NTNU
Norwegian University of
Science and Technology

Maintenance Excellence

Adrian Diaz Gonzalez

Reliability, Availability, Maintainability and Safety (RAMS)
Submission date: June 2018
Supervisor: Per Schjølberg, MTP

Norwegian University of Science and Technology
Department of Mechanical and Industrial Engineering

Date 11.06.2018

Faculty of Engineering
Department of Mechanical and Industrial Engineering

MASTER’S THESIS SPRING 2018
FOR
STUD.TECHN. Adrian Diaz Gonzalez

Maintenance Excellence

<u>Contact</u>:
At the department (supervisor, co-supervisor): Per Schjølberg
From the industry: Sverre Iver Aastorp

Address:

NO-7491 TRONDHEIM
Norway

Org.nr. 974 767 880
Email:
mtp-info@mtp.ntnu.no
https://www.ntnu.edu/mtp

NTNU Statnett

RAMS

Reliability, Availability,
Maintainability, and Safety

Master Thesis

Maintenance Excellence

Department of Mechanical and Industrial Engineering

Norwegian University of Science and Technology

Adrian Diaz Gonzalez

Spring 2018

Supervisor: Per Schjølberg

External supervisor: Sverre Iver Aastorp

Preface

This master thesis is written as a part of the international Master's program in RAMS (Reliability, Availability, Maintainability and Safety) at the Norwegian University of Science and Technology (NTNU). The course TPK 4950 – Reliability, Availability, Maintainability and Safety, Master's Thesis; from the Department of Mechanical and Industrial Engineering is a 30 credit Master course where the Master's thesis is carried out.

This project has been carried out by the Master student Adrian Diaz Gonzalez of the Department of Mechanical and Industrial Engineering at NTNU. He comes from Mexico City, where he got his bachelor's degree in mechanical engineering.

The topic of this Master thesis was proposed by Statnett, who is contributing as an industrial partner and the NTNU supervisor Per Schjølberg.

Trondheim, 2018-06-11

Adrian Diaz Gonzalez

Acknowledgment

I would like to thank my supervisor Per Schjølberg, firstly for all time and attention he provided since the very first day we talked about doing this Master's thesis within the maintenance field. Secondly, for the help, guidance and inputs offered throughout the thesis. I would like to point out that I am incredibly grateful for the opportunity I had of doing my Master's thesis having Per as a supervisor.

Furthermore, I would like to thank Sverre Iver Aastorp for provide the great opportunity of having Statnett as an industry collaborator.

Also, I would like to extend a thanks to my family who has been very supportive, as well as inspirational through this last two years that lasted this master. As well, to my dear mom who travelled from Mexico and helped me out the last month by taking care of my dear 18 months old son, Jesper. Finally, a special thanks to my wonderful wife, who despite of been now through her 39 weeks of pregnancy, was incredibly supportive and patient with me through my Master's studies.

Abstract

The concept of maintenance has been evolving in the industry through the years. Maintenance passed from been a necessary evil to a concept where organisations can generate value through maintenance activities. Implementing the right maintenance strategy can generate great benefits to a company by increasing the reliability of the assets, as well as increase production which generate higher profits and create a safe working environment, just to mention some examples.

A great challenge that enterprises are facing is how to determine the maintenance strategy which can comply with all the necessities of the organisation and generate the largest revenue. Other challenges are to know how to invest, which assets to invests and how is going to be the return on investment. Investment must be considered and well analysed since technology is evolving and changing the way companies work by the implementation of industry 4.0 in the maintenance field.

This master thesis focuses on analysing relevant models used to achieve maintenance excellence through study cases. Also, a maintenance excellence model is proposed, which is made based on a relevant review of the different maintenance excellence models that are presented. In addition, the model proposed considers critical factors within RAMS.

Furthermore, technology is changing the way how industries are working with the implementation of industry 4.0. So, through this thesis it was reviewed from relevant condition monitoring techniques that can be applied in Statnett, to the implementation of predictive maintenance and industry 4.0 within the enterprise.

In summary, this thesis examines how to achieve maintenance excellence within the enterprise in combination of the application of new digital technologies available in the market. The results are: reduction of the workload to personnel, optimisation of procedures and creation of effective ways of working without compromising reliability, maintainability and safety.

Contents

Figures

Tables

Chapter 1

Introduction

1.1 Background and problem description

Electricity is one of the most critical infrastructure in Norway, basically means that without electricity a lot of things will stop working. Thus, Norway like other modern society is dependent of a reliable power supply.

Statnett is a national state enterprise responsible for the power grid in Norway. Besides, it is the transmission system operator in Norway who is responsible of assess, develop and maintain the balance between generation and consumption of electricity. Additionally, Statnett works continuously to improve the power grid to be able to satisfy present and future energy demands.

The demand of energy in the country has been increasing in the latest years, and it is expected to continue in this way since both, the society and new technologies, are dependent of electricity consumption. Thus, Norway needs an extensive grid for the transmission of power from producers to consumers.

Since Statnett is responsible of the transmission system, they are also responsible of maintaining in good state their assets. In Statnett, RCM (Reliability Centred Maintenance) plays a big role in the maintenance strategy which is aimed to both new assets and old assets.

Aging of assets is becoming a problem; therefore, it is important to elaborate a maintenance strategy which is going to determine whether the maintenance activity will focus in the lifetime extension of the asset or make an investment by improving or replacing the asset which can have a better working performance and have an uptime improvement.

Technology is advancing and creating innovative solutions within the maintenance field, but before moving towards new technologies, it is important to create a solid maintenance foundation that can support the process all the way to operational excellence which is achieved with maintenance excellence. So, the probability of success when implementing new technologies will be higher since it is going to exist a solid maintenance foundation and a strong organisational structure that can support and sustain those new technologies.

This thesis is going to propose a model to achieve maintenance excellence which can be applied within Statnett, as well as review relevant condition monitoring techniques that are useful in power plants, and how smart maintenance can be applied in those techniques.

1.2 Objectives

This thesis focuses on providing solutions to the problems described above. Thus, the main objectives are:

1) To review literature regarding maintenance excellence, condition monitoring, predictive maintenance and industry 4.0.
2) To study relevant models through study cases to evaluate the effectiveness of the models.
3) To propose a maintenance excellence model based on the models reviewed.
4) To find condition monitoring technologies that can be useful within an electric power plant.
5) To study how condition monitoring techniques can be part of a predictive maintenance program.
6) To study and recommend an implementation process of industry 4.0 to the maintenance field.

1.3 Limitations

In the thesis is proposed a maintenance excellence model which was made based on a review of different relevant maintenance excellence models. Due to external factors, it was not possible to test and evaluate the model proposed within the Statnett organisation.

In addition, ultrasonic condition monitoring applications were reviewed and only relevant study cases where considered. It is important to mention that all the study cases reviewed in this thesis were chosen in order to reflect probable scenario cases that could happen on assets which are common in Statnett’s electric power plants.

1.4 Structure of the report

In this section, it will be commented the structure of the following chapters.

In chapter 2, it has been studied in detail maintenance excellence. It is explained the meaning of maintenance excellence and its foundations which are quite significant when an enterprise is aiming towards maintenance excellence. Many models were reviewed, considering important study cases where the maintenance excellence was measured. By the end of the chapter, it is suggested a model to implement maintenance excellence.

Chapter 3 is about condition monitoring, in specific those techniques that are useful in electric power plants. The standard ISO 29821which is about ultrasound techniques that can be applied to electric equipment such as transformers, was reviewed as part of condition monitoring. Also, it is presented a technical condition assessment through a study case applied in a transformer.

Finally, it is studied how condition monitoring can be part of a predictive maintenance program and its implementation.

Chapter 4 presents the integration of predictive maintenance and industry 4.0. It is analysed how beneficial is to combine predictive maintenance and new digital technologies, which represents the smart maintenance. Through this chapter is reviewed the specific capabilities that provides this new kind of maintenance strategy which aims to maximise assets lifetime, increase equipment reliability and reduce maintenance costs by anticipating failures.

Chapter 5 includes the discussion and conclusion of this thesis.

Chapter 2

Maintenance excellence

2.1 Introduction

Nowadays, maintenance doesn’t mean an expense for organisations, on the contrary, it means a way to create value for the company. Maintenance excellence means to perform well all activities related to maintenance, no matter the strategy or method executed.

Due to complexity of every organisation, it is impossible for experts to create one method to achieve exceptional maintenance performance. So, depending of many factors within the organisation, the methodologies to achieve maintenance excellence shall be selected.

The evolution of technology simplifies human tasks and the maintenance field has been benefited by the creation of tools which make more systematic and easier maintenance tasks. Therefore, today is possible for almost any company to achieve maintenance excellence.

This chapter examines different approaches of how companies created a solid foundation to accomplish maintenance excellence and how they kept with that direction.

2.2 Maintenance excellence

Maintenance excellence represents the way an organisation utilises all its resources to maintain all assets to an acceptable performance level that create value for its customers.

It is mentioned in (Jardine and Campbell, 2001), three types of objectives to the journey of maintenance excellence:

- Strategic: Everything begins with establishing a destination which is the place where the maintenance management should take in the future. The next step is to identify the actual company’s condition, reliability, availability, maintenance costs and maintenance strategies and working environment, as well as if those strategies are achieved. By knowing those things, it will be possible to see the distance between where the company is and where it is going to be. Finally, it shall be established a period and which resources such as human, financial and physical can be used to arrive to the destination defined.

- Tactical: A computerised maintenance management system (CMMS) is ideal to keep on track the maintenance process. This system can be very helpful when planning, scheduling and organising different maintenance activities, also it becomes handful when measure performance at all levels.
- Continuous improvement: This requires a constant effort from everyone involved to make it happen. A method will be needed, so all the workforce shall be engaged with it to achieve a systematic maintenance management.

In order to achieve maintenance excellence, four components must be taken into account as it is shown in the figure below. The figure was inspired on (Campbell et al., 2016).

