various simulation methodologies.

Agent based modelling: "Agent based modelling focuses on the individual active components of a system".

With agent-based modelling, agents also known as active entities are identified and their behavior defined. They can be people, households, vehicles, equipment, products, or companies, what is relevant to the system. The connection of these agent is den set, environment variables defined, and simulations run. The system's global dynamics then emerge from the interaction of the many individual behaviours. (El-Thalji, 2019)

State charts is most used in agent-based modelling to define the behaviours of the agents. They are also often used in discrete event modelling, e.g. to simulate machine failure.

System dynamics: a method which allows the user to study the dynamic behavior of a casually structured system with feedback loops and consequently lack of equilibrium in the system.

System dynamics is a very abstract modelling method. It ignores the fine details of a system, such as the individual characteristics of people, products, or events, and provides a general representation of a complex system. These abstract simulation models can be used for long-term, strategic modelling and simulation. Stock & Flow Diagrams are used for System Dynamics modelling. (El-Thalji, 2019)

Discrete event modelling: This is a methodology which the system would be considered as a process, which contains a sequence of operations.

Discrete event simulation focuses on the processes of a system with a medium abstraction level. Specific physical details, such as car geometry or train acceleration, are not represented. Industry, logistics and healthcare often uses discrete event simulation.

Anylogic describes nicely how discrete events is used: "*Using discrete modelling of event simulation, the movement of a train from point A to point B is modelled with two events, namely a departure and an arrival.*" (El-Thalji, 2019)

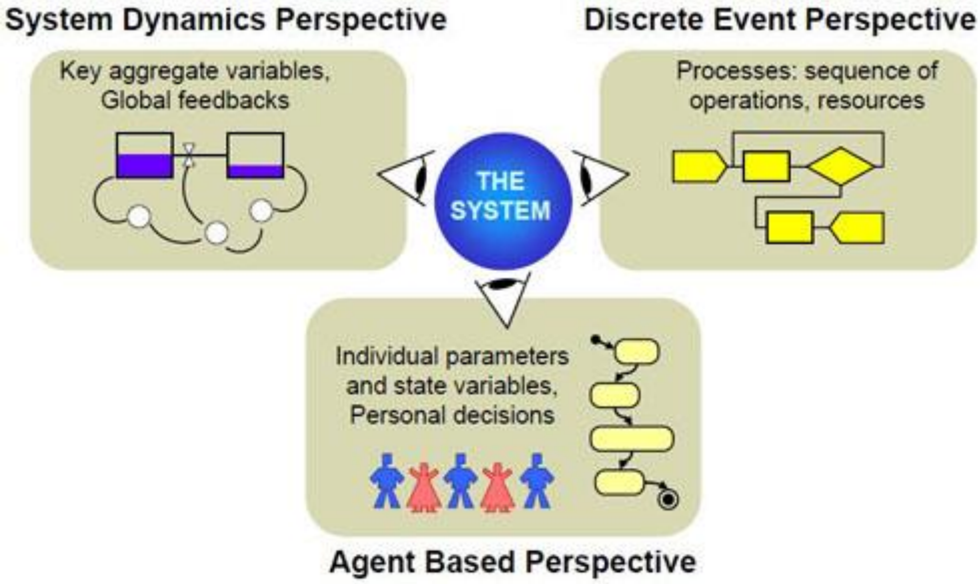

Figure 4:the different simulation methods

Table 1: Methodologies for building models

Randers	Forrester	Sternman
11. Conceptualise	1. system description	1. problem articulation
2. Formulate	2. quantify (converting the description into level and rate equations)	2. dynamic hypothesis 3. formulate
3. Simulate and test	3. simulate	4. Simulate
	4. design alternative policies and structure	
	5. debate and educate	5. policy formulation and policy
4. implement	6. implement changes in policies and structure	

There are differences in the methodologies, but all the basic steps are the same. These steps are important in all methodologies; the conceptualising of the problem, the simulation of the model, testing and implementing. Concept phase is the system analysis and architecting the model structure and interfaces. The next part is formulation which deals with preparing the computational model and its inputs. Simulation and testing include the running the reference and alternative scenarios so the model structure can be verified and validated. The last step is the implementation. This is the step where the solution is implemented if the model gives adequate and satisfying results. The different steps are presented in figure 5.

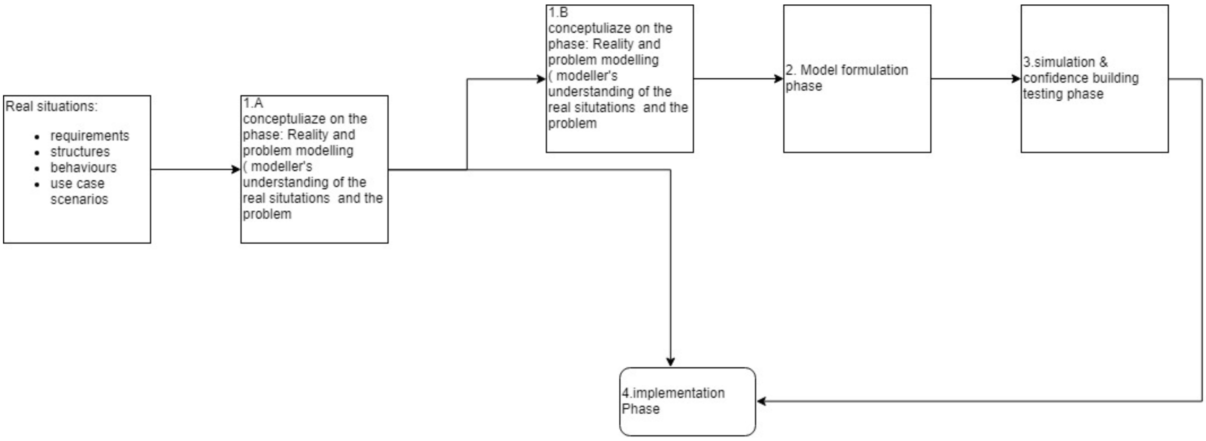

Figure 5: implementation of the models

However, in this thesis these 4 steps are going to be subdivided into 5 steps as shown in figure 6 so the reader may get a clearer picture of the process.

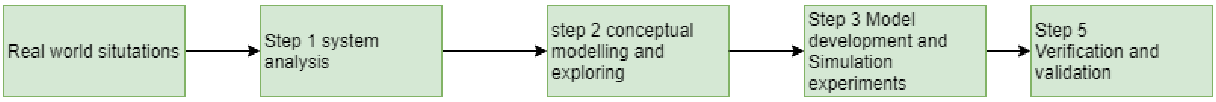

Figure 6: 5 steps of implementing the models((El-Thalji, 2019))

3.2 System Analysis

As it was mentioned in chapter 3.1, simulations are used to:

- Understand behaviours
- evaluate different behaviours
- compare different behaviours and optimise design or different management scenario
- predict the impacts of interventions, changes in design and operating policy.

Thus, it is very important to understand the challenges/problem that simulations are going to deal with. The problem highlighted in this thesis were discussed with an expert and the supervisor of this thesis. Additional research was done in order to fully understand the challenges the industry faced. After the challenges faced are highlighted and become clearer, then the system going to be modelled or needs to be understood.

3.3 Conceptual modelling

The conceptual model sections deal with everything that has to do with Industrial asset that are going to be modelled and their productions and maintenance operations. In this modelling the following issues are required:

1. Define all spaces, layouts (production facilitates), sites (Gas processing plant), networks (agents) and routes which is the productions processes and maintenance services.
2. Modell all processes related to maintenance services and equipment failure.
3. Define what model is going to predict, which in this thesis is to see if
4. Identify the key stakeholders who have interest for your scenario and would use the scenario.
5. Then the inter-linkages should be determined and relationships that will affect the system
6. Identify key uncertainties

3.4Model development and simulation experiments

This chapter describes how scenario modelling can help to develop an understand of the system behaviour, influencing factors and uncertainties. It shall help to explain or interpret observations and real measurements. It started with a hypothesis that were to be evaluated. The hypothesis in this thesis was to see if a predictive maintenance can be implemented on a gas exporting plant. The modelling tools chosen were Anylogic and the simulation method to be a combination of agent based and system dynamics. The goals where then defined and independent and dependent variables where identified. Within the model deterministic values were assigned for the variables and required parameters assigned for the entities that are defined. They are well defined and explained in tables in chapter 6. Properties of chosen design are validated through interview with an expert. In the model the expected model outcomes (model purpose) are linked with specific functions. Maintenance events, events/ failures, cost per hours and if there are spare part cost are linked to the outcomes. After these requirements were fulfilled the experiment was conducted.

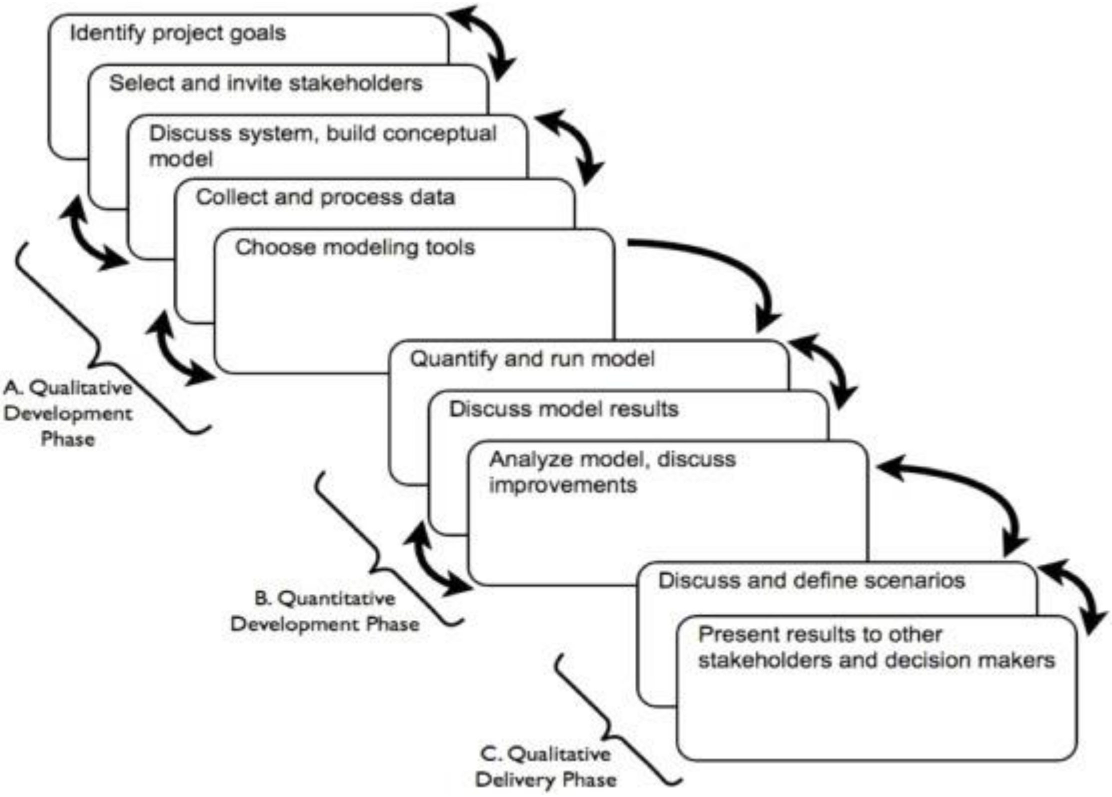

Figure 7: designing an experiment (El-Thalji, 2019)

Table 2:intervention types

Intervention type	Potential effects	Illustrations method
Operating or maintenance policy	Changes in the process of interest (Pol). Pol includes process sequences, process interfaces. The policy of interest may be modelled.	Functional diagram or sequential diagram
Technology integration	Technology of interest (Toi) may be modelled in addition to system of interest (SoI) and the links between SoI and ToI	N2 diagram or IDEF diagram
Design concepts/configurations	System of interest changes that can could be spatial space, asset deterioration process, physical interfaces. Design of interest (DoI) can be modelled.	IDEF diagram and N2 diagram

3.5 Verification and Validation

Verification and validation of data simulation models is carried out during the development of a simulation model with the goal of creating an accurate and reliable model. [1] [2] according to Sargent *" a Simulation models are increasingly used to solve problems and help make decisions. The developers and users of these models, the makers who use information derived from the results of these models, and the people affected by decisions based on such models, everyone is rightly concerned about whether a model and its results are "correct.* (Sargent, 2011)

This concern is addressed through confirmation and validation of the simulation model.