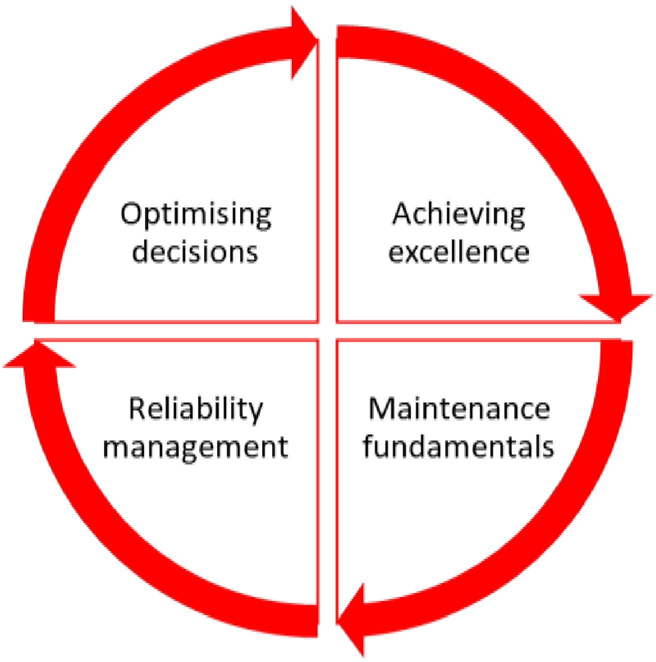


Figure 1. The four maintenance excellence components (Campbell et al., 2016)

- Maintenance fundamentals. This consists on the execution of maintenance management, developing the right maintenance strategies and processes used for equipment reliability. To have an overview and control maintenance processes is part of this step. Also, it is important to measure the results obtained from every process because in this way it is possible to understand, compare and manage processes. CMMS should be considered since this tool helps to organise and schedule activities, as well as to manage spare parts.
- Reliability management. It is important to have an overview and a robust understanding of how works all assets in the plant. By doing a criticality analysis of the equipment, a maintenance strategy can be developed to make those critical assets more reliable. The reliability centred maintenance (RCM) methodology is recommended in this step.

- Optimising maintenance decisions. To optimise maintenance strategies on assets, data about failure frequency is required to find failure probabilities and predict when the next failure will take place. So, at this point is where reliability management takes place.
- Achieving excellence. To get to this point, firstly is necessary to assess the current state of the plant and be aware of the gap between where the company currently is and where it will be. Then, the fundamentals are build and implemented accordingly to a strategy and at last the output of previous steps is reviewed and evaluated. At this point, the previous three components of maintenance excellence should be well applied.

Maintenance managers put big efforts to excel maintenance operations because they are aware of the great value that represents maintenance to the company. Under the following example which comes from (Campbell et al., 2016), it will be shown the benefit of maintenance excellence and the value that creates for a company.

A company that does large investments in maintenance excellence is considered for this example. So, the company wants to know the result of its investment and to do that, the capacity needs to be measured:

$$\textit{Capacity} = \textit{Availability} \bullet \textit{Utilisation} \bullet \textit{Process rate} \bullet \textit{Quality rate}$$

It is assumed that all assets are having a desired performance and quality's production is acceptable. Regarding cost, it is quite complex to predict it since many factors can contribute to that. Anyway, it is known that breakdowns are costly for the maintenance department. So, it is used a rule of thumb to estimate the cost-saving of an industrial environment:

$$\$1 \textit{ Predictive, Preventive, Planned} = \$1.5 \textit{ Unplanned, Unscheduled} = \$3 \textit{ Breakdown}$$

As the rule of thumb states, planned maintenance is cheaper than unplanned and both are even cheaper than breakdowns. Thus, a unit of maintenance effectiveness costs $1 when planned, $1.5 when unplanned and $3 when a breakdown happens.

So, it is assumed that the total annual maintenance budget is $100 million with a distribution of 50% planned maintenance, 30% unplanned and unscheduled maintenance and 20% breakdown. Then,

$$(50\% \bullet 1) + (30\% \bullet 1.5) + (20\% \bullet 3) = 50 + 45 + 60 = 155 \textit{ “equivalent planned units”}$$

$$\textit{Planned work costs } 50/155 \bullet \$100 \textit{ million} = \$32 \textit{ million, or } \$0.645 \textit{ million per unit}$$

$$\textit{Unplanned work costs } 45/155 \bullet \$100 \textit{ million} = \$29 \textit{ million}$$

$$\textit{Emergency work costs } 60/155 \bullet \$100 \textit{ million} = \$39 \textit{ million}$$

Now, a maintenance improvement is considered, where the work distributions change from the previous one mentioned above. So, now it is considered 60% planned maintenance, 25% unplanned and unscheduled maintenance and 15% breakdown:

Planned work costs $0.645 • 1 • 60% = $39 million

Unplanned work costs $0.645 • 1.5 • 25% = $24 million

Emergency work costs $0.645 • 3 • 15% = $29 million

Total = $92 million

Saving potential = $100 million - $92 million = $8 million

As it is shown in the example, maintenance excellence can represent an acceptable revenue for the organisation and therefore it is crucial to develop a solid foundation and the right strategy for the company, aiming to create great value through maintenance activities.

2.3 Foundations for maintenance excellence

The following part comes from an article (Dunn, 2001). It is about a discussion among the board of directors of the Foundation for Industrial Maintenance Excellence, which is a group that conducts the North American Maintenance Excellence (NAME) Award program. There were nine persons who intervene in this discussion: Richard L. Dunn (Editor at Plant Engineering) , V. Robert Schmalbach (Chairman, Foundation for Industrial Maintenance Excellence), Thomas P. Williams (Manager at North America Plant Engineering 3M), Rick Herold (Director of Manufacturing Engineering at Harman-Motive, Inc.), Ronald H. Morgan (Director Manufacturing Engineering at R. J. Reynolds Tobacco Co.), John L. Blumenshine (Vice President at Facilities S&C Electric Co.), Ed Mayer (Director Plant Engineering at Syngenta), Don Asmus (Plant Maintenance Manager at Buckeye Florida) and Dennis Hartman (Consultant at Dupont).

The discussion focused mainly in two concepts: What makes a successful maintenance organisation? And how managers can work towards maintenance excellence?

2.3.1 Where to start to pursue maintenance excellence?

Accordingly to the article (Dunn, 2001), a good starting point of maintenance excellence is to understand completely the business mission of the company, because maintenance activities are going to be planned and carried out accordingly to the company's business mission. i.e. possibly, in some cases cost is more important than uptime and reliability.

A maintenance excellence foundation is going to be needed in the company. Thus, it is important to define roles and responsibilities of the workforce in order to build up that foundation, which is going to focus on having the assets maintained and working to an acceptable level (Dunn, 2001).

A strategic plan must be developed, it should consist into, firstly, realise the actual situation; then, identify goals and in which way the goals can be measured. Also, establish priorities and it is crucial to have knowledge of what is important for the company and for the customer. As well, part of the strategy includes to select the right people for the job that needs to be done, to be aware of the skills needed to execute the working order and ensure that the workforce who is going to perform the maintenance activity receives the right training in order to do a good job (Dunn, 2001). Having in place all recommendations mentioned above, the company will be certainly driven to the right direction, where the company will be able to measure and evaluate the whole process.

The maintenance department must be in line with the enterprise business plan, the same plan that all departments and personnel must follow. Maintenance is quite important for the company because is basically the intermediary between the company and the assets which produce the enterprise's revenue (Dunn, 2001). So, it is important to be aware of what does maintenance represents for the company and how it contributes to the company's strategy, as well as how does it impact other areas within the organisation.

2.3.2 How to get management support?

An important part needed to develop Maintenance Excellence within the company is to get management support. Especially if the maintenance organisation is not mature. It is possible to achieve some goals within the Maintenance Excellence plan when at least operational management offers support. In the article (Dunn, 2001) is mentioned by one of the persons involved in the discussion that a good strategy to get top management support is to let them know that the maintenance department is willing to continuously improve the maintenance process. It is essential to let management know the different limitations that can exists in the organisation, such as capacity limitation, resource limitation, etc. so they can be aware of the actual situation of how the organisation is operating.

It is relevant for the company to understand how critical is to conduct planned maintenance and the good influence of it. If all assets are working as they are supposed to and have a high availability is due to a good maintenance policy. Reliable assets when operated correctly, can provide a predictable capacity or output with 100% quality, since they are going to have high levels of availability (Dunn, 2001).

2.3.3 Where to start to get organised to execute improvements?

It is mentioned in (Dunn, 2001) that it exists two crucial elements in the strategic part of maintenance excellence in order to start getting organised to carry out improvements. Firstly, plant documentation which includes assets, parts, etc. all those engineering documents of the plant. Secondly, to assess the equipment's criticality, since the strategic will be build up according to the criticality.

It was found in the maintenance excellence award (Dunn, 2001) that companies which have very low-cost maintenance operations are those that:

- do maintenance planning and scheduling
- do PM and PdM
- have a well-developed CMMS.

2.3.4 How companies can move out from corrective maintenance mode and start moving towards maintenance excellence?

Firstly, it is crucial to know where the company is standing regarding the maintenance pyramid hierarchy, so it can be known what is working well and what doesn't. So, this is a good start since the areas where improvements can begin will be identified.

In (Dunn, 2001), it is presented the "plant engineering pyramid" or "maintenance pyramid" which was used at 3M and created by Tom Williams. The pyramid is showed below, where concepts related to environment, health and safety plans are considered to create a solid foundation.

The pyramid is formed by three blocks, fundamentals, technologies & tactics and optimisation, which are aimed to achieve operational excellence.

The foundation of the pyramid starts with the first block-fundamentals. In this block, it is crucial to establish the maintenance fundamentals because from this starting point the pyramid is going to be build up. So, the maintenance strategy is defined in detail and all areas and activities related to the plant are considered.

After having well established the maintenance foundation, then the second block-technology & tactics takes place, where all technologies and tools available are utilised in order to support and make more efficient the maintenance management and all activities related to maintenance. At this point, different maintenance techniques are used such as failure mode analysis and total productive maintenance, just to mention some examples. Also, reliability engineering and different maintenance strategies are implemented such as predictive maintenance, where maintenance activities are planned based on the tactics and strategies defined by the management.

In the last block-optimisation, a maintenance strategy which is going to optimise maintenance processes is implemented, also it is measured the effectiveness of the strategy. It is recommended to implement reliability centred maintenance (RCM) which is a technique that focuses in the reliability of assets and its components. It is a structured methodology where the maintenance strategy is defined considering asset's operation by analysing how the item will fail, determining the consequence of each failure and assessing the maintenance strategy that is going to be executed on the asset with the finality of achieve an acceptance performance of the system (Labib, 2010). For measuring the effectiveness of the strategy, the overall equipment effectiveness is recommended, where equipment's efficiency is measured.

When the organisation has achieved the top of the pyramid, operation excellence is achieved. Also, the right side of the figure below divides the pyramid in two areas, independent and interdependent, which means that the maintenance department at the organisation is going to move from independence to interdependence, where many plants in the organisation and other plant groups such as business partners work together towards the same goal.