Simulations models never mimic the real system, they are just approximate imitations of the real world meaning a model should be verified and validated to a degree that fulfil some standards requirements. How the system analysis, conceptual modelling, scenario modelling and verification and validation model linked is shown figure 8. (El-Thalji, 2019)

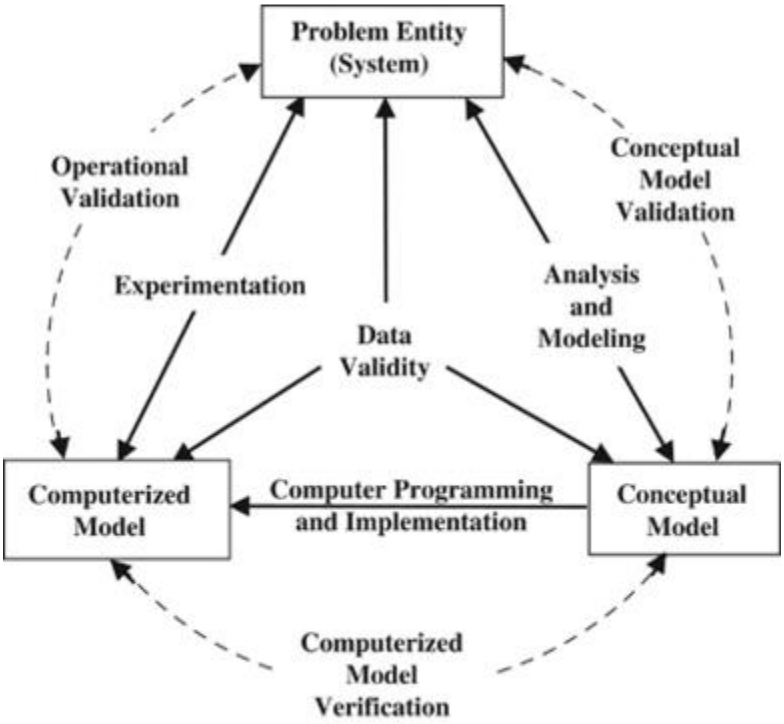

Figure 8: Verification and validation circle (El-Thalji, 2019)

The decision methods to determine if a simulation model is valid used in this thesis are:

1. The results of the various test and evaluations performed as part of the model developed process are validated by the developer itself.
2. The second way of validating was to let an expert which knowledge about the real-world scenarios that where model decide the validity of the model. This approach is useful when the size of the team that develops the simulation is small.
3. The third approach that were used is the independent verification and validation (IV &V) method, where the main objective is to use a third independent party to decide whether a simulation is valid or not. A fellow Anylogic modeler where asked to look over the model itself and checked that the state chart and codes were used correctly.

4.0 System Analysis

This chapter presents system analysis of the chosen system. It presents the case company, stakeholders, their requirements and needs.

4.1 Case company

In this thesis the case company that are going to be studied is the processing gas plant. The processing plant is in county in western Norway, was operational in 2007. It was originally built as onshore facility for processing and exporting gas extracted by pipeline from a field in the Norwegian Sea. After extensive upgrading, the plant can now process gas from other Norwegian fields bound into the polar-line pipeline. The facilities export capacity is currently 84 million standard cubic meters of gas per day. The plant is owned by the joint venture, has technical service provider and an operator.

4.2 stakeholder and business needs

There are multiple stakeholders involved in this system. There are the owners of the facility, the operator, and the Technical service provider (TPS). All these stakeholders have different needs and requirements to the maintenance system in place and the maintenance that are going to be suggested. That means they must be consulted, and they should have a say when implementing new system since they are the one who is going to use the product. In this thesis the requirement and needs have been provided by an expert who is affiliated with the case company.

Most of gas plants in Norway is joint ventures who owns the transportation infrastructure and all the equipment’s in the facilities. The main concern for the owners is increased profit. The operator is responsible for the facility to work without interruptions while the technical service provider is responsible for the facility’s daily operation and maintenance.

The associated needs and requirements from the mentioned stakeholders are summarised thoroughly in table 3.

Table 3: stakeholder analysis

Stakeholder	Needs	Requirements	Criteria
Inspectors	Easily accessible, equipment, good visibility	Equipment ready for operations, System update data frequently, can store data	Stability, reliability
Monitoring crew	Monitoring system, acceptable values, correct values	Equipment will be able to detect minor damages, show deviation quickly to monitoring crew	Easy to use, Sensitivity, reliability
CMS Provider	Communication with inspectors and monitoring, equipment, correct values from the monitoring crew	Reliable equipment, can detect and analyse values quickly	Reliability, Accuracy
maintenance team	Dependent on information from the on-site maintenance crew and/or fabricator of the component they are doing maintenance on.	Excellent communication source between on-site and hired maintenance team, avoid component replacement during full production	HSE (Health, Safety and Environment), reliable communication
Operator	A reliable system that meets the criteria of the clients that relies on gas from the facility.	Fulfil the production order from power company, profitability, follow the regulations	Cost effective, reliability
Owners	More profit	Less downtime	Maximizing possible profit

N2 diagram below illustrates the interfaces between production, asset and maintenance services and the owner and CMS provider.

Figure 9: N2 diagram describing the interface between different parts in the system analysed.

Owner					output
	Operator/production	Load			profit
Performance	Failure /losses	Asset	Notifications	real-time data management	opportunistic maintenance
Reliable production	Minimise unnecessary downtime	Health recovery/replace	Maintenance service	Predictive maintenance	Service time used
Reliable software				CMS provider	Alarm trigger

5.0 Conceptual modelling

5.1 The asset of interest: Centrifugal Compressor

The fundamental purpose of our compressor is to enable the operator to sell gas to consumers. The compressor train receives first rich gas from one of the connected offshore facilities which it separates. It separates into lighter hydrocarbons and heavy hydrocarbons. The lighter hydrocarbons are sold to the costumers. Then, the sales gas is fed to the centrifugal compressor that compresses it from 62 barg to 185 barg by dynamically increasing its velocity, which enables transporting the sales gas through the Langeled subsea pipeline and to its end-users in the UK.

The thesis is not going to delve into technical details of the compressor but focus more on maintenance management. The purpose of the thesis is to:

When processing, storing, and transporting gas it is often necessary to increase the pressure of the gas in the oil and gas industry. To compress gas, there are two different principals are used. The two principals are intermittent or discontinuous flow mode and the continuous flow mode. The continuous flow mode is related to dynamic and the ejector compressors while the intermittent flow mode is related positive displacement compressors. The figure 10 shows the classification of compressors. (Massala, 2018)

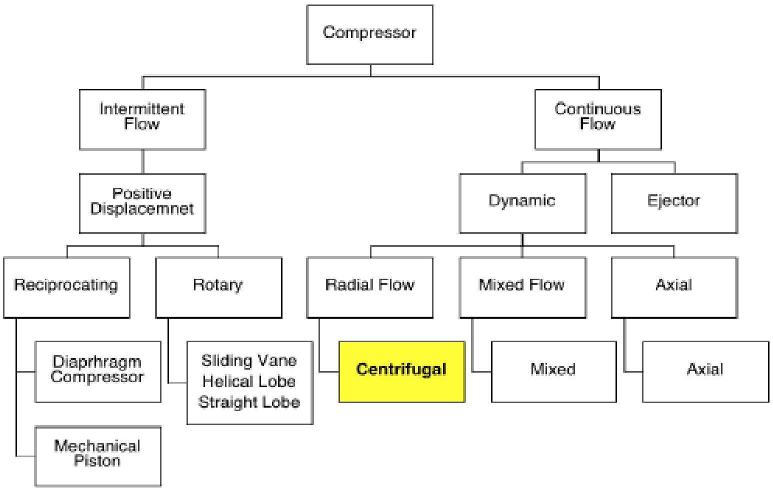

Figure 10:classification of compressor (Massala, 2018)

The centrifugal compressor became popular in the 1950 and 1960 because of its efficiency and lower maintenance compared to the reciprocating compressor the most used compressor until 1960. The centrifugal is these days used as the main compressor in the pipeline and process industries. The main reason for using the centrifugal compressor is the advantages like compactness, lightweight and low energy consumptions. A centrifugal compressor has fewer wearing parts, resulting in lower operating costs in terms of replacement parts, repairs, and downtime. (Massala, 2018)

The fundamental purpose of the centrifugal compressor is to enable the operator to sell gas to consumers. The compressor train receives first rich gas from one of the connected offshore facilities which it separates. It separates into lighter hydrocarbons and heavy hydrocarbons. The lighter hydrocarbons are sold to the costumers. Then, the sales gas is fed to the centrifugal compressor that compresses it from 62 barg to 185 barg by dynamically increasing its velocity, which enables transporting the sales gas through the Langeled subsea pipeline and to its end-users in the UK.

The thesis will not delve into technical details of the compressor, but focus more on maintenance management and maintenance cost can be reduced using PDM and by using predicted failures implement opportunistic maintenance, review and calculate time used on checking and propose a se if the model can be used to enhance the monitoring system. All these thing if done correctly have a positive impact on the operation of the facility.

5.1.1 Data collection

The collection of data in this thesis is based on interview, values derived from scientific books and some assumptions made by the author. In this thesis a face-to-face interview where conducted, where the interviewer asked a series of questions to the interviewee in person and through telephone and noted down the responses. This form of data collection is suitable when there are only a few respondents. Information on how the facility is operated and monitoring and maintenance management is provided by an expert.

The repair times and failure times are derived from the books gas and oil reliability engineering modelling an analysis by Eduardo Calixto and Oreda offshore and Onshore reliability Data. Mean maintenance and replace time for different components where provided by an expert affiliated with a gas processing plant.

The cost of repair, maintenance and cost of working crew are assumed based on typical cost estimation in the industry. These data are sensitive for their operation and considered a trade secret making it difficult to obtain them from the case company.

It was difficult to estimate daily revenue, service crew cost, replacement cost, repair cost and maintenance cost of the asset. Specially the daily revenue was complicated since the asset of interest is a compressors in a complex and enormous facility. This is however a generic model, so the end users can change those parameters and put the desired value that fits their need.

5.2 Current asset monitoring system

Now the compressor has to some extent sensor technology and condition monitoring. The purpose of the current monitoring system is to gain control of the critical compression system since its function is important for end users to get the gas they bought. Knowing the criticality of the system when it comes to operational availability the maintenance system should establish the technical integrity for the life cycle of the system.

The scenario for monitoring use case illustrated in Figure 4 is based on input from discussions and interviews from PHD-student at the case company. In short, the monitoring use scenario starts with TSP, which obtains both process and health parameters from STS, which is mainly analysed through trending. The operational deviation is then revealed when the trends measurements deviate from historical trends. In such a case, the TSP informs the operator who successively informs the owner. In the following, TSP and the operator study the best operating window to perform the necessary maintenance action based on the forecasted production plan and perceived the severity and criticism of the abnormality supported by the trend measurements. When a specific future maintenance action is planned, TSP generates a work order in its own SAP system and begins acquiring the necessary resources. In addition, TSP and the operator must develop a risk analysis e.g. safe job analysis (SJA) before the maintenance phase. In some situations, there is no time to analyse and plan for maintenance, and the equipment is therefore immediately turned off and remedial measures.

5.3.0 Current maintenance architecture

5.3.1 Preventive Maintenance

The operator and technical service provider like most organizations try to prevent failure before it occurs by performing regular checks on their equipment. One big challenge gas processing facility is facing with preventive maintenance is determining when to do maintenance. Since they do not know when failure is likely to occur, they must be conservative in the planning, especially since they are operating safety-critical equipment. But by scheduling maintenance very early, they are wasting machine life that is still usable, and this adds to the costs.

5.3.2 Corrective maintenance

In certain situations, there is no time for analysing and planning for maintenance, thus the equipment is immediately shut down and corrective actions are executed. With reactive maintenance, the machine is driven to its limit and repairs are performed only after the machine fails. Dealing with a complex system with some very expensive parts, the operators cannot take the risk of running the equipment to a failure, as it will be extremely costly to repair damaged parts and resulting in shutting down of the entire plant. But, more importantly, it is a safety issue. The operator has overcome this issue by having redundancy system with additional compressors. The current maintenance architect is described in figure 11

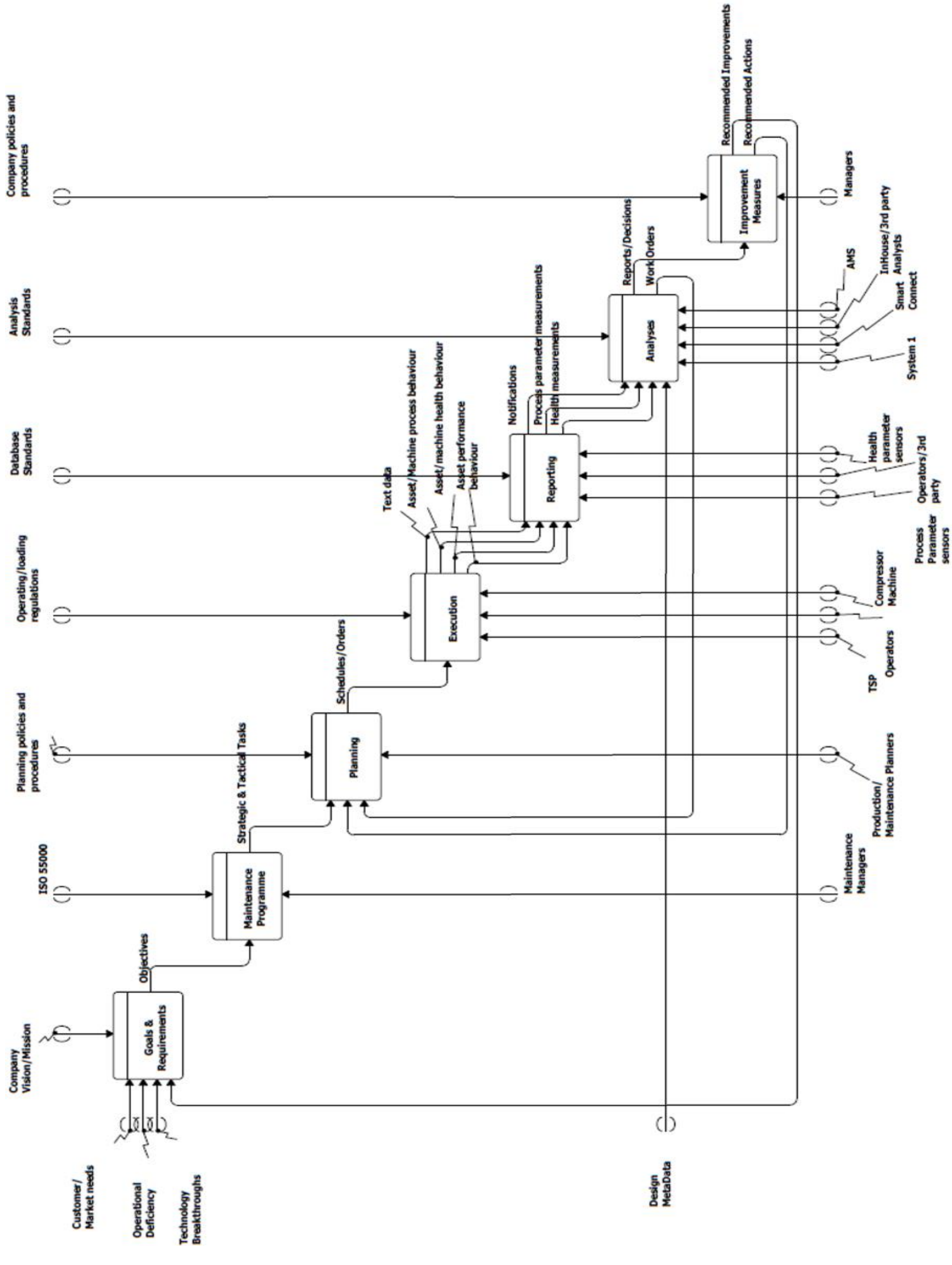

Figure 11: maintenance system of the asset (retrieved from research done by an expert, not yet published)

6. Model development

Chapter 6 presents the development of the model and descriptions of variables, parameters and functions.

Agent based modelling is mostly used when developing the model for this thesis but some system dynamic modelling were also used.
“Agent based modelling focuses on the individual active components of a system”.
agents also known as active entities are identified and their behavior defined. The agents relevant for this system are main agent, service crew agent and equipment unit. They are thoroughly described in this chapter with state charts, transitions, parameters, functions and variables.

6.1 Main Agent.

It is very easy and straight forward to design Any logic model. In the agent-based modelling, what is important is object in the real system that are going to be modelled and studied.

There are three agents in this model.

- Main Agent, the everything is defined.
- Equipment unit(compressor) with associated state charts.
- TSP Crew Agent (the service agent).

The main agent is the top-level object of the model where all global thing is defined such as space and request queue management for the service crew. One equipment unit class and 3 service crews are embedded into the main agent. This is something that can be changed by the end-user of the model. The layout and space settings of the model are defined in the environment object embedded in the main agent.

6.2 Service crew agent

Figure 3 illustrated how the technical service crew agent is modelled. The service crew is a mobile agent, unlike the stationary equipment unit agent, so moving in the space is part of agent behaviour. The behavior of this agent is to take a request from the equipment unit, drive to the equipment that needs to be repaired or replaced, do the assigned work. After the task is successfully done the service crew is programmed to return home unless there is another equipment that needs to be worked on or a maintenance order outstanding. The maintenance crew are dispatched from the maintenance centre, called home in service crew agent model. The sequence diagram on figure 12 illustrates and visualises how the service crew.

Service crew agent and equipment unit agent depends on each other. When a component fails a message is sent to the maintenance centre who will notify the TSP crew, which takes the assignment and drives to the failed component. If the service crew are in a working state doing repair, replacement or maintenance and another component send request for service the message is ignored, since the service crew is in working state. This is the case if there is only one service crew personell available, otherwise the maintenance centre will dispatch another service crew member.

The 4 states of the service crew are shown in figure 13 and the corresponding transitions triggers of and actions of these states is summarized in table 4.

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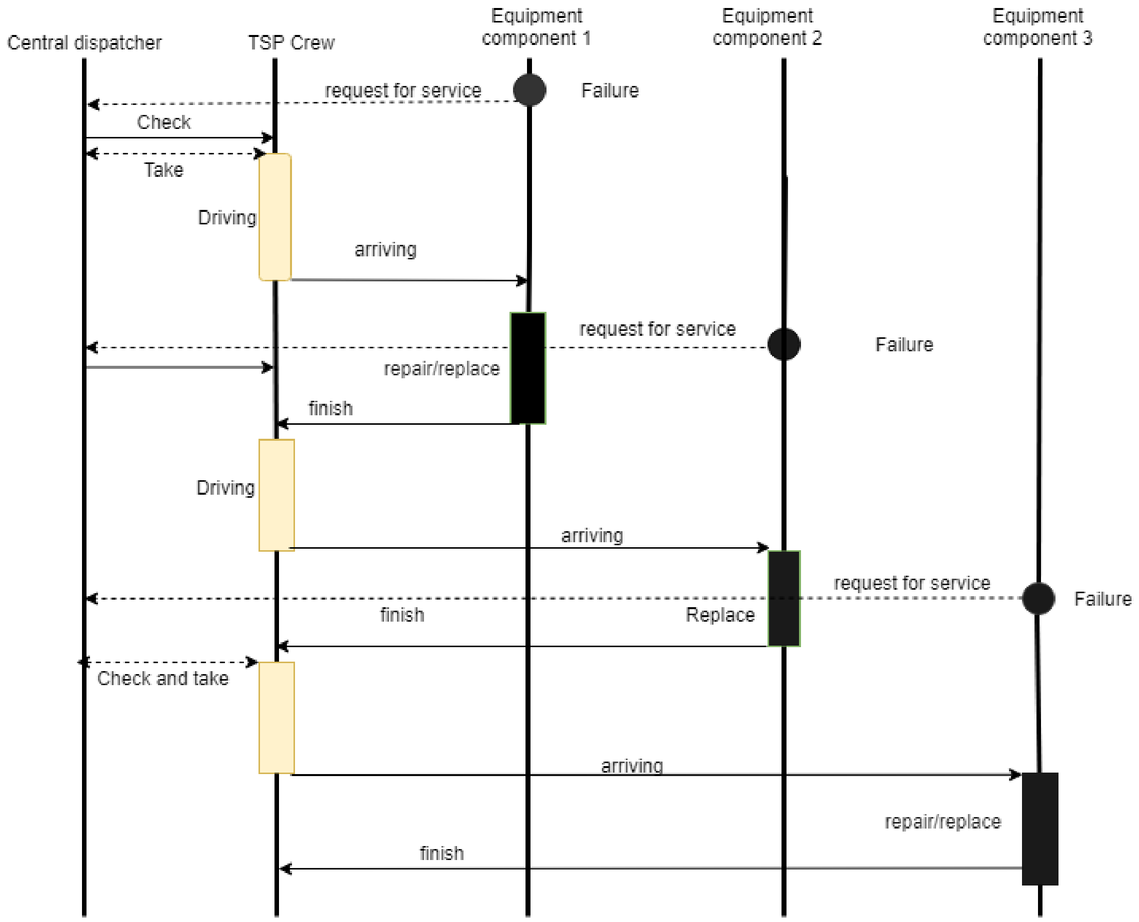


Figure 12: how the service work

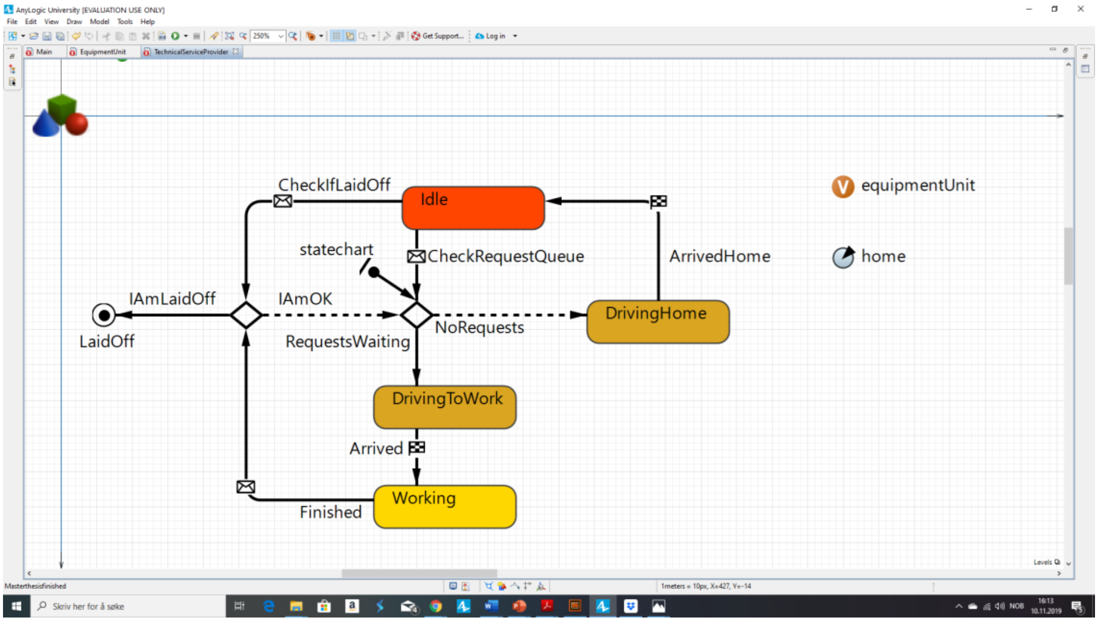


Figure 13: service crew agent((Borschev, 2013)

Table 4: service crew Agent

Transition	Triggered by and explanation
CheckLaidOff	Message Message type: string Message: "CHECK IF LAID OFF" This transitions checks if the worker is done with the repair and don't have anything else to do. So instead of him walking around in the model, he is "laid" off.
Arrived	Triggered by the agent arrival. Action: Send(this, equipmentUnit) = **null**; When the job is done the equipment, unit releases the service crew.
Finished	Message Message Type: String Message: Finnished Action: equipmentUnit = **null**; equipment unit releases the service crew - forget it This transition is triggered by the equipment unit, it releases the service crew and the action code then erases the reference to the equipment unit.
Arrived Home	Triggered by the agent arrival. No conditions. It is triggered by the arrival of service crew
Request waiting	Conditional: main.thereAreRequests() identifies request in the ques Action: equipmentUnit = main.getRequest(); Gives top priority to the request moveTo(equipmentUnit.getX() + 5, equipmentUnit.getY() Drives the crew to the equipment unit.
Equipment unit-function	Gets data from equipment unit. It is a reference to the equipment unit which handles the request from the crew, and it is null at other times. Request in this context means failed, replacement or maintenance.
Home-Parameter	Other shape Polyline It defines where the service crew is placed in the main agent.