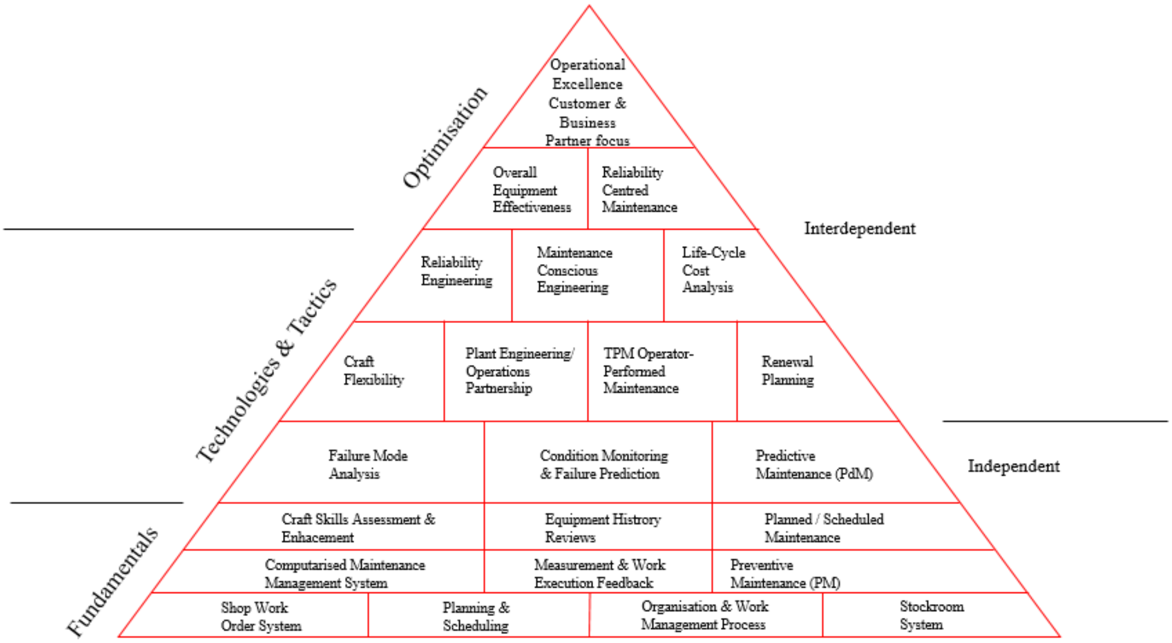


Figure 2. Plant engineering pyramid or maintenance pyramid (Dunn, 2001)

When referring to the maintenance pyramid, it is important to mention that different pyramids can be found, where normally those pyramids are tailored according to a specific case, but at the end, the pyramids don't differ much from each other. Below, it is showed the reliability pyramid from the Maintenance Excellence Institute which also aims to operational excellence. That pyramid is considered since is newer than the pyramid presented before.

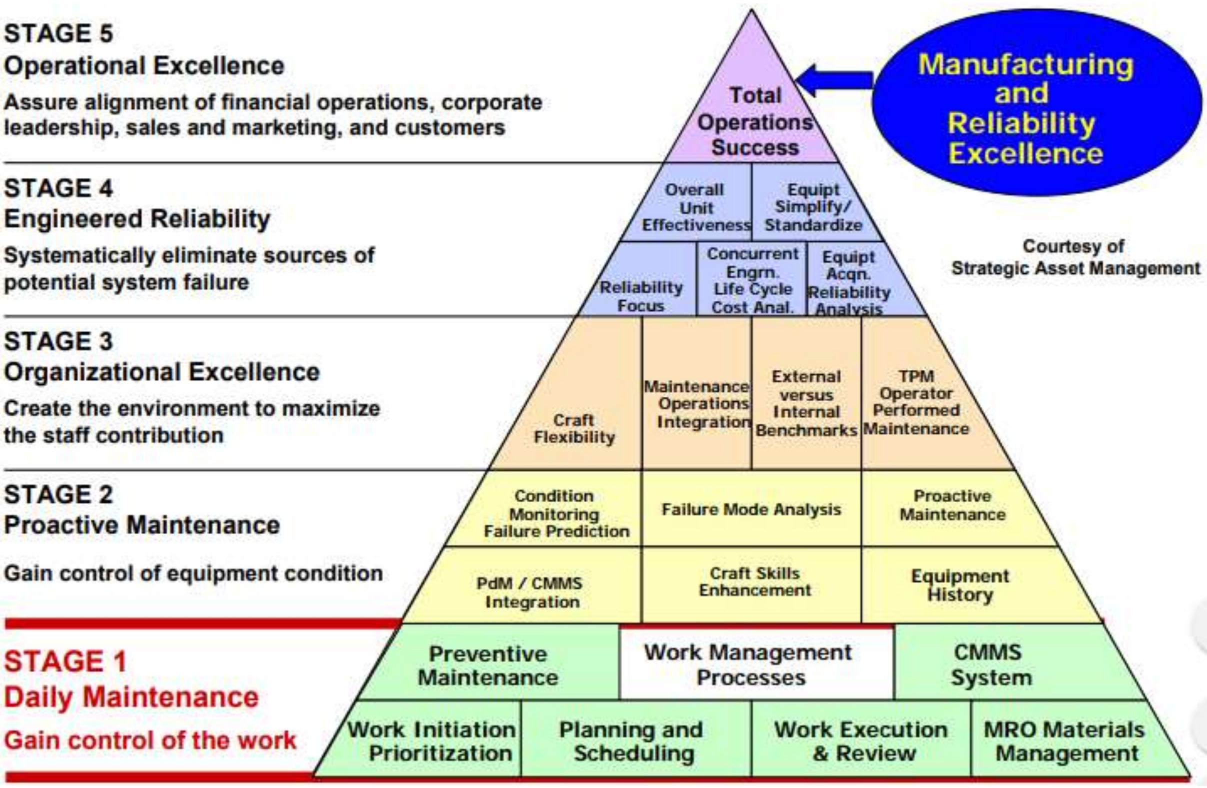


Figure 3. The reliability pyramid from the Maintenance Excellence Institute (Institute, 2010)

The pyramid above is divided in five stages which working together accomplish manufacturing and reliability excellence. Below, it is going to be detailed each of the pyramid's stages:

- Stage 1-Daily maintenance. This is considered to be the maintenance fundaments where work management processes are carried out. Maintenance strategies, methods and tools are defined at this point. Having established this stage, a solid foundation is created and ready to support the whole structure.
- Stage 2-Proactive maintenance. Maintenance strategies are established at this stage, also it is provided techniques that help to make those strategies more effective. As well, in this stage it is required that the workforce acts proactively, which is to anticipate and act before failures are presented.
- Stage 3-Organisational maintenance. This stage consists in creating a working environment which enables the personnel to work in an effective way. The maintenance performance is maximised by implementing strategies that aim to constant improvement of the maintenance structure and processes.
- Stage 4-Engineered reliability. This stage is focused on reliability where failures in the equipment are identified through systematic analysis. Techniques as FMECA and RCM are suggested to increase the reliability of assets.
- Stage 5-Operational excellence. This stage is achieved as a consequence of the correct implementation of previous stages. In addition, it is needed to coordinate financial operations, corporate leadership, sales & marketing and customers in order to achieve total operational success, manufacturing and reliability excellence.

After analysing both of the pyramids, it was identified the same goal, which is to achieve and sustain operational excellence. Operational excellence is achieved by maintenance excellence, where both of the pyramids focus. The pyramids are similar and slight differences can be found. Besides, both of the pyramids need a solid maintenance foundation, it is also required to establish in detail a maintenance strategy that can take the company all the way to its goal where a constant improvement is crucial to ensure the success of the process.

After strengths and weaknesses areas of the company are identified, it is recommended to assess the current situation of the company using as reference the maintenance or reliability pyramid. So, a plan can be defined in order to move towards maintenance excellence.

To change from doing CM (too much unplanned or emergency maintenance) to Maintenance Excellence, a criticality analysis is needed and it will show the strategy to follow, which assets are necessary to maintain with high uptime and which ones can run to failure (Dunn, 2001). So, an initial maintenance plan can be to cut emergency/unplanned maintenance and complete 100% on-time the planned work.

When things are on place and PM is carried out, then assets are not suddenly breaking down anymore, so the department can use more people/resources to do continuous improvement in projects, to get into predictive functions and to improve reliability in the assets (Dunn, 2001).

To be a world-class maintenance company, it is essential to document in an effective way what and how maintenance is involved in the company. A well-developed CMMS and managing materials/spare parts are critical to achieve maintenance excellence (Dunn, 2001).

2.3.5 What is excellence in maintenance materials management?

Storerooms play a big role in the maintenance activities. So, the goal of maintenance material management excellence is to spend the minimum of investment in materials/spare parts and have them available when needed.

A plan must be developed to have in the storage place those critical parts/materials needed to maintain production as it is planned. Scheduling is critical, so the purchasing department must know how long takes to get a spare part from the vendor or manufacturer to the plant. Also, how to plan and schedule the maintenance activities before they take place or are implemented.

Also, it is important to have a good organisation in the storeroom, to have things on place with description and name, so a spare part does not have different names for different people. A crucial factor to achieve this, involves a good communication among the company and suppliers.

2.3.6 Conclusion about foundations for maintenance excellence

When a company is moving towards maintenance excellence some steps which are previously mentioned need to be followed in a structured way. It was also discussed how to start the maintenance excellence process and how keep it running. So, the key elements in this article are: firstly, is to organise, then know your assets and have a system which can be in control of the inventory, for instance a CMMS. Afterwards, it is required to be systematically organised to approach the problems in the plant and finally to plan how the business needs to be structured.

In addition, the maintenance pyramid presents at the very top as a goal operational excellence, which is a combination of many concepts that working together can take an organisation to that goal. Operational excellence is a result of the maintenance excellence, where strategies are applied in an effective way, so high availability of the equipment (uptime) is achieved. The maintenance pyramid is a solid structure since it covers all concepts related to RAMS, where reliability, maintenance and safety are considered at all time.

The maintenance manager plays a big role in the maintenance excellence process. The manager must have a good understanding of not only maintenance, but also understand the business, processes, equipment, materials/spare parts and human resources, finally contracting and contractors.

The figure below mentions some specific areas within an organisation where it is crucial to excel their performance to have a bigger chance of success towards maintenance excellence.