6.3 Equipment unit agent

This chapter describes the equipment unit agent. The equipment unit and the corresponding state chart is something that is of great interest for us. After all it is the equipment who generates revenues for our facility. The equipment's fails from time to time and there are needs for repairing or replacing when it is due. The model includes the annually maintenance scheduled every summer.

6.3.1 Monitoring of the asset

The compressor is in operational state (Normal) and is checked by CMS provider, 30min every day and by TPS once every month. This is in line with how the monitoring system of the studied case is described in the previous conceptual chapter. CMS provider checks for anomalies and the result of that check will result in two things. If there is a potential failure, they will reach out too TSP so they can conduct their own checking. If the CMS provider check does not show any anomalies it goes back to the normal working state. If here is no failure after TSP check it will also go back to normal working state.

It is crucial to understand the functions, parameters, transitions, events, and variables of the model. These things are explained thoroughly in table 5,6 and 7.

6.3.2 Failures in the equipment unit.

If there is a failure, the transition goes from working State to the different failure states, which will message the service crew, described in the previous chapter, to arrive. When the TSP crew arrives, they will determine if the equipment needs replacement or repair. The replacement of the component will be based on reaching a certain age for the component or a probability for replacement of the components. When the service crew has replaced or repaired the failed component, they will go back to the dispatch centre, waiting for the next time the equipment fails. The snapshot of the equipment unit agent in figure 14 shows the state charts of the equipment unit in the model and how everything is connected. Different colours are used for the states to emphasize the meaning of the states visually. The same colour scheme is used for the visualization of statistics in the various plots.

The failures of the components in the model are based on failure rates. Failure data is a fundamental element of predictive maintenance. Yet this data may not exist if maintenance is performed so frequently that no failures occur. Simulation tools can help data engineers generate these necessary failure data. One can also use mathematical models to calculate the probability of occurrence for situations using patterns. In this way, it is possible to predict impending errors or determine optimal maintenance cycles - without any need to happen first.

Three components can fail, and two of them can either be replaced or repaired. Component 2 is just replaced.

The failure rate for component 1 is one failure for every 4.49 years, the failure rate of component 2 is one failure every 4.1 years, and failure rate for component 3 is one failure every 6 years.

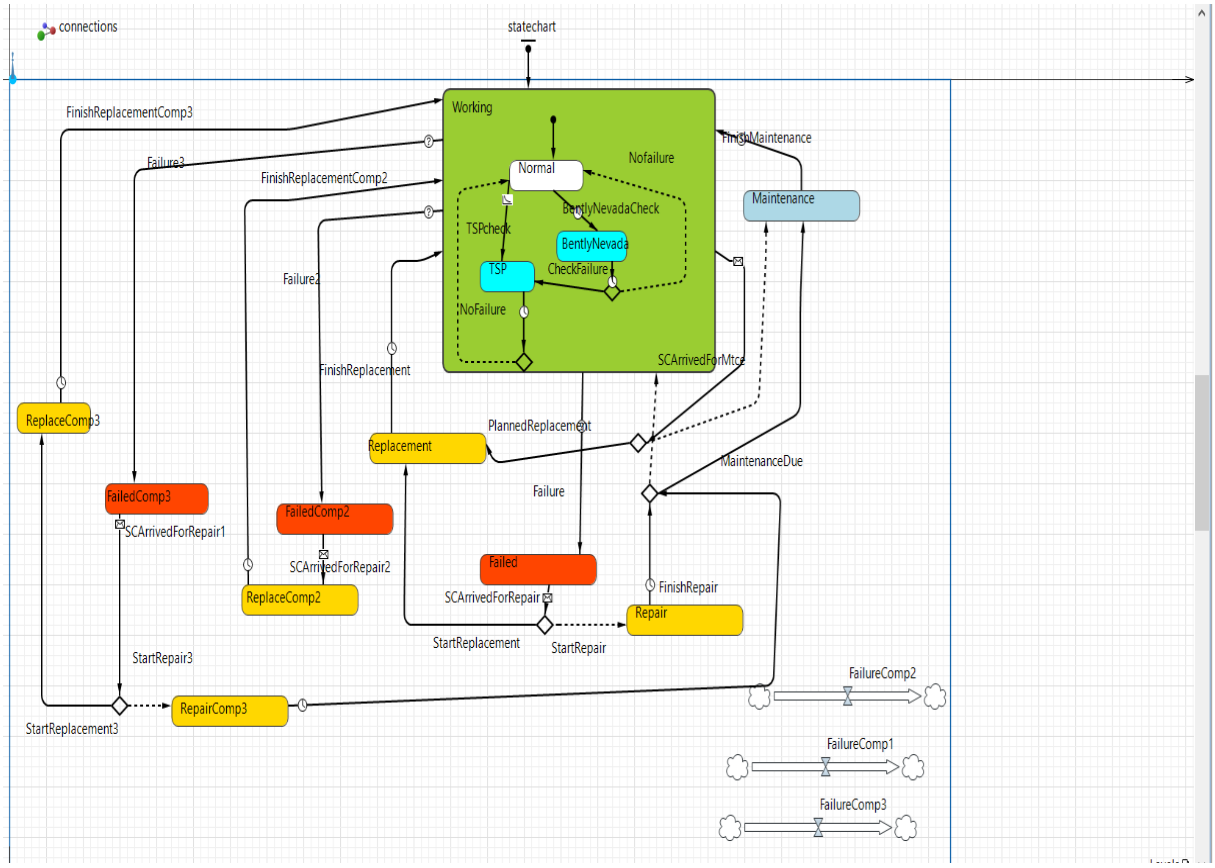


Figure 14: equipment unit

Table 5:parameters used

Parameter	Value	Explanation
Maintenance mean Time	3 hours	The average time the service crew use on maintenance
Replacement meantime 3	3 hours	The average time the service crew use on replacing component 3
Replacement meantime 2	43 hours	The average time the service crew use on replacing component 2
Replacement meantime	23 hours	The average time the service crew use on replacing component 1
Repair typical Time	5 hours (SINTEF & NTNU, 2015)	Repair time for component 1
Repair typical Time3	5 hours	Repair time for component 3
ProbabilityReplacementNeeded	0.1	The probability needed of replacement for the components.
MaintenancePeriod	90 days	Maintenance period for the asset

Table 6: Variables, function and event of the model

Name	Type	Code and explanations
Time Last Replacement	Variable	Double public: this variable represents the last time the components were replaced
Time Last Maintenance	variable	uniform (-MaintenancePeriod, 0)
Service Crew	Variable	Gets crews from the service crew agent
Age	Function	**return** time () - TimeLastReplacement; This function is an age function that control the age of the components, so the model can replace the components when time for replacement is due.
Colo	function	The colour function shows the states of the components. Depending on the colour they will send service crew to do maintenance, repair or replacement.

Maintenance Timer	Event	main.requestMaintenance(**this**);
		//mtce is due - request mtce
		When maintenance is due, this event will request maintenance and send crew to do maintenance

Colo

```
if( inState( Working ) ) {
        if( MaintenanceTimer.isActive() )
return deepSkyBlue;
        return gold;
} else if( inState( Failed ) ) {
        return orangeRed;
} else {
        return limeGreen;
}
```

Table 7: transition

CMS provider check	Triggered by rate Rate: 0.5hour per day
Check failures	Condition Condition: randomTrue(PotentialFailureProbability
NoFailure	Default meaning if there are no failure it will go back to working
TSPCheck	Triggered by rate
Failure Comp1 FailureComp2 FailureComo3 This are flow rates.	Component 1 (pulseTrain(1639,0.166,1639,7304) Component 2(pulseTrain(1497,0.166,1497,7304)) Component 3(pulseTrain(2191,0.166,2191,7304)

Failure for component 1, 2 and 3	Condition: `FailureComp1 > 0`
	`FailureComp2 > 0`
	`FailureComp3 > 0`

	Action: main.requestService(**this**); A failure has occurred, request service from the service crew
SCAarrivedforRepair for component 1and 3	Triggered by message Message type: ServiceCrew, notifies service crew in the service crew agent
	Action: serviceCrew = msg; this action remembers the service crew that arrives
Finnish repair for component 1 and 3	Triggered by timeout: triangular(RepairTypicalTime(1,3) * 0.5, RepairTypicalTime(1,3), RepairTypicalTime(1,3) * 2.5) (1,3) means the different repair times for component 1 and 3.
	Action: main.WorkCost += main.RepairCost; this action updates balance
Start Replacement for component 1,2 and 3	Condition: main.ReplaceOldEquipment && age() > main.MtcePeriodsToReplace * MaintenancePeriod || randomTrue(ProbabilityReplacementNeeded) a component is either replaced after chosen age for replacing the component or if there is probability that replacement is the only option
Start repair	It is a default transition linked to the replacement transition through a branch. If there is no replacement, then the service crew will do repair.
Finish replacement for component 1,2 and 3	Timeout: triangular(ReplacementMeanTime(1,2,3)*0.5, ReplacementMeanTime(1,2,3),ReplacementMeanTime(1,2,3)*1.5) (1,2,3) refers to replacement mean times for the given components.

	Action:
	send("FINISHED", serviceCrew);
	serviceCrew = null;
	
	TimeLastReplacement = time();
	TimeLastMaintenance = time();
	MaintenanceTimer.restart(MaintenancePeriod);
	
	main.WorkCost += main.ReplacementCost;

MaintenanceDue	Condition: ! MaintenanceTimer.isActive(), maintenance is due, so the service crew will do the maintenance
FinishMaintenance	Timeout: triangular(MaintenanceMeanTime * 0.5, MaintenanceMeanTime, MaintenanceMeanTime * 1.5)

	Action :
	send("FINISHED", serviceCrew);
	serviceCrew = null;
	
	TimeLastMaintenance = time();
	MaintenanceTimer.restart(MaintenancePeriod);
	
	main.WorkCost += main.MaintenanceCost;

PlannedReplacement	main.ReplaceOldEquipment && age() > main.MtcePeriodsToReplace * MaintenancePeriod When a chosen age for component 1 is reached it will be replaced

7.0 Simulation findings

This chapter shows the outputs of the model. How predictive maintenance and alarm-based maintenance can be used is explained in this chapter.

This chapter will provide a collection of the output from the model.

The value on the x-axis of the failure and checking plots are days. There are plots that describes the availability of the Asset, the profit, and the associated expenses and revenue. It also shows the time spent on checking and monitoring and the failures of the components.

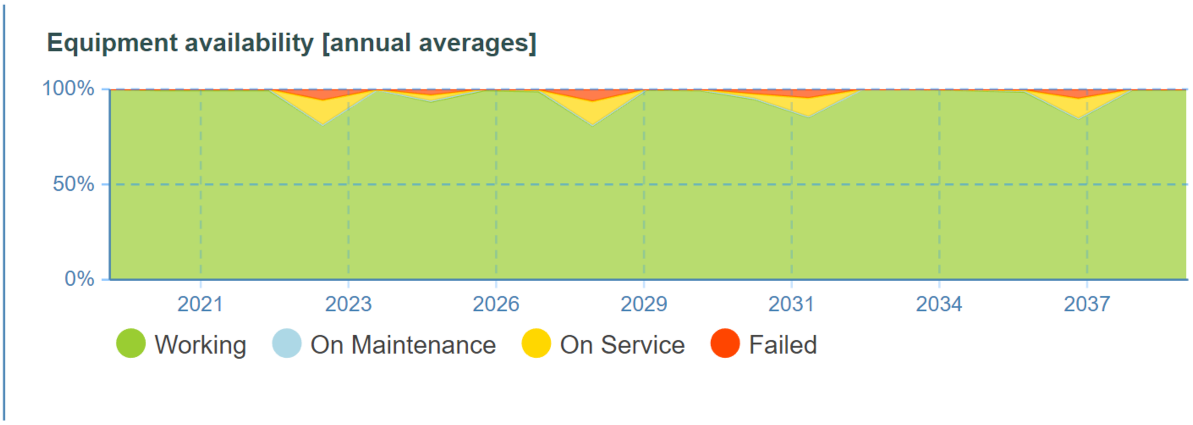


Figure 15: Availability of the asset with the failures and no predictive maintenance

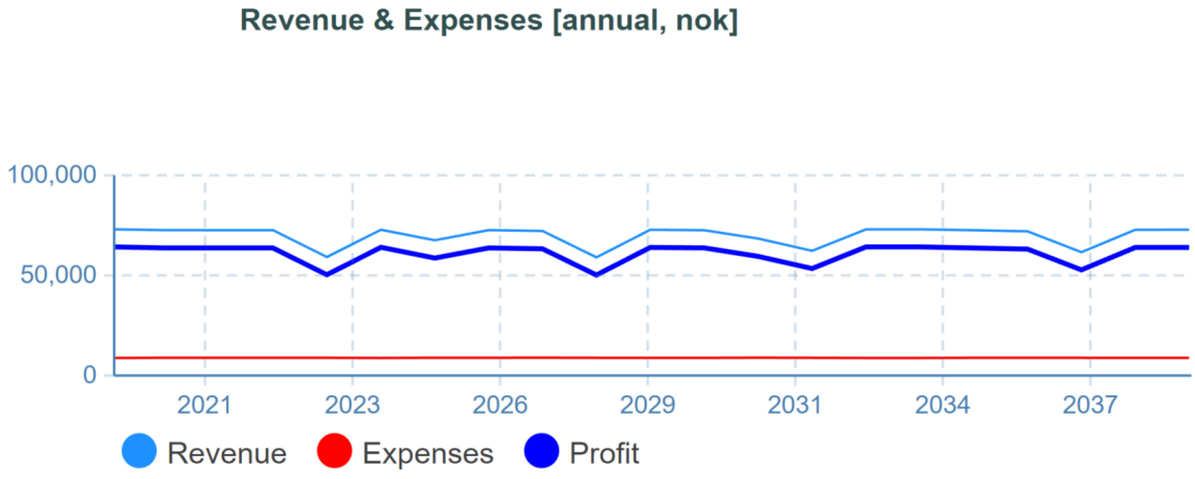


Figure 16: profit, revenue, and expenses without predictive maintenance

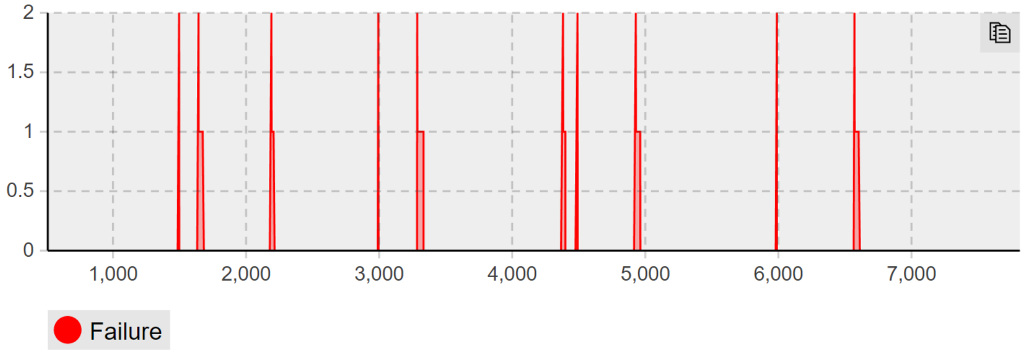


Figure 17: failures of the components

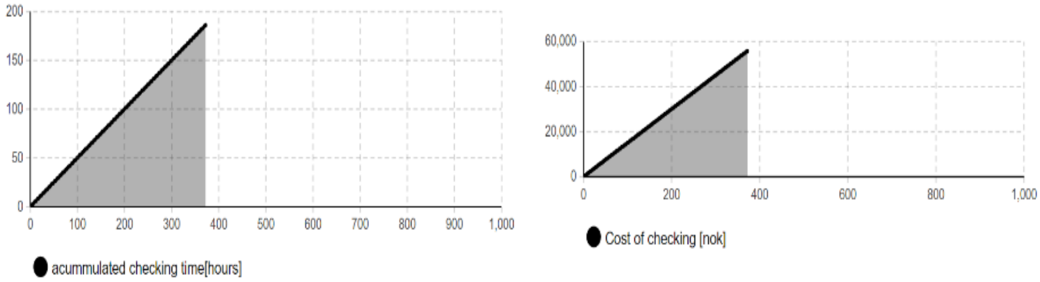


Figure 18: checking time with current check-based monitoring system

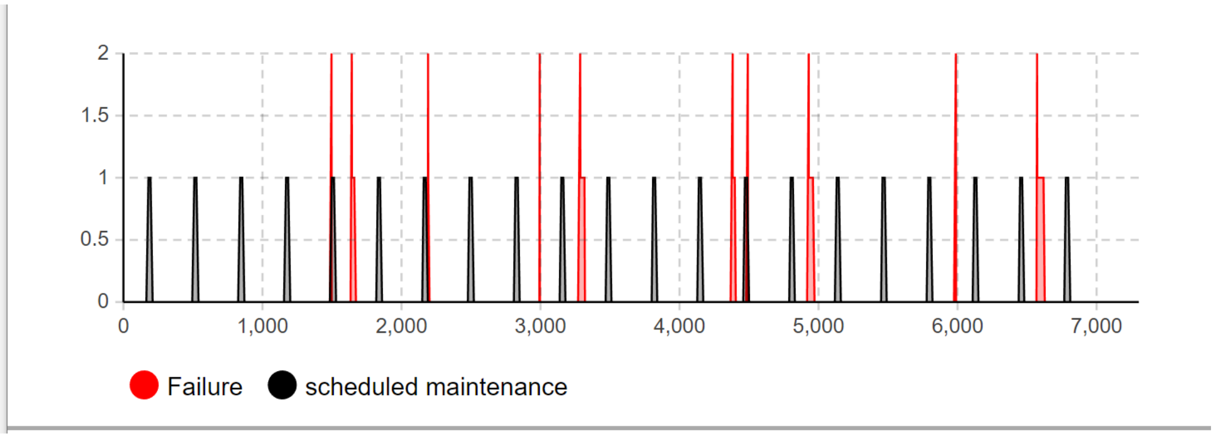


Figure 19: failure and scheduled maintenance

7.1 Predictive maintenance and opportunistic maintenance

The first step in a predictive maintenance solution is to prepare the data. This includes data entry, clean-up and functional construction. Predictive maintenance issues usually include data such as:

- Machine information (eg engine size, product, and model)
- Telemetry data (eg sensor data such as temperature, pressure, vibration, fluid properties and operating speed
- Maintenance and intervention history: the repair history of a machine and runtime logs
- Failure history: the failure history of a specific machine or component.

Data must include examples of both success and failure in order to predict failure. Many examples will result in a better, more generalizable predictive maintenance model. It is also important to have data from devices that have failed and for those that are still in use. Data may include readings from equipment that has failed due to the specific problems, and from devices that have failed for other reasons. In both cases, more data will lead to a better solution. In addition to choosing the right algorithms, a successful model requires fine-tuned parameters. These are parameters, such as the number of layers in a nervous system, that are specified before the training process starts. parameters are often specified by the data scientist through trial and error. They affect the accuracy and performance of the model, and it often takes many iterations before the optimal values are found. In this model, the predicting time is set to 6 months before the scheduled maintenantence, so failures predicted close to scheduled maintenance . That means the algorithm and condition set by software engineers predict failures that can happen during the next 6 months. During the interview with the expert, he said that systems can predict failures in near future, generally between 6monts-1 year with. Predicting failures over this interval will most likely be impossible or the predicted failures will be subject to a great deal of uncertainty. (Wallner, 2019) (Microsoft, 2019)

The technical service crew in the plant do maintenance in the summer, when gas exported to the countries in Europe is low. The largest peak of energy demands occurs during the winter, when cold weather increases the demand for natural gas for space heating in the residential and commercial sectors which makes it impossible or at least very difficult to do maintenance. By implementing PDM, the operator who is responsible for operating the facility can use opportunistic maintenance to repair and replace the parts that were predicted to fail if the failures occur close to the scheduled maintenance.

The goal of opportunistic maintenance is to improve system availability and reduce production loss; The key to success, however, is being able to decide when to replace a component over its useful life to achieve cost-effective improvement. (Thomas, evrat, & Benoît, 2008)

Opportunistic maintenance is considered effective for an oil and gas wealth due to the high level of dependence presented by the various systems. When considering the centrifugal compressor, a failure event in a system or a component is likely to shut down other parts of the compressor, which will affect the ability for the facility to work properly.

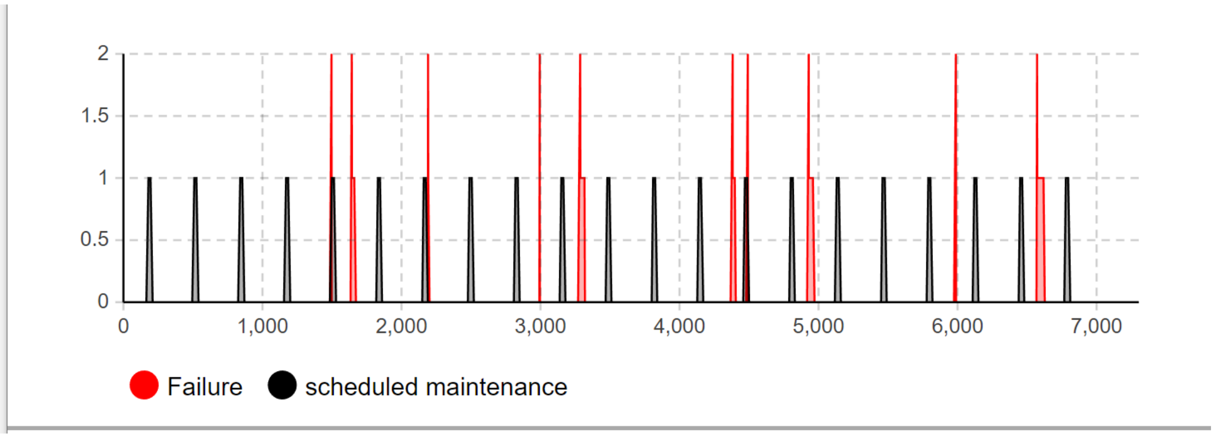


Figure 20: failures and scheduled maintenance

In figure 20 there are several failures if predicted with correct time range occur at the same time or close to the scheduled maintenance. There is no point for the crew to wait and come back for the scheduled maintenance when they are at the site and performing a maintenance task. Some of the failures seems to appear before scheduled maintenance, when working on those failures, the scheduled maintenance can be done at the same time. The maintenance resources are already at the site to do a job, and the operator do not have to mobilise crew or equipment twice in short time frame. As a result, significant costs can be saved compared to waiting for the regular maintenance plan for the equipment maintained. This will likely increase the production efficiency and increased availability of the asset if done correctly. Figure 21 shows that 8 out of 10 failures can potentially be predicted and be done at the same time as the scheduled maintenance and as for the two failures that can’t be predicted, the time set for prediction is too far from when i is supposed to fail.