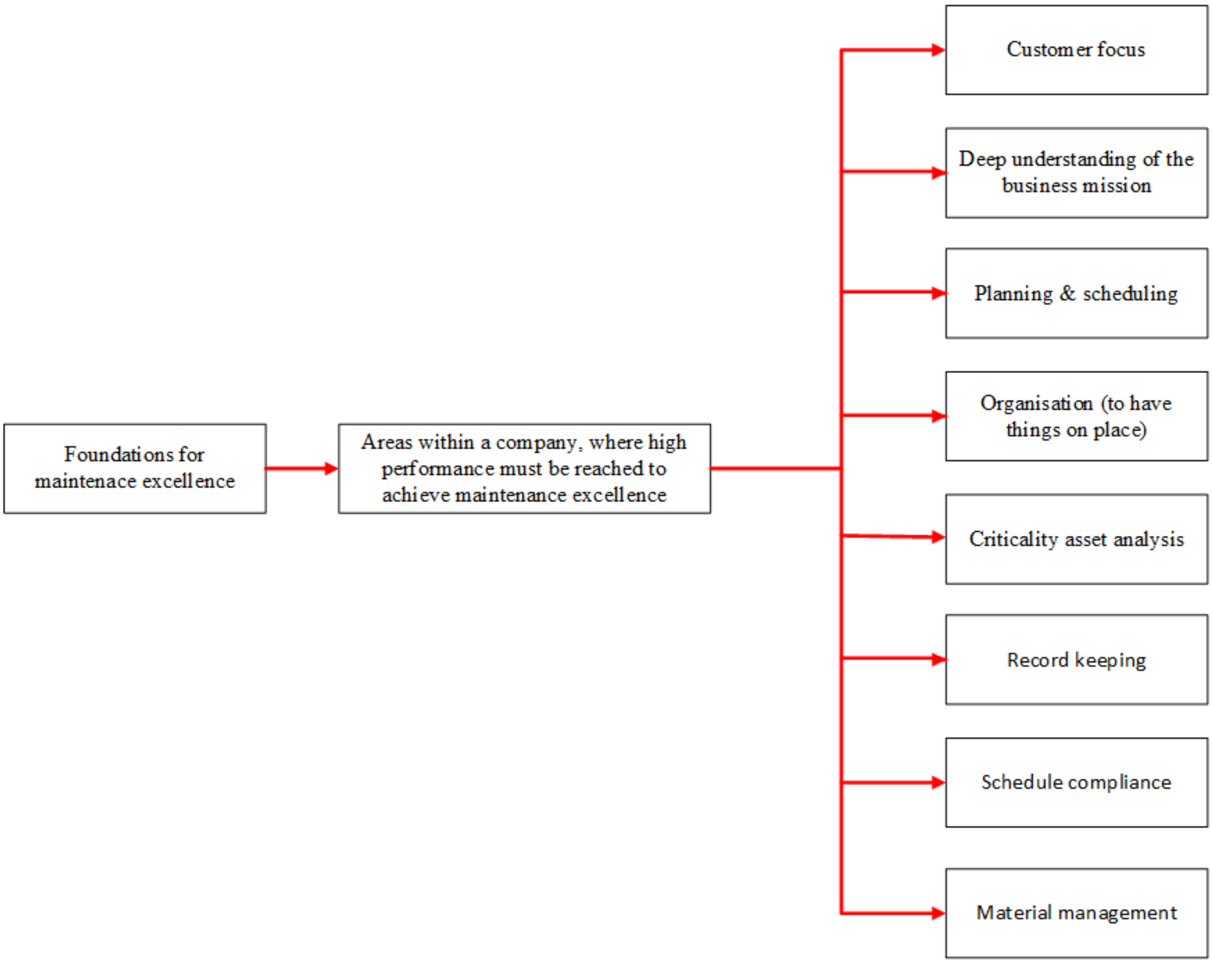


Figure 4. Foundations for maintenance excellence

2.4 Maintenance excellence models

It exists a great diversity of methodologies to implement maintenance excellence within an organisation. Indeed, every single organisation is different, thus it doesn't exist one methodology towards maintenance excellence. Therefore, in this section it will be introduced different methods and models that aim to the same goal, which is to achieve maintenance excellence within an organisation.

2.4.1 Implementing maintenance excellence

This approach comes from (Jardine and Campbell, 2001) and consists of three steps which put in place a maintenance excellence program:

- Step 1: Discover. This consists in knowing exactly the level of maintenance maturity of your organisation. A strategy and goals shall be implemented. Research and benchmarking are useful tools when doing this step.
- Step 2: Develop. The maintenance excellence foundation must be build, also a plan with a timeline must be created. All employees, from management to operators must be engaged to carry out the plan.
- Step 3: Deploy. In this step is important to have the right personnel from the different activities that need to be carried out, each of those activities shall be documented. Establish milestones, choose pilot areas, installation and training are important activities which must be considered.

The figure below, which comes from (Jardine and Campbell, 2001), shows a model that includes how the three steps previously mentioned are integrated into the maintenance excellence model.

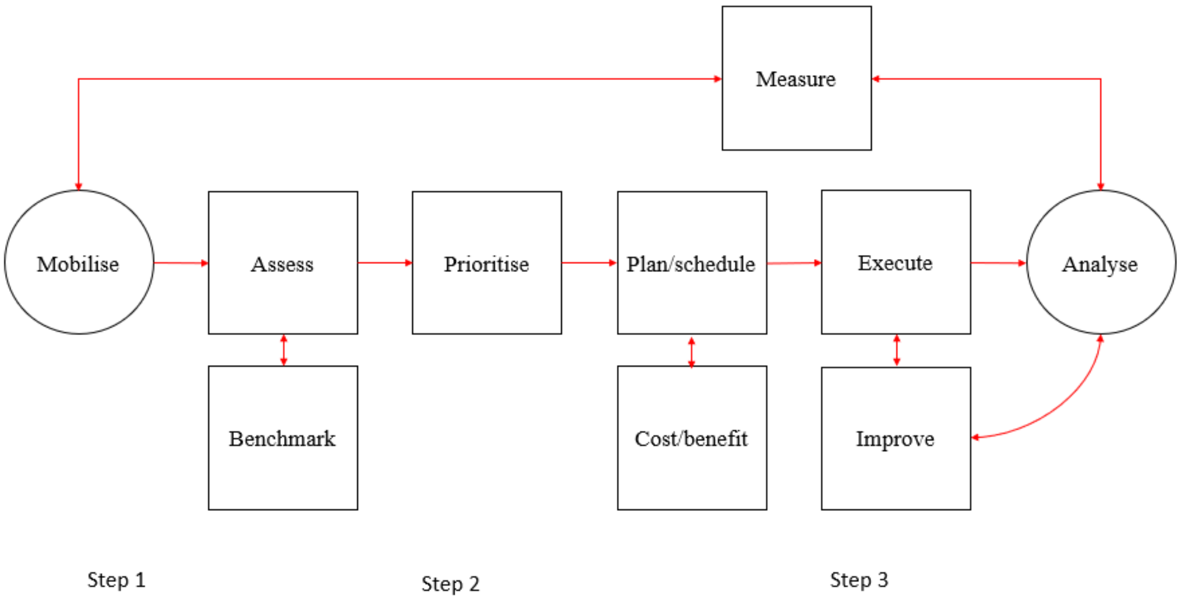


Figure 5. Maintenance excellence implementation model (Jardine and Campbell, 2001)

As it can be seen from the picture above, step one consists of mobilise, asses and benchmark; step two consists of prioritise, plan schedule and cost benefit; step three consists of execute, improve and analyse.

The following will describe in detail all sub-steps that belongs to each of the three main steps previously mentioned.

Step1. Everything starts with mobilise in step one. Here it is meant to define the structure of the project and choose a work area as a pilot project.

A working plan must be created, so the plan will present modifications as the project develops. Then, assess consists in knowing where the company is regarding maintenance management by identifying the areas of strength and weakness. To do this, it must be answered some questionnaires and templates and then the results can be compared with the results of the best practice companies are doing. This activity will show the company where to change and how to do it to achieve same results as other companies that do best practices.

Finally, benchmark is the last part of this step. To really take advantage of this, it is crucial to identify from the previous part (assess) what the organisation needs to improve, then select those key factors for maintenance success that can really impact the company and take it to the desired goal. It is recommended to look at both outside and inside your industry to those ones who perform with excellence the key factors you need for your maintenance success. After that, compare performance measures, analyse and learn the processes that took others to where you want to go and reach excellence maintenance (Jardine and Campbell, 2001).

Step 2. To prioritise is the first phase in this step and its reason is because it is not possible to implement everything at once. Thus, it must be planned to implement gradually those activities with great benefits in a short period that are reachable, so eventually more complex activities can be implemented with the time. Afterwards, plan & schedule take place, to do this activity is recommended to use software tools, it exists different programs in the market that could be used to make this activity easier and keep on track the realisation of the project.

While doing this step, it is recommended to include personnel from different disciplines that are related to maintenance to ensure the success of the project. The last part in this step consists in calculate the cost-benefit of the investment, it is important to take into account that when cost is involved, it is possible to get an accurate output of the benefit, whilst to estimate benefits from other activities such as training and consulting, can be challenging to quantify them and get an accurate result for cost-benefit (Jardine and Campbell, 2001).

Step 3. Execute is the first thing to do in this step. To do this, it is recommended to start with a pilot project where all implementations can be tested and when everything works as is supposed to, a full rollout can be implemented; by doing this, the probability of success is higher.

When designing the plan, it is quite important to be organised and to detail every single part of the plan; then, include everyone involved and show them how the plan looks like, so everyone is aware of their responsibilities and it will be visible to see and measure the progress of each step.

Finally, the evaluation of the pilot project takes place. Analyse the results obtained and see if the output corresponds to the settled expectations. Take into account that in spite of how well done was everything carried out in the pilot project, it always exists something to be adjusted or improved (Jardine and Campbell, 2001).

2.4.1.1 Benefits and limitations of the model reviewed

This is a complete maintenance excellence model that considers every single part of the maintenance organisation. It provides an organised method to start the journey towards the maintenance excellence.

This model consists on implementing maintenance excellence through three systematics steps, where firstly it is necessary to know the current maintenance maturity level of the organisation and identify strengths and weakness of the maintenance department. After identifying where the company stands, regarding the maintenance point of view, it is possible to define the structure of the model which will take the organisation to the desired goal.

Then, the maintenance excellence foundation must be build and planned. Here, in this step it is possible to detect some limitations because the model doesn't provide exactly a systematic way to build up and plan the solid foundation needed for the correct execution of the model. Indeed, it is necessary to prioritise activities, plan & schedule and to calculate the cost-benefit of the investment, but that is not enough to satisfy the requirements of building a solid maintenance excellence foundation. Other factors that involves reliability of the assets and safety of the personnel, should be considered as well to be a complete model that consider all areas.

The last step of the model, when this is applied in the company, it requires complete engagement of all personnel involved, so the probability of success during deployment can increase. A pilot project is recommended, so after a while this can be evaluated, thus identify the areas of improvement and if the pilot is successful, then the model can be rolled out to other projects.

From a RAMS point of view, this model lacks important aspects such as risk assessment and risk management of the working areas and assets. Also, a reliability program that optimises the maintenance strategies is needed.

2.4.2 A holistic approach to maintenance excellence

Accordingly to (2017), maintenance excellence goes beyond strategies or processes of the maintenance department. This approach takes maintenance as a journey, not a destination, which means that it is an ongoing process that is in constant progress.

In (2017), Thadalil Santhosh states that a continuous world class performance in a factory begins with reliability and maintenance excellence. KPI’s such as reliability, availability, performance and quality have high influence in the operational excellence of the diverse activities in a company. To achieve reliability excellence, it shall be implemented a methodology that integrates leadership and a hefty management change to sustain an important concept which consists in the increment of asset reliability that will be guaranteed by maintenance excellence, considering work processes, business and a workforce represented by committed employees.

An optimal operational process that it is characterised for the absence of breakdowns, slow performance and defects, is achieved by the Sarens Nass Smet Industries (SNSI) holistic approach to maintenance excellence. This optimal operational process also influences the working environment, creating a safe working area.

The SNSI holistic approach focuses on two things, autonomous maintenance and planned preventive maintenance. The output of this approach is taking to the limit asset’s operational efficiency supported by continuous progress (2017).

Autonomous maintenance consists in sharing responsibilities and to assign routine tasks to the right person; for example, simple maintenance activities such as cleaning, lubricating and equipment inspections are assigned to an operator. By this, the operator oversees the condition and performance of the asset, so the operator will be able to identify possible failures that can lead to an asset breakdown. Considering the previous example where it was described the labour of an operator, SNSI’s approach empower the relationship between the operator and the equipment that he/she is in charge on.

Maintenance routines should be clear, assigning the right person for the required maintenance task. This will maintain the asset in good shape, so high productivity (increasing uptime, reducing cycle times and eliminating defects) can be achieved and this will avoid sudden equipment failure or breakdowns.

Planning preventive maintenance is cheaper than doing corrective maintenance. A planned, scheduled and well documented maintenance is highly recommended to achieve maintenance excellence. Also, maintenance activities should be scheduled when the equipment is not operating (2017). Maintenance excellence also contributes to reduce spare parts inventory costs, since all activities are planned and scheduled, so a better overview of spare parts is achieved.

SNSI's approach recommends working on Kaizen (continuous improvement). A culture of constant improvement is needed in the company. Team work in reduced groups of workers is recommended to work proactively to accomplish improvements in equipment operations. Other benefit of this approach is the combination of cross-functional employees that identify, register and solve problems. By doing this, a continuous improvement should be achieved.

Operational excellence, which derives from maintenance excellence, can be ensured by measuring often efficiency and effectiveness of the process; utilising key metrics and the appropriate knowledge through employee training and development.

The figure below, which comes from (2017), it is a table that represents how the reliability excellence is achieved through planned preventive maintenance. It also describes how the SNSI's philosophical approach is used in certain cases of operational losses such as downtime losses, speed losses and yield losses. The different operational losses cases are described, as well as the SNSI's approach used to overcome to the losses.

Table 1. Reliability excellence through planned preventive maintenance (2017)

Operational Loss	**Instances**	**Description**	**SNSI`s Philosophical Approach**
AVAILABILITY (Downtime Losses)	Breakdown (Unplanned stops)	Random machine failures causing stoppages of more than 10 minutes	• Autonomous maintenance • Planned maintenance (equipment care) • Focused continuous process improvement
	Set-ups/Adjustments (Planned stops)	Time lost due to a planned event such as a changeover, set-up or make ready event	• Education & training programs
PERFORMANCE (Speed Losses)	Reduced speed (Slow cycles)	Not running at the ideal speed caused by wear/poor maintenance/operator inefficiency	• Standard machine set-up • Standard process set-up • Planned maintenance • Education & training programs
	Minor stops/idling (small stops)	Stoppages of less than 10 minutes caused by misfeeds/blocked or dirty hoses	• Autonomous maintenance • Focused continuous process improvement

QUALITY (Yield Losses)	Yield (Start-up losses)	Time taken for the equipment to reach stable process after changeover or on starting the machine	• Planned maintenance • Standard operating procedures/checklist • Education & training programs
	Defects (Scrap/rework)	Customers rejects requiring rework/scrap during operations	• Autonomous maintenance • Focused continuous process improvement

2.4.2.1 *Benefit of the SNSI holistic approach to maintenance excellence*

When analysing this method from a RAMS perspective, the model is based on reliability and maintenance excellence where it exists a mutual influence on each other; effective maintenance strategies on assets provides higher reliabilities on those assets. In addition, the model considers the safety related to the workers by ensuring safe working areas.

The strength of this approach is found by operational excellence, where the reliability and availability of assets is directed influenced by the maintenance activities, which means that performing maintenance excellence in a company will result into high reliability, availability, uptime and production. Also, a continuous improvement is achieved by applying Kaizen on all the processes and constant training to the personnel.

2.4.3 An enterprise approach to reliability

In (Farr, 2009), it is demonstrated how a maintenance excellence process (MEP) was applied in Ash Grove Cement Company. This company has been implementing an Enterprise Reliability Strategy (ERS) for more than 10 years. Through the paper, the initial vision of MEP, its objectives, organisational structure behind implementation, lessons learned, and the impact created in the company are discussed.

The benefits of implementing a ERS are considerable costs reductions and the increment in production without investing in new equipment (Farr, 2009).

To implement ERS in Ash Grove Cement Company and its different plants, the MEP needed to be implemented as well. So, from the very beginning, some initial objectives were defined and consisted on:

1) *Reduce Maintenance Cost per ton of production by 20%*
2) *Reduce Kiln Stops Due to Maintenance by 50%*
3) *Increase Kiln Uptime by 5%*
4) *Reduce Inventory Costs by 20%*
5) *Reduce Man-Hours per ton by 20%*
6) *Increase level of Planned Maintenance to 85%*

7) *Reduce Recordable Accidents by 20%*

8) *Improve Employee Skill Levels*

9) *Establish reliable equipment maintenance, repair, and replacement records*

10) *Enhance morale among management and the hourly workforce as they learn to enjoy a proactive environment instead of surviving in chaos.*

The MEP implements processes and procedures that manage assets in an effective way on the daily basis. It is required that all personnel involved within MEP understands the process deeply and follows up what has been established for the process.

There are two important factors which are applied for work processes, productivity and proactivity, where special emphasis is placed since these are crucial for the application of MEP.

By Productivity, it is meant to increase production in an effective way to create cost saving or reduce costs. For example, for an employee to work productively, firstly he/she must understand the job's assignment, then the resources/tools needed for the assignment should be in place and available, equipment and plant must be coordinated to carry out the activity needed and so on. This means that a lot of people is involved in the process, so the worker can carry on his/her assignment, also, different things must be in place and ready when needed. So, work planning and work scheduling are vital to work productive in the plant.

By proactivity is meant that all work force can act or control a situation rather than responding to it after it has happened, the personnel must anticipate and act in advance towards unexpected situations and failures that can create any problems. Being proactive helps to anticipate problematic situations, so they can be identified before they turn to be serious or catastrophic incidents in the plant.

Methods as PdM can help the company to act proactively (Farr, 2009) because assets are monitored regularly. Thus, it is possible to know their actual state and current degradation, so breakdowns can be foreseen and avoided.

2.4.3.1 Preparing for implementation – Organisational implementation structure

Ash Grove Cement Company decided to implement ERS in all its plants. Therefore three groups, which are in detail described below, were formed to guide the implementation process and roll out the ERS (Farr, 2009).

- Group 1. Executive steering committee.

This group was formed by: Vice-presidents from manufacturing & manufacturing services. Task: Set a long-term strategy and chose important topics.

- Group 2. Consulting firm.

Consultants had expertise in work process development, work process implementation and reliability engineering.

Task: They were responsible of guiding the steering committee.

- Group 3. MEP task force.

This group was formed by: Plant managers, maintenance managers and corporate support personnel.

Task: In charge of the tactical details of the implementation. They reported directly to MEP steering committee.

This three groups were used during the planning phase. Afterwards, when MEP moved from planning phase to implementation phase, each plant of the enterprise created a MEP action team.

MEP action team was formed by minimum: plant manager, production manager, maintenance manager, planner, purchasing agent and a crew supervisor; and the team was accountable for specific implementation of plant details such as:

- Redefine roles and responsibilities for some workers.
- Organise and establish agendas.
- Identification of training requirements.

Also, a site champion was designed to each MEP action team for every plant. This worker was accountable for leading the MEP action team. The site champion was an employee who had special, intensive training on MEP concepts. This employee was chosen among: maintenance managers, planners, production superintendents, plant engineers and clerks. His/her task was basically to sell the MEP concept and to supervise MEP implementation.

Training conferences and workshops sponsored by consultants were attended by site champions and they frequently travelled to other plants to interact with each other.

Consultants guided and supported the implementation process. All along early phases, consultants were organised geographically, thus they were accountable of several plants. During latter phases they were organised based on their expertise, so they travelled to the plants where they were required.

Executive support was of great importance during the implementation process of MEP. The president of the organisation made MEP the company’s top priority. So, MEP steering committee, task force, site champions and employees, all together contributed in the creation of the maintenance excellence processes.