How the opportunistic maintenance can affect the availability is something of great interest, so two figures are included to show the benefits of the opportunistic maintenance. Figure 22 shows the availability when the failures are not fixed at the same time as the scheduled maintenance. The following figure, figure 23, shows when the opportunistic maintenance is utilised. It is evident that the availability increases for the asset in the years when failures can be predicted and be fixed at the same as the scheduled maintenance and the operator and owner can reap the benefits of opportunistic maintenance.

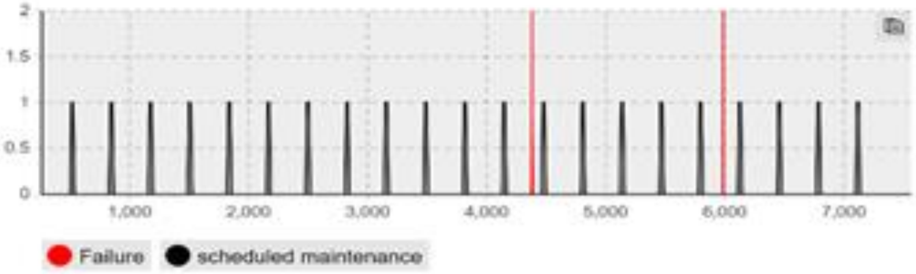


Figure 21: PDM and opportunistic maintenance utilized

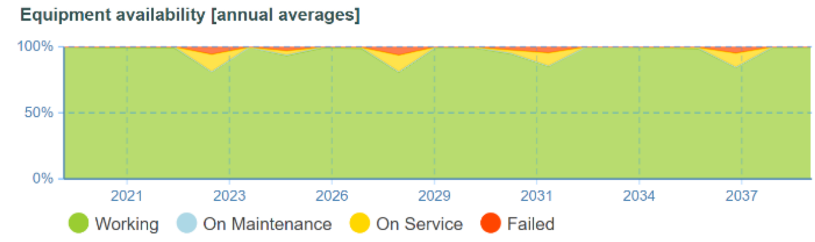


Figure 22: availability; PDM and opportunistic maintenance not utilized

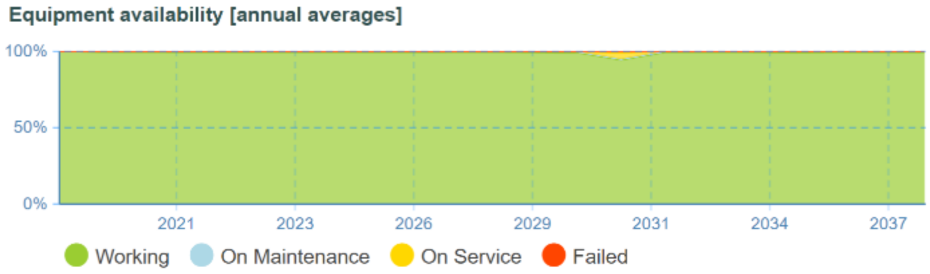


Figure 23: availability; PdM and opportunistic maintenance are utilized

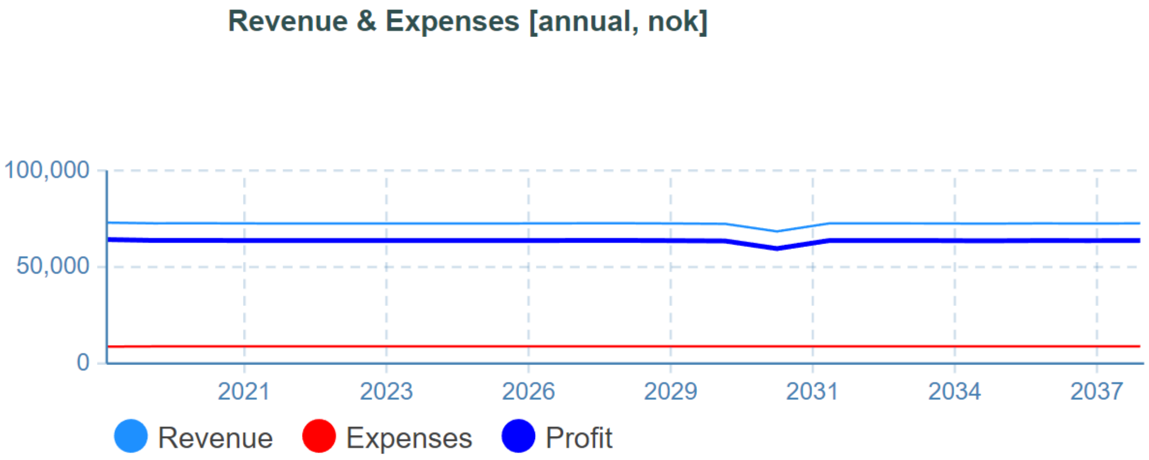


Figure 24: profit, revenue, and expenses; PDM and opportunistic maintenance utilized

7.2 Alarm based condition-based monitoring system

Instead of tracing only real events - such as finding anomalies in trend data- during action tracking, new technologies have been developed that automates the monitor of the deterioration and failures of components. (Strczkiewicz, 2015). The model on this chapter is developed using system dynamics. The loading of the asset is simulated, and when it reaches a certain limit the machine stops, and it needs to be fixed. It is important to know that the limit doesn’t have to be based on loading, but it was used for thesis because it was easy to model and assume, and vibrations data which is normally used would have been difficult obtain without case company. It is modelled so the failure of this model corresponds with the failure used in previous chapter. The failure for component 2 was one failure every 4.1 year or 1497 days as used in the failure plots.

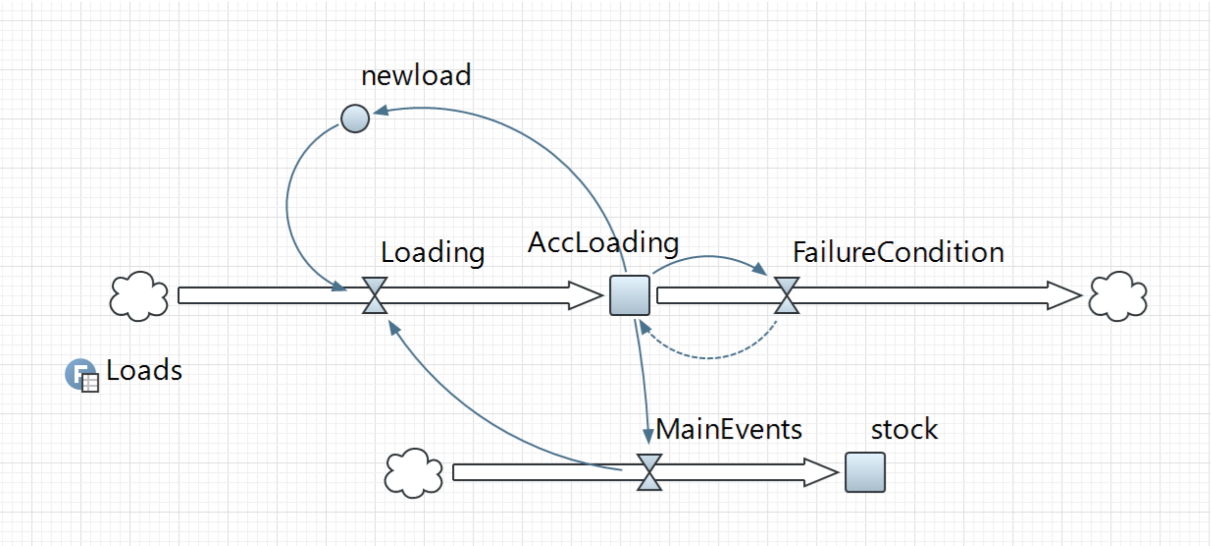


Figure 25: The loading of the asset; based on (El-Thalji, 2019)

Table 8: explanation of the system dynamic model

Name	Code and explanation
Loads	1=50, 2=65, 3=95, 5=150 The different loading of the asset
FailureCondition	`rint(AccLoading)== uniform_discr(350000)? AccLoading=0 :0` This is the failure condition, when it reaches 350000 it will fail.
MainEvents	`rint(AccLoading) == 400000 ? 1 : 0`
Loading	`rint(MainEvents) > 0 ? 0 : (Loads(random()+newload)*uniform(0,5))`
newload	`AccLoading <=50000 ? Loads(random()):0` `New load is added so the model wil give accumalted load.`

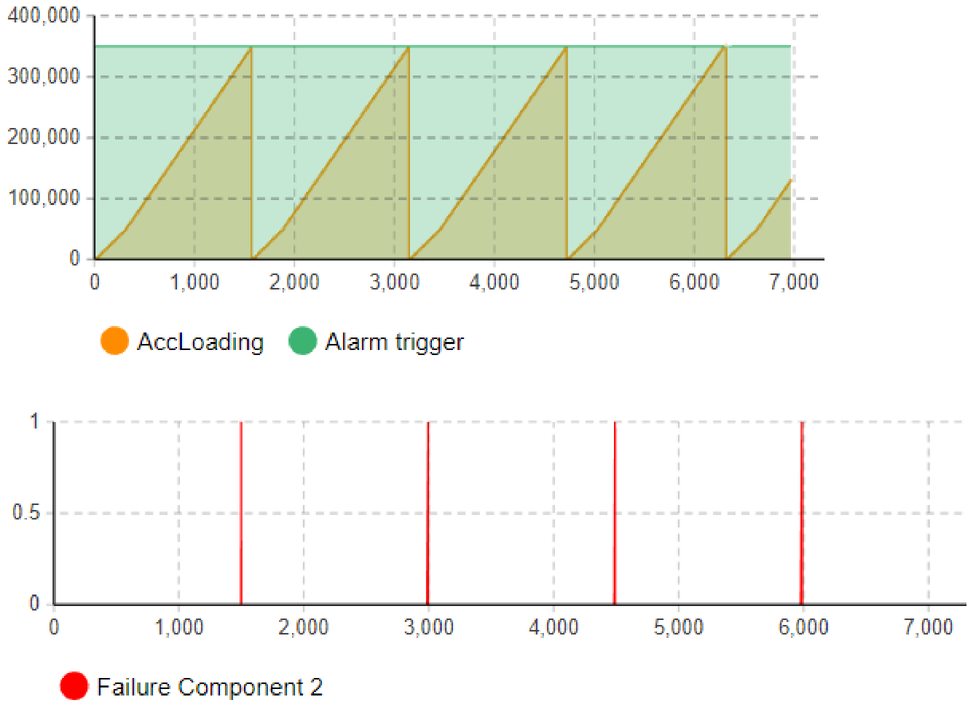


Figure 26: Accloading with alarm trigger + failure component 2

Detection and classification of alarm threshold violations in condition monitoring systems working in highly varying operational conditions

When a certain component of an asset does not work properly, it can mean that something bad is about to happen. Most condition-based monitoring systems enables the users to define some alarm thresholds which will enhance the efficiency of the monitoring and maintenance of assets. All of these can be measured by the process control system, action can be initiated to determine the cause of the triggering of the alarm or if the alarm is critical shut down the machine in order to prevent damage and failure. In figure 26 the breakdown of component 2 illustrates the alarm-based condition monitoring which are based on loading. When it reaches a certain limit, it will shut down and measures must be taken. In this thesis only one component is shown, but it can be done for all components who is monitored and have sensors installed.

Sensors provides the raw data that are collected and stored either in a local server, a cloud system or both. A CMS provider will be responsible for facilitating the monitoring system and be responsible for the sensors. The installing of the sensors and setting up the system needs to be done by qualified people for the data to be reliable and trustworthy and the monitoring frequency shall be high enough to capture any change of importance according to ISO 13379.