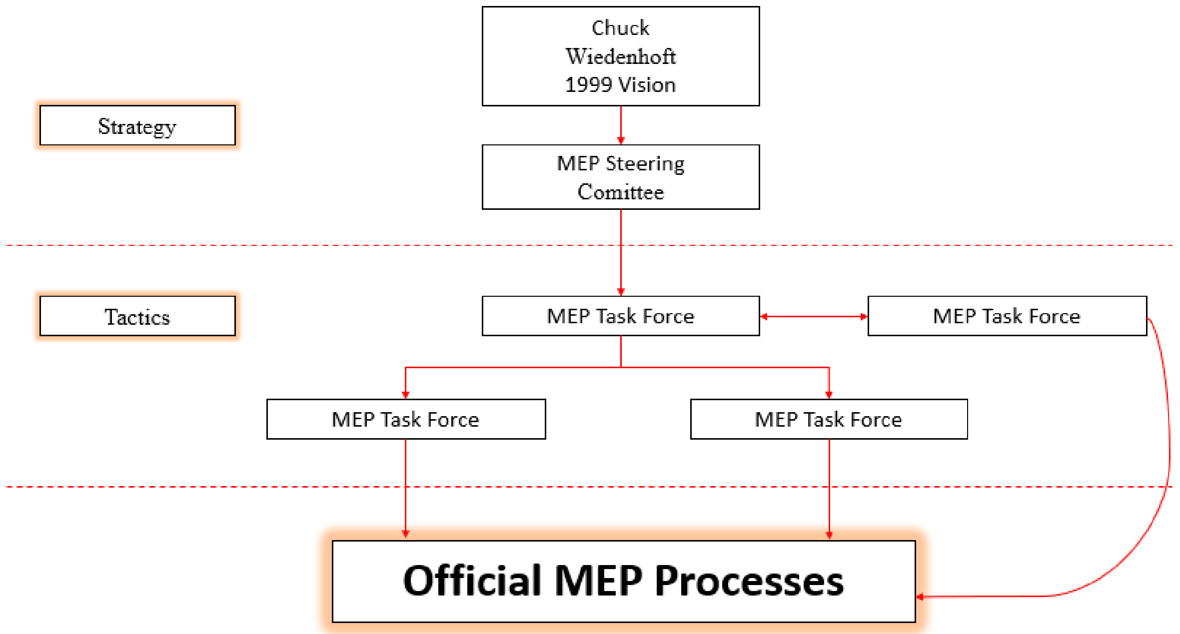


Figure 6. The organisational implementation structure (Farr, 2009)

The figure above, which comes from (Farr, 2009), shows how the official MEP process was carried out in Ash Grove cement company. From the figure, it is seen that the organisational implementation structure was divided into strategy and tactics, where the MEP steering committee was responsible for implementing the strategy and the MEP task force was responsible for implementing the tactics

2.4.3.2 Preparing for the implementation – Standardising the data structure

It is mention in the article (Farr, 2009) that a key element for an organisation to implement an ERS is the standardisation of the data collection structure. Having this in place, it is guaranteed that decisions, procedures and performance indicators are effective; that personnel is going to be able to use the correct tools and software necessary to provide the correct solution or output, as well as an accurate communication among the organisation. For example, it is necessary to use a CMMS that is functional for all locations and work processes used in the plants to accomplish the MEP objectives. Also, a CMMS can help to the standardisation of equipment classification, for example, when using the system unapproved names, these are not going to be possible to be used or accessed in the system.

2.4.3.3 Preparing for the implementation – Establishing equipment criticalities

To achieve the MEP, it was necessary to establish a criticality analysis of the assets. This analysis, ranks the equipment accordingly to a criticality rank defined by the company (Farr, 2009). Resources are concentrated in what was defined the most important equipment after the criticality analysis was carried out, so the reliability of those assets could be improved.

After carrying out a criticality analysis of the assets, it was identified the crucial assets and it was determined what kind of maintenance activity was going to be applied to those assets. Also, it was decided on which equipment will be applied condition monitoring technology.

The company defined the criticality rankings according to: significant impact, measurable impact, potential impact and no impact.

2.4.3.4 Implementation – Work processes

MEP Task Force created an implementation schedule after the data structure was in place. This concept was carried out in 3 phases, where every six months it was implemented work processes, performance indicators and associated standards in small quantities.

Reliability consultants made flow-charts & instruction sheets which were reviewed, modified and approved by the MEP task force. Then a pilot plant was chosen to test out the concept intensively for 3-5 weeks, during this time the pilot was further refined. After the pilot was complete and successful, the Site Champions gathered in a central location for training, which consisted on a formal roll-out schedule to the rest of the plants.

Finally, consultants were on place in each plant, monitoring the process and providing coaching.

2.4.3.5 Implementation – Maintenance & parts strategies

Several years ago, the company had a corrective maintenance policy which was very costly, and failures happened quite often. Afterwards, the maintenance policy got better when the company carried out a PM policy (Farr, 2009). So, an experienced employee was accountable for inspecting the equipment and due to that, this person was able to detect failures before they occurred. Unfortunately, this experienced worker didn’t write down in detail the activities and procedures that was carried out. So, when this employee wasn’t at the plant, no one else was able to perform the PM activities.

Therefore, MEP focused in writing down the procedures and details used during inspection. So, by documenting activities and processes, the knowledge was available for everyone at the plant when it was required.

Strategies were built based on Failure Modes, Effects & Criticality Analysis (FMECA). This is a systematic analysis used for technical systems which consists on identifying the different failure modes of subsystems or component parts of an asset/equipment that can be presented while the asset is on operation; this system reliability method also assess the effects of all the failure modes found in the system (Rausand, 2013). The benefit of this analysis lies in having identified all possible failure modes, so improvement actions are developed in order to prevent those failures to happen, and by this the reliability of the asset/equipment increases (Farr, 2009).

Reliability engineers were hired to develop FMECAs for the different assets and those documents helped when de PM policies were created. So, the maintenance strategy included the employee (a worker with a defined skill set) who was going to perform the maintenance activity, description of the inspection, its frequency, how the activity should be carried out (i.e., equipment should be shut down or running) and how much time does the activity takes to be performed by the skilled employee.

The figure below shows a typical FMECA table which is a sample portion of the analysis made to a gearbox , the information of the FMECA table comes from (Farr, 2009).

Table 2. FMECA sample of a gearbox (Farr, 2009)

FMECA	Gear box	Criticality: 1	MTBF	Years
Component	**Failure cause**	**Task**	**Frequency**	**Keep spare**
Back stop	Mechanical failure 104 weeks between failures	Visual operations inspection (while running) Check for excessive vibration alignment, unusual noise or odour, temperature, lubricant level and leakage. Inspect the external surfaces for wear, contamination, cracks leaks, or loose bolts.	Daily	No
Back stop	Mechanical failure 104 weeks between failures	Visual mechanical inspection (shutdown) Clean and inspect all accessible external and internal surfaces and components. Check for cracks, chips, wear, warps, breaks, binding, erosion, corrosion, fatigue, proper sealing, proper lubrication, misalignment, loose bolts and contamination.	Annual	No
Back stop	Mechanical failure 104 weeks between failures	Visual mechanical inspection (while running) Inspect all accessible external surfaces and components. Check for cracks, chips, breaks, binding, erosion, fatigue, leaks, proper sealing, proper lubrication, contamination or misalignment.	Weekly	No
Bearings	Lubrication failure 104 weeks between failures	Check oil level Check oil level at oil reservoir and fill as required to the indicated level. Do not overfill.	Daily	No
Bearings	Lubrication failure 104 weeks between failures	Replace lubricant Drain and flush lubricant reservoir. Ensure the contaminants are removed. Refill with appropriate lubricant.	3 years	No

Documents generated in Maintenance & Parts strategies should be living documents and in order to achieve that, all information should remain in CMMS (Farr, 2009). The benefit of this activity was long-term interest of the plant because procedures weren't glossed over. The enterprise suggested to its different plants to have a continuous improvement. Plants were encouraged to evaluate the inspections, add inspections, change frequencies, etc.

2.4.3.6 An enterprise approach to reliability – 10 years in the making

Every year, the enterprise Ash Grove MEP steering committee measures the results of each plant after the implementation of MEP and compares those results with the original goals which were establish from the very beginning, so it is possible to see in what extend the goals were achieved. After 10 years, it is clear to see that almost all goals have been achieved and maintained, that proves that a MEP which works for an ERS.

At the company, employees pointed out that MEP stands for a process and not for a program, since a process stays and prevails for always whereas a program has a deadline (Farr, 2009). MEP became something very common at the company and it brought an organised and systematic way of performing diverse activities. These procedures ensured how activities were carried out, no matter who was performing them, also it provided continuity to the work, after personnel retired.

2.4.3.7 *Benefits and limitations of the MEP*

This method is demonstrated through a study case, where an ERS shows great benefits as considerable costs-reductions in work processes, and an increment of production without investing in new equipment.

The enterprise approach to reliability is showed in the figure below, where the approach demonstrates how both ERS and MEP were applied in a big company.

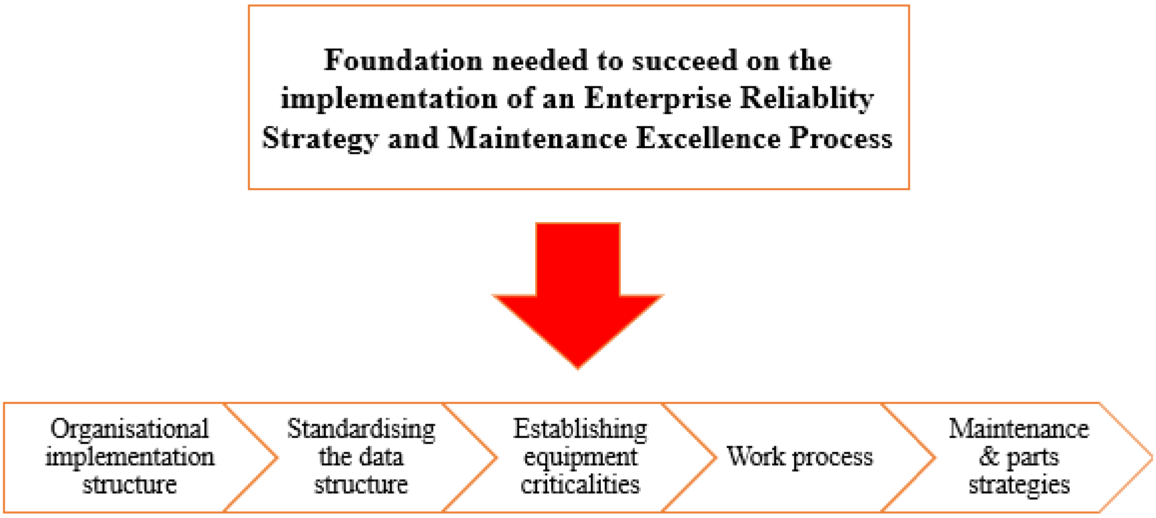


Figure 7. An enterprise approach to reliability and maintenance excellence

The benefit of this method lays in the implementation and procedures that manages assets in an effective way to achieve both high reliability of the assets and a continuous maintenance excellence process. Also, this method sets measurable objectives from the very beginning of the process with the purpose of finding out whether the objectives were achieved and to what extend were they accomplished.

Two factors, which are applied in work processes are crucial for the success of this method. By productivity, the increase of production is achieved and the decreased of costs as well; by proactivity, the anticipation of failures is gained.

From a RAMS point of view, the method satisfies the maintenance strategies which were build up based on FMECA. In addition, FMECA, which is a systematic technique for failure analysis of technical systems also assess the risk related to the failure modes found in the analysis and establishes risk-reducing measures.

The limitation of this approach lays on the organisational implementation structure, which becomes very complex because the method is not only applied in one plant, but it is applied throughout the whole enterprise. So, each of the plants of the organisation must work together in a systematic way towards the same objectives. To achieve a maintenance excellence success by applying this approach, each plant of the enterprise and personnel (from managers to operators) shall be engage and possess a deep understanding of the method.

2.4.4 Measurement of maintenance excellence

In (Djurovic et al., 2015) it is proposed a conceptual model of maintenance performance measurement (MPM) based on maintenance performance indicators (MPI). These indicators evaluate the effect of maintenance on the process performance to analyse the effectiveness of maintenance decisions.

Companies seek to achieve maintenance excellence because this will ensure them a high-quality process based on continuous improvement, which can be translate in world class maintenance practices.

It doesn´t exist one guideline that can show companies the way to achieve maintenance excellence since all organisations have their own complexity. When companies achieve excellence, they must keep performing and developing all those activities that brought them there to sustain the excellence process.

There are many practices and methodologies that helps the improvement of maintenance strategies, such as: total productivity maintenance (TPM), reliability centred maintenance (RCM), risk-based inspection (RBI), computerised maintenance management system (CMMS), etc. It doesn´t matter which of those concepts is used by a company, the problem arise when more than one of those practices are used at the same time on activities, making them complicated and unfinished (Djurovic et al., 2015). Therefore, it is important that the maintenance foundation is solid and well defined, so maintenance excellence can be reached.

A very critical requirement to achieve world class maintenance is the Total Maintenance Excellence Index (TMEI), which represents the maintenance performance (Djurovic et al., 2015) within a company.

A construction organisation case was used in (Djurovic et al., 2015) in order to exemplify the measurement of maintenance excellence. The company is dedicated to the construction of roads and road infrastructure. Modern machinery and transport equipment was used, as well as 200 workers approximately. This company did a self-assessment in 2013 on the area of business excellence according to the European Foundation for Quality Management (EFQM) model. The preliminary results are shown in the figure below which was extracted from (Djurovic et al., 2015).

Table 3. Result of a self-assessment according to EFQM model(Djurovic et al., 2015)

Criterion	EFQM Excellence Model	RatingcompaniesonEFQM Model	Comments
Enablers	500	320	Need Improvement
Leadership	100	80	Satisfies
People	90	60	Need Improvement
Strategy	80	50	Need Improvement
Partnership & Resources	90	50	Need significant improvement
Processes	140	80	Need significant improvement
Results	500	370	Need Improvement
People Results	90	70	Satisfies
Customer Results	200	150	Satisfies
Society Results	60	50	Satisfies
Business Results	150	100	Need significant improvement
Total	1000	690	Level of excellence: Emphasized continuous improvement

As it is seen from the table above, the EFQM excellence model consists on measure nine different criterion which are divided by enablers and results where each of those have a score of 500 points, so together they sum a total of 1000 points. The different criterion for enablers are: leadership, people, strategy, partnership & resources and processes; and the results criterion are: people results, customer results, society results and business results.

The company scored a total of 320 points for enablers, which means that improvements are needed. Within enablers criterion, only the leadership criterion obtained a satisfactory result, people and strategy criterion need improvement and at last partnership & resources and processes must have significant improvements.

On the other hand, the company scored a total of 370 points for results, which means that improvements are needed. All results criterion, with the exception of business results, obtained a satisfactory result; thus, business result needs significant improvement.

The total rating company result on EFQM model was 690 points out of 1000 points, where the level of excellence recommends to emphasis on continuous improvement.

Although the assessment was informal, it was useful for the organisation since the results showed that the company accentuate on continuous improvement and further improvement can be implemented.

It was carried out at the same time, both, the research of the level of maintenance successfulness, and the process of self-assessment corresponding to the EFQM model, by applying an approved model of the Dublin Institute of Technology which consider six areas of research (Djurovic et al., 2015).

Table 4. Research results of level of successful maintenance (Djurovic et al., 2015)

	Areas of research	The max value	Middle realized value	Rank
1	Management (Organization)	5	3,8	IV
2	Employees – Qualification structure	5	3	VI
3	Planning in maintenance	5	4	III
4	Maintenance process (Maintenance techniques and technologies)	5	4,4	I - II
5	Equipment reliability	5	4,4	I - II
6	Business characteristics (Costs, Economy)	5	3,25	V
	Achieved level of success of maintenance		3,871 (77,42 %)	

The figure above presents the results of the level of successful maintenance in six areas of research: management (organisation), employees - qualification structure, planning in maintenance, maintenance process (maintenance techniques and technologies), equipment reliability and business characteristics.

The maximum value score assigned for each area is 5 points, giving a total of 30 points when the maximum level of success of maintenance is achieved. As it is possible to see from the figure above, the area of equipment reliability and maintenance process got the best result, 4,4 points out of 5. In contrast the employees' area and business characteristics got the worst results, 3 and 3,25 respectively. So, the total achieved level of success of maintenance of the company is 3,871, which represents a 77,42%.

The figure below is the graphical representation from the research results of level of successful maintenance of the company which was obtained from the table previously presented.

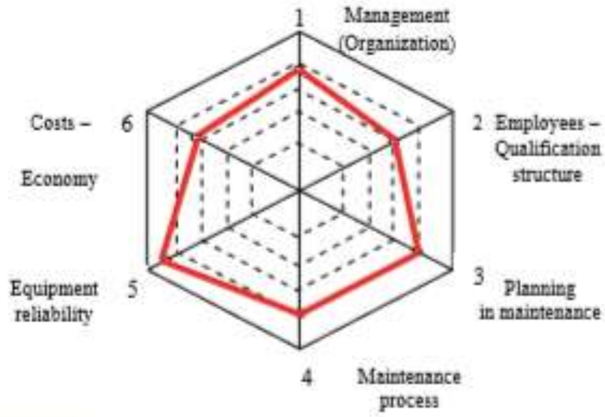


Figure 8. Graphical representation from the research results of level of successful maintenance (Djurovic et al., 2015)

The Dublin Institute of Technology developed the model of maintenance excellence index which quantifies maintenance activities on the basis of metric elements (Djurovic et al., 2015). In the figure below, it is showed the basis of the model of maintenance excellence index and the different maintenance activities evaluated. To calculate the index value, 10 elements must be considered (from A to J).

Table 5. The basis of the model of maintenance excellence index (Djurovic et al., 2015)

A. Performance Measures (from 10 to 15)													F. Performance Level Scores	G. Weighted Value of Metric	
B. Current Month – Performance Values													Performance Level	Descriptive	Numerical
C. Performance Goal													10	Extremely important	10
D. Baseline Performances													9	Very important	9
													8	Important	8
													7	Less important	7
													6	Influential	6
													5	Less influential	5
													4		
													3		
													2		
													1		
													0		
E. Performance Level Score													Index of Excellence	Excellent	
														Very good	
H. Weighted Value of Metric by Importance														Satisfies	
														Not satisfactory	
I. Performance Level Score (E × H)															
J. Max TMEI Value															

The construction company used the results from level of successful maintenance together with the model of maintenance excellence index for further research. So, instead of considering 10 elements, they considered 12 elements. Because of this modification, the figure below shows the relation between the model of maintenance excellence index and the studied organisation.

Table 6. Maintenance excellence index model relates to the construction company (Djurovic et al., 2015)

Maintenance Excellence Index Example (Research in construction company)															
A. Performance Measures	1. % Actual maintenance costs per unit of production	2. % Labour cost within 5 % of cost estimate	3. % Overall maintenance budget compliance	4. % Overall realized the PM activities	5. % Overall compliance of the maintenance plan	6. % Planned work in relation to unplanned work	7. % Rework (repetition of work)	8. % Work orders with reliable planned time	9. % Critical asset availability	10. % Utilization time	11. % Work time availability	12. % Stock availability - spare parts	F. Performance Level Scores	G. Weighted Value of Metric	
B. Current Month	1,30	90	94	90	94	68	75	50	90	75	90	90	Perf. Level	Descriptive	Numerical
C. Performance Goal	100	95	98	95	100	80	85	60	95	80	98	95	10	Extremely important	10
D. Baseline Performance	1,05	94	96	94	98	78	83	58	94	78	98	94	9	Very important	9
	1,10	93	94	93	96	76	81	56	93	76	96	92	8	Important	8
	1,15	92	92	92	94	74	79	54	92	74	94	90	7	Less important	7
	1,20	91	90	91	92	72	77	52	91	72	92	88	6	Influential	6
	1,25	90	88	90	90	70	75	50	90	70	90	86	5	Less influential	5
	1,30	89	86	89	88	68	73	48	89	68	88	84	4		
	1,35	88	84	88	86	66	71	46	88	66	86	82	3		
	1,40	87	82	87	84	64	70	44	87	64	84	80	2		
	1,45	86	80	86	82	62	69	42	86	62	82	78	1		
	1,50	85	78	85	80	60	67	40	85	60	80	76	0		
E. Performance Level Score	4	5	8	5	7	4	5	5	5	8	5	7	Index of Excellence	Excellent	700 ÷ 870
														Very good	500 ÷ 699
H. Weighted Value of Metric by Importance	10	6	8	8	9	6	6	7	10	9	8	9		Satisfies	350 ÷ 499
														Not satisfactory	<350
I. Performance Level Score (E) × Weight (H)	40	30	64	40	63	24	30	35	50	72	40	63	551	Very good	
J. Max. MEI Value (H × 10)	100	60	80	80	90	60	60	70	100	90	80	90	870		

Looking at the results, it was suggested to improve in areas such as: A1, A2, A4, A6 and A7, whereas satisfactory results were obtained in areas such as: A3, A5, A8, A9, A10, A11 and A12 (Djurovic et al., 2015). The overall result of the study is positive since it was obtained a 57% of maintenance excellence index.

2.4.4.1 Benefits of measuring maintenance excellence

The measurement of maintenance excellence takes relevance when a company wants to be certain whether the strategy used is working for the organisation and in which areas is possible to improve. Therefore, it is important to quantify the process, so results can be compared to know the impact of the model used.

A study case is used to exemplify the maintenance excellence measurement through a model developed by the Dublin Institute of Technology which combines the research of level of maintenance successfulness and the process of self-assessment corresponding to the EFQM model.

The model reviewed is a conceptual model of maintenance performance measurement that is based on maintenance performance indicators. Those indicators analyse the effectiveness of maintenance decisions through the process performance.

Furthermore, the model quantifies different maintenance activities based on metric elements, also it is flexible when applying the metric units that measures the maintenance characteristics. This is an effective way to calculate the total maintenance excellence index which is a representation of the maintenance level and its performance within an organisation.

2.5 Maintenance excellence discussion

Maintenance excellence means to excel all performance activities related to maintenance within an organisation. This will create great economic benefits and hefty revenues to any enterprise by increasing productivity, assets' reliability and availability, also reducing maintenance costs and downtime by an effective planning and scheduling of all activities related to the maintenance field.