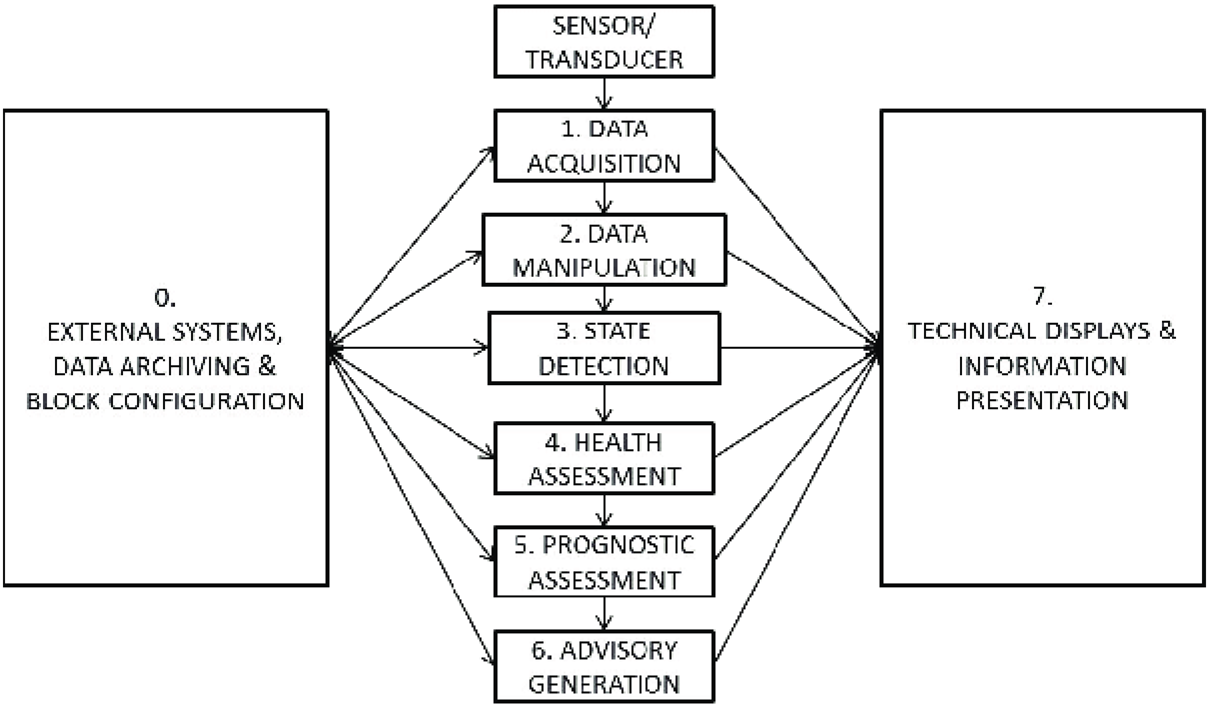


Figure 27:The ISO 13374-1 processing model. (13374-3:2012 ISO, 2017)

Data will be collected and assessed by the machine and stored in the cloud or in a local server. Figure 27 shows how the processing model of a monitoring system is designed. The system implemented should be automated so that the people responsible for the monitoring only get notified if there is an issue that should be examined or if the compressor must be shutdown. The way it can be achieved is by having a dashboard that generates visual pictures of the performance of the asset. The notification will appear as green, yellow, or red in the software dashboard based on the condition of the monitored component. Green notifications in the system are within the alarm limit, while red is outside of the alarm limit. The status window of the system lists all the components that are monitored and makes it easy to identify which component is at risk of failure. It is important that the alerts are connected to the PDM Centre or CMMS to ensure a fast and effective action to resolve the issue. In the future the monitoring system could be integrated into the cmms system used by the operator. Work order and all the documentation needed could then be generated by the condition monitoring system streamlining the whole process from notification too doing the task of repairing or replacing. When this alarm-based monitoring system is implemented, there is no point in checking every 30 minutes as they do today. They can rather check once every month. New equipment does not need frequently checking. Figure 27 shows the time spent on checking with this new system of only once per month.

Table 9: trigger levels

Severity	Response Time	Maintenance response
Low	> 4 months	Stable operation- no response
Moderate	< 1 month	Plan and prepare Work order. Reschedule planned maintenance.
high	< 24 hours	No time for preparing Work order, immediate action required.

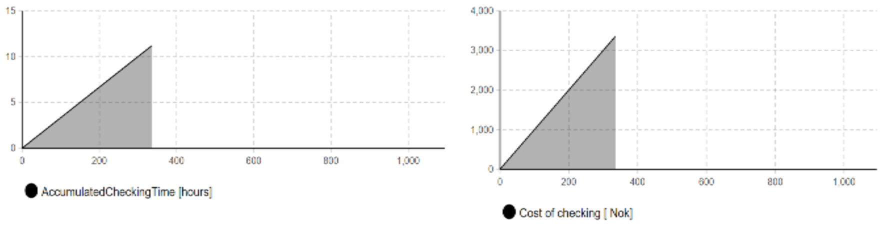


Figure 28: checking Time spent with new monitoring system

7.3 Impact of the models

This chapter's main focus is to put everything in too the same place. It may be difficult for the reader to have a clear picture of these plot are connected and how they affect each other. If these are plots are difficult to see, please go up too see full version of the plots or go down to table 10 where it is the impact is explained.

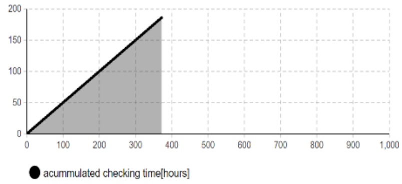
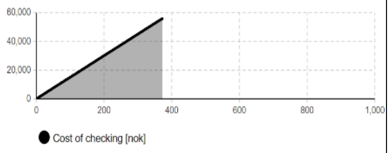
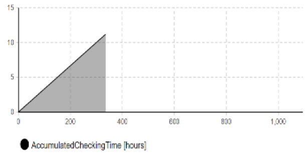
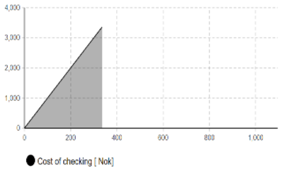
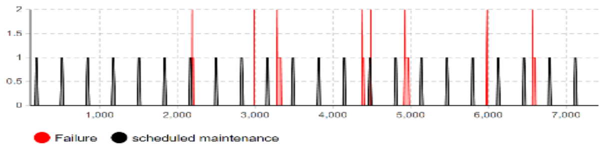
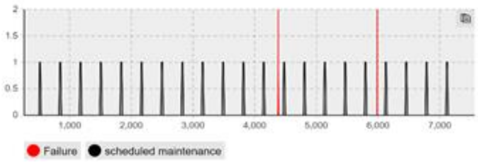
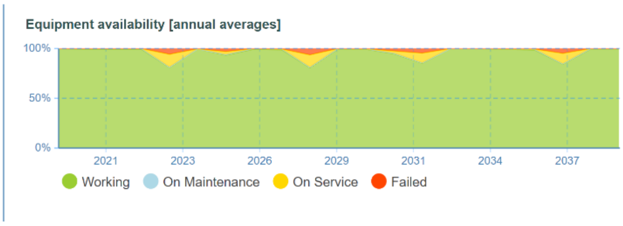
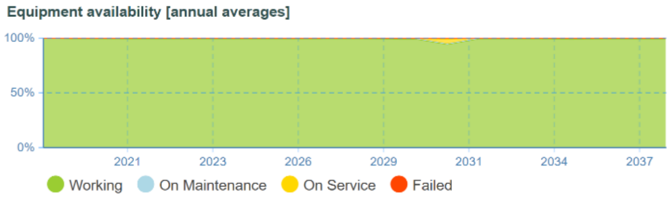
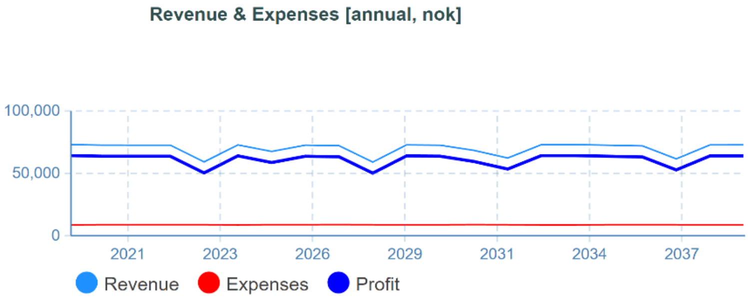
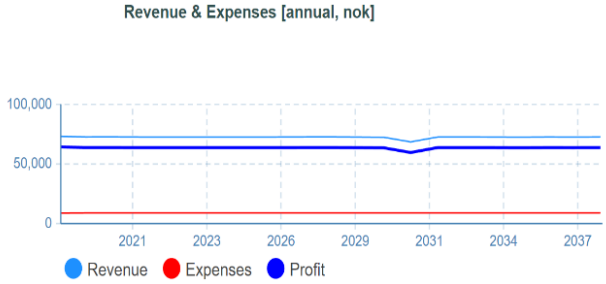
Current maintenance system	PDM system
 	 
	
	
	

Table 10: impact of the current system and PdM system

Impact	Current maintenance system	PDM system
Condition monitoring	Checking based: The monitoring of the asset in the computational is based on checking 30 minutes per day by the CMS provider, and once a month by the TSP. The data is checked for anomalies.	Alarm based: In the scenario model the condition monitoring system is alarm based. When the asset reaches a predefined limit, it will notify the monitoring crew and based on the severity of the notification they will accordingly.
Checking Time saved	In the computational model the Data is checked 30 minutes every days. That is equivalent to 182.5hours every year. The cost of that check is roughly 54750 for one person assuming the hourly pay rate Is 300 NOK.	The scenario model is based on Alarm triggered, making continuously checking excess. Since the condition monitoring is computerised and the system will notify when, it is assumed that they will only check only data once a month to see that everything is correct, and the system is working. once every month equals 12.16 hours. The cost for checking is then 3650 NOK.
Failures	No predictive maintenance system in place. Preventive and reactive maintenance is current applied.	80% of the failures can be predicted. Improves greatly the availability of the asset.
Availability	Since there are more failures the availability is also lower. Too be more precis, the failures are still there, but they are not predicted.	Less failures means more availability, but by using the scheduled maintenance to do predicted failures that occurs approximately at the same time, the availability will be higher.
Profit	Follows same logic as the availability, doing both and scheduled maintenance separate result in less availability decreasing the profit.	The profit is higher in the scenario model due to less failures and higher availability compared to the computational model.

8. Verification and Validation Tests

The decision methods to determine if a simulation model is valid used in this thesis are:

1. The results of the various test and evaluations performed as part of the model developed process are validated by the developer itself.
2. The second way of validating was to let an expert which knowledge about the real-world scenarios that where model decide the validity of the model. This approach is useful when the size of the team that develops the simulation is small.
3. The third approach that were used is the independent verification and validation (IV &V) method, where the main objective is to use a third independent party to decide whether a simulation is valid or not. A fellow Anylogic modeler where asked to look over the model itself and checked that the state chart and codes were used correctly. The remarks and comments by the expert are described in table 11.

Table 11:validations and verifications

Aspect	Verification test (by modeller)	Validation test (by experts, real data)	Comments
Model structure (reference case)	Ok.	I think the models seem to be good, both the 'Computational' illustrating the asset and the 'Scenario' that is based on failure rates.	A qualitative interview has been conducted to gain insight in the structure of facility. The structure of the model was build based on this information.
Model behaviour (reference case)	ok	According to the expert the models accommodate the intention and need for simulation by yielding the outputs in terms of impacts that you want to simulate.	The model behaviour was working as described as the modeler intended. The model was then sent to the expert who approved it.
Inputs(parameters)	Ok.	The inputs are reasonable, and the real value is quite comparable to some of the values the modeler have set for the different maintenance actions.	The values that were changed after consulting the expert: 1. Maintenance mean time had to bet set to 3 hours. 2. Replacement of component 1 to be 23hrs. 3. Replacement of component to be 43hrs. 4. Replacement of component 3 to be 3hrs.
Processes (rates, functions)	ok	The process of the model is viewed by the experts as good. The rates were either given by the experts or obtained through books and then approved by the expert.	

9. Discussion and conclusion

	Current maintenance system	New maintenance system
Condition monitoring	Personell checking for anomalies	Alarm based condition monitoring
Maintenance	Preventive and reactive maintenance.	Predictive maintenance: 80% failures predicted. Working on failures done at the same as scheduled maintenance utilising opportunistic maintenance
Checking time	182.5 hours	12 hours

By using a simulation software, a generic business model for PDM services with different stakeholders have been simulated. The case study in this thesis was a gas processing plant that exported gas to Europa and the asset of interest is a centrifugal compressor. The model assessed the current condition monitoring and maintenance system.

In order to see if a new technology or implementing new policies is **the right cours**e for a company, **we need** to simulate a real-world scenario of the facility using modelling tools. That way, they do not have to invest considerable amount of money in a technology that does not necessarily meet the needs of the stakeholders.

Three components were assessed in the simulation model, but it is important to remember that centrifugal compressor comprises of more than three components and all those components cannot be equipped with sensors, only the most critical components are monitored. Furthermore, not all errors can be predicted. Some failures occur due to human error, such as equipment not properly installed, or repair done incorrectly leading to a secondary failure. There may also be a technological error. The plot showed that the availability was over 90%, but that that did not include when the scheduled maintenance was done. The scheduled maintenance is already planned, and the equipment will be shut down anyway for the maintenance, hence the opportunistic maintenance.

There are two examples that are worth mentioning and that could be compared to this thesis when discussing the use of simulation to improve maintenance and optimising asset performance. YPF, the largest oil and gas company in Argentina, aimed to reduce its cost associated with oil wells' maintenance downtime and the breakdown of its equipment. They hired a consultant company specializing in bringing solutions based on modelling, simulation, and optimization. As a rule, it is best to allow modelling experts to create the models and get input from the engineers and end-users of the model to verify the results. They chose Anylogic simulation software for its unique flexibility, which allowed them to model specific resource behaviours and custom process rules. The results of this simulation provided YPF with project management and decision support tool for maintenance scheduling. It helped to provide the facilities operational efficiency and the result was as follows:

1. 11% increase in work order execution
2. Preventive maintenance fulfilment increased to 95% in time period of six months.
3. 56% reduction backlog reduction of corrective maintenance
4. 50% reduction of unplanned downtime production losses. (Anylogic, 2016)

The difference between the YPF simulations and the simulations of this thesis are the complexity of the simulated system. They developed a model for the entire facility while this thesis only focused on a compressor and three components of the compressor. That explains the lower number they got compared to the numbers obtained in this thesis.

DNV GL- is another company that conducts simulations of wide range of technologies and systems. They conducted a simulation using Maro and Taro which are two simulations programme developed by dnv gl. In 2015 they conducted a simulation analysis to see if they could utilise opportunistic maintenance. The results in those simulations were increase in production efficiency, reduced number of mobilisations numbers for unscheduled helicopters, higher revenues, due to higher efficiency, and at the same time reduced operational expenditure. This is in line with what this thesis outlined, whereby utilising opportunistic maintenance the downtime of the equipment went down and the availability increased. This thesis went further and outlined the possibility of repairing a predicted failure at the same time as scheduled yearly maintenance. The service crew were not mobilised twice, first if they were tasked with working on the failures and then mobilized again to do scheduled maintenance. (borges, 2015)

When an organization have decided to implement predictive maintenance and alarm-based conditions monitoring system they must consider the issue of outsourcing it or keep it inhouse. Like the case study in this thesis the majority of the organisations use a combination of in-house system and outsourcing the system (Mobley, 2002, s. 63). There are several advantages for outsourcing the predictive maintenance system and monitoring of assets. Most of the O&G companies often focus on their core business and would rather give the responsibility for predictive maintenance and monitoring of assets to companies who provides these services.

The opportunities of cost saving are something organizations can achieve by outsourcing the maintenance systems. It costs a lot of money to acquire, operate, and maintain the sensors and software systems. By using an outsourced contractor, the contractor will achieve flexibility in delivering the right staffing level and desired set of skills quickly, with less cost and time investment, as well as providing skills that may or may not be available within internal staff.

Although the operators and owners outsource the monitoring system to contractors, they do not give them full access to the data gathered from the asset. The data is stored on a local server, and the contractors will only get access when they are given permission by the operator and the owners. Continuous access to the data allows maintenance systems to be significantly improved by comparing the data from the similar components used in different facilities and by using big data and IoT to predict failures with more accuracy.

The reasons why they do not give them access are complex, but they are afraid that they will become too powerful and that they will become too dependent on them. The second issue is cybersecurity. When data is created and transmitted, it makes it easier to compromise and steal information and even take the whole company as hostage. More and more sensitive data is available in different parts of the monitoring system, and the risk is higher for a malicious attack. The figure below illustrates the different attack points in a modern monitoring system. Cyber security is extremely important for enterprises these days with an increase in ransomware attacks. (Deloitte, 2019) Few months ago, Norsk Hydro became one of the latest victims of such ransomware attack with loses up to 450 mill Nok. With risk like this it is no wonder that operators and owners of these oil and gas facilities are reluctant to give full access to CBS suppliers. (Hovland, 2019)

Conclusion

This thesis is about how we can, through modelling, generate a business model for predictive maintenance. There are some important factors that should be considered when deciding whether to implement a predictive maintenance program or not. In this study, we see that the predictive maintenance will improve the availability and the affect the downtime of the production process. The operator has implemented a redundancy system with two extra compressors which is utilised when the main compressor has failed or undergoing scheduled maintenance. From the perspective of the owner, their sole purpose is to sell and export gas with as low as interruptions as possible. Hence the redundancy system, which they will happily invest in, instead of an unproved predictive system

Predictive maintenance can however be a great advantage at the facility, due to the many great advantages it brings.

The compressor downtime can be very expensive for the owner and operators while the maintenance can be time-consuming and resource intensive. Implementing a PdM will save the crew a lot of time used on inspecting and monitoring the system. The time and personell that are freed up can be used on more complex parts where predictive maintenance cannot be useful.

One of the success factors for predictive maintenance is that the company has a unified CMMS platform where data storage and data analysis are also implemented. It must be user-friendly and communicate with other maintenance-related programs and support IoT.

Having a common system is good in that it can learn from each other and take advantage of the synergy effect this provides.

Introducing predictable maintenance is not something that will give instant success when implemented. Many predictable maintenance programs have not achieved the desired result in recent years. There are usually many reasons for the predictive maintenance not to work as planned and in most cases, it has nothing to do with the technology, but more with management and poor concept development in the initial phase.

There are several obstacles that organizations need to overcome for it to succeed when implementing predictive maintenance.

1. do not make everything a predictive task

- when an organisation **is** implementing a predictive maintenance, it could be easy to decide to use the technology for every monitoring point in the facility. This only leads to overwhelming the monitoring system with data and only increase the cost of on-line monitoring. In the initial phase, the predictive maintenance should only be implemented in the most critical parts.

2. Do not expect immediate results

- When PDM is implemented, decision makers tend to think that once data is online and available, they can immediately make decisions. But similar to every other software, the people responsible for implementing the PDM service have to allow the software to accumulate historical data before they can see results and trends in equipment performance. Some of the anomalies can only be captured during seasonal changes or different kind of loading. Results should not be expected immediately, and the data will not identify and detect all kind of problems from start. The more data that becomes available, the easier will it be for the system to develop good and reliable prediction models.

3. Need for consistency

- One important finding from this thesis is the need consistency over time, since the maintenance system deployed in the facility is different from the PDM system that are proposed to be implemented. The consistency over time means everything from adequate staffing, giving proper training, having skilled personnel, change in program direction / technology, define the program adequately at first, and implementing a consistent model to monitor effectiveness of the program over time. False starts and stops cause confusion in the process and usually result in a lack of faith in the workers who see the company investing in "change" but then quickly revert to old patterns. It is therefore of outmost importance to give the technical personell proper training and teach them how the system works.

Reference

Albrice , D. (2016). *assetinsights*. Retrieved from What is maintenance?: https://assetinsights.net/Articles/What-are-the-Different-Types-of-Maintenance-David-Albrice.pdf

Anylogic. (2016). *Anylogic*. Retrieved from Anylogic: https://www.anylogic.com/maintenance-scheduling-tool-for-the-oil-and-gas-industry/

Boman, K. (2017). *Filling in the gaps*. Retrieved from oedigital: https://www.oedigital.com/news/445189-filling-in-the-gaps

borges, V. (2015). *Opportunistic Maintenance.* DNV GL.

Borschev, A. (2013). The big book of simulation modeling. In *multimethod modeling with anylogic* (pp. 158-159). AnyLogic North America.

BREE, S. D. (2019, july 6). *BIG DATA IN AVIATION - REDUCE COSTS THRU PREDICTIVE MAINTENANCE* . Retrieved from Exsyn aviation: https://www.exsyn.com/blog/big-data-in-aviation-predictive-maintenance

calixto, e. (2016). *Gas and oil reliability engineering modelling and analysis.* Oxford: Gulf professional publishing.

Coleman, c., satish, d., Mahesh , C., & Ed , D. (2017). Making maintenance smarter.

Deloitte. (2019). *Taking data hostage: The rise of ransomware.* Deloitte.

El-Thalji, I. (2019). Asset dynamics modelling and simulations. 120.

Gassco. (2019, 12). *Nyhamna Processing plant*. Retrieved from gassco.no: https://www.gassco.no/en/our-activities/processing-plants/nyhamna-prosessanlegg/

Gulati, R., Kahn , J., & Baldwin, R. (2010). The Professionals Guide To Maintenance And Reliability Terminology. In *The Professionals Guide To Maintenance And Reliability Terminology.* Reliabilityweb.com.

Hovland, K. M. (2019, april 30). *e24.no.* Retrieved from e24.no: https://e24.no/boers-og-finans/i/7078VV/cyberangrep-har-kostet-hydro-opptil-450-millioner

hughes, B. (2017). *The impact of digital on unplanned downtime and ofsshore oil and gas perspective.* Baker Hughes.

Hupjé, E. (2018, june 21). *roadtoreliability*. Retrieved from https://www.roadtoreliability.com/types-of-maintenance

ISO. (2017). Condition monitoring and diagnostics of machines — Data processing, communication and presentation — Part 3: Communication. p. 21.

Jardine, A., & Albert Tsang. (2006). Maintenance, replacemet, and reliability theory and applications. In *Maintenance, replacemet, and reliability theory and applications* (pp. 2-3). New york: Taylor & Francis group, LLC.

Massala, D. c. (2018). *Ram Analysis applied to centrifugal gas compressors "case study of an oil and gas company".* Lisboa: instituto superior tecnico, universidade de lisboa, Portugal.

Microsoft. (2019). *microsoft*. Retrieved from microsoft: https://azure.microsoft.com/nb-no/use-cases/predictive-maintenance/

Mobley, K. (2002). *An itnroduction to predictive maintenance.* Woburn: elsevier.

Ramesh Gulati, J. K. (2019). *https://reliabilityweb.com/tips/article/definition_preventive_maintenance*. Retrieved from https://reliabilityweb.com/tips/article/definition_preventive_maintenance:

Sargent, R. G. (2011). Verification and validations of simulation models.

Singhal, K. (2018). maintenance management. In *Production and operation management* (pp. 207-209). Production and Operations Management Society.

SINTEF, & NTNU. (2015). Oreda offshore and onnshore reliability data. In SINTEF, *Oreda offshore and onnshore reliability data* (p. 70). Trondheim.

Strczkiewicz, M. (2015). *Detection and classification of alarm threshold.*

Thomas, É., evrat, E., & Benoît, I. (2008). *OVERVIEW ON OPPORTUNISTIC MAINTENANCE .* Szczecin: Centre de Recherche en Automatique de Nancy (CRAN) .

Wallner, P. (2019, december). *Moving Predictive Maintenance from Theory to Practice*. Retrieved from kdnuggets.com: https://www.kdnuggets.com/2019/12/mathworks-predictive-maintenance-theory-practice.html

Wan hazrulnizzzam, m., mohd nizzam, a., Mazli, H., & Deros, B. (2009). *Maintenance Management System for Upstream operations in oil and gas industry: case study.* World Academy of Science, Engineering and Technology.