Through this chapter, maintenance excellence was reviewed and analysed from different perspectives. All models presented are not so different from each other, for example some models focus more on the organisational part than others. Thus, it is quite complicated to choose one model as the best one or the most representative for maintenance excellence.

Something important to mention is that no matter which model or methodology is chosen, it is utterly recommended to follow every single step of the model and that all workforce is engaged to apply the model, so the probability of success within maintenance excellence can be high.

Through this master thesis, outstanding methodologies are reviewed regarding maintenance excellence. But analysing from a RAMS perspective, none of the methods can satisfy that perspective entirely. Therefore, it will be suggested one method which is an output of all methods previously mentioned, a method that combines the best practices from the ones reviewed.

2.6 Implementation of a proposed maintenance excellence model

2.6.1 Introduction

On previous sections it was presented different models which were lacking some aspects within the RAMS criteria, for example, some methods barely mentioned the importance of creating a safety work environment. Therefore, the model proposed in this section will be based on a RAMS point of view which can correspond entirely to RAMS criteria.

In addition, it is important to point out that the models previously mentioned, all focus in creating revenue through maintenance activities, and since the proposed model uses the fundaments from methods previously introduced, it will also consider gaining value to the organisation through maintenance activities.

2.6.2 Methodology

Before applying the model, it is important to know the current maintenance situation of the company. To have an overview of the maintenance management status of the company will provide valuable information about all activities and procedures that are done accordingly to what was planned, as well as to reveal all those areas where improvements are needed and in what extend must the improvements be implemented.

Aside from having an overview of the maintenance management situation, an evaluation of the maintenance foundation will be needed. It is elemental to have a well-defined and solid maintenance foundation, since the rest of the processes will be build up on that foundation.

The main purpose of this methodology is to achieve and sustain a maintenance excellence model. To achieve that objective, a plan and a strategy is needed. So, after assessing the maintenance management and maintenance foundation, it will be shown where the company stands. Additionally, it will be clearer the gap between where the company currently stands and where the company wants to be. This is essential to know when establishing the plan and strategy, so the right measures can be developed and included in the plan and strategy that will be followed to achieve the desired objective.

Documentation and standardisation of working processes and procedures are essential when implementing the proposed maintenance excellence model. By doing that, it will be ensured the correct performance of the different activities, no matter who are carrying out those activities. Also, to document procedures makes available the knowledge to everyone at the company.

It is quite relevant the creation of procedures, its standardisation and its documentation because that will ensure the result of maintenance activities. Software tools are essential to keep track of the assets, as well as to make easier and have an overview of planning & scheduling activities. The organisation should use all different kind of tools available to make all activities more effective.

It is recommended that when applying the proposed method within an enterprise, it starts with a pilot project. It is easy to tests, handle and have an overview of the pilot project, so when desired results are presented, then the model can be rolled out to bigger projects before it is rolled out to the whole organisation.

The figure below was inspired on the typical TPM pillars, where at the top it is situated the desired goal, maintenance excellence. The level below focuses on the maintenance excellence components. Under that level, the fundamental pillars of maintenance excellence can be seen and finally, at the bottom of the pillars, it is located the 5s methodology which is used as a foundation of the fundamental pillars of maintenance excellence.

It is quite important to apply the 5s methodology through the whole maintenance excellence model proposed since this methodology ensures effective working processes and effective working places.

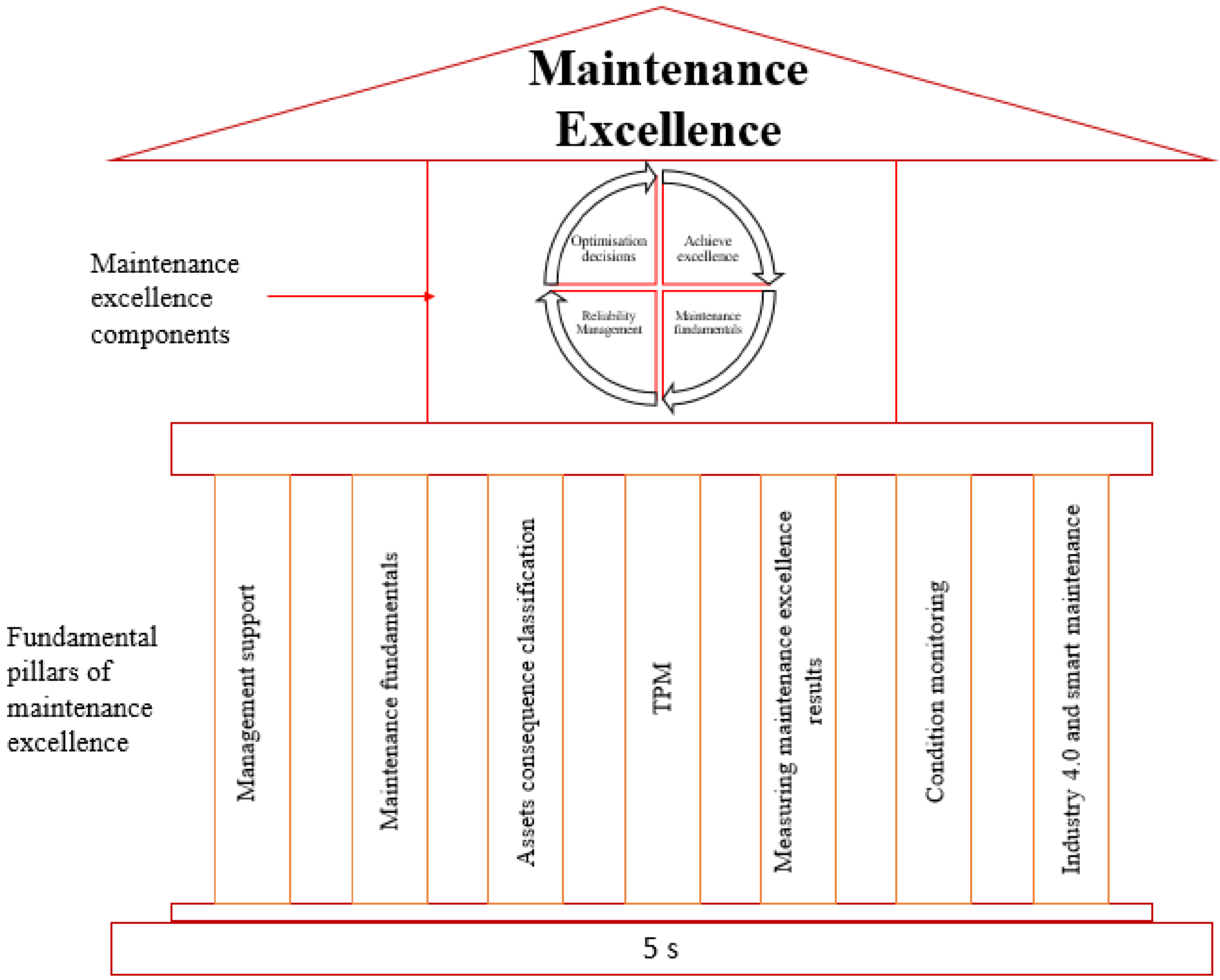


Figure 9. Maintenance excellence house and pillars

Next, it will be described each of the levels previously mentioned from the figure above.

- 5s methodology

The 5s methodology was developed in Japan and nowadays is broadly used in different industries. It is called 5s because the methodology utilises 5 Japanese words which start with the letter “s” (Seiri, Seiton, Seiso, Seiketsu and Shitsuke) This methodology consists in five phases which create an efficient and effective working place/environment. The translation of those Japanese words is sort, set in order, shine, standardise and sustain (Agustiady, 2016). The result of this methodology is given by creating a clean, organised and systematic working place and work processes.

It is essential to consider at all moments the 5s methodology when applying the maintenance excellence model proposed, because this methodology increases the probability of success of the model through its philosophy.

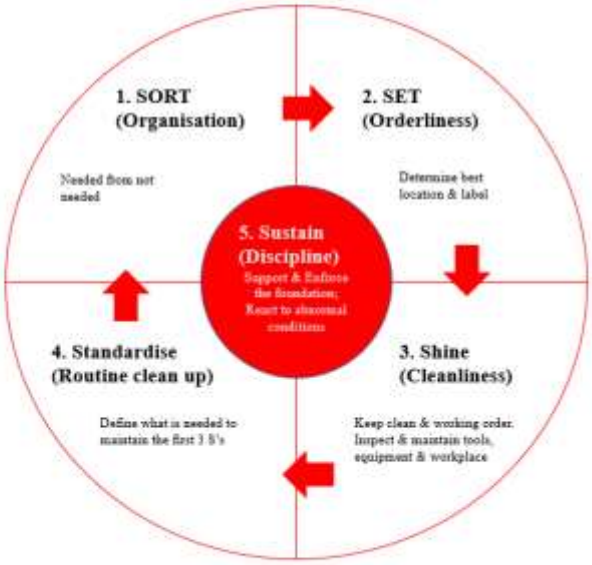


Figure 10. 5s methodology (Agustiady, 2016)

- Fundamental pillars of maintenance excellence

In this section, it will be described each of the pillars that makes possible the maintenance excellence, except for the condition monitoring pillar and the industry 4.0 and smart maintenance pillar, both of those pillars are going to be reviewed separated in the next chapters.

- First pillar - Management support

Indeed, the maintenance department cannot achieve maintenance excellence by their own, to accomplish this goal, it will be needed the participation and engagement of the different departments in the organisation.

Management is responsible to establish the plan and strategy to follow, schedule activities and create all those procedures needed to achieve maintenance excellence.

In addition, management shall ensure that the plan and strategy is detailed and clear for all personnel involved. It is crucial that the workforce has a deep understanding of the model, so everyone is aware of their assignment and knows what it is expected from them. Also, management is responsible to delegate and assign the different activities to the competent personnel, as well as create teamwork to facilitate the working activities.

- Second pillar - Maintenance fundamentals

The maintenance fundamentals are related to the work management process and to maintenance management, where daily maintenance tasks takes place to gain control over the work carried out.

Different maintenance activities such as planning & scheduling are defined, as well as work prioritisation and what maintenance strategy will be implemented. Also, material management, CMMS system and equipment history review are considered.

- Third pillar - Assets consequence classification

Since part of the maintenance excellence model is focused on the assets, it is important to have an overview of all assets and understand deeply how they work and how can they fail, so when developing a plan and strategy, the assets consequence classification is considered as well.

According to (Z-008:2017, 2017), the consequence classification or also called criticality analysis is done after carrying out a risk assessment of the asset, where different techniques can be used as FMECA, just to mention one example. The execution of this analysis will provide valuable information about the different failure modes of subsystems or component parts of the asset. Also, since the analysis is based on risk assessment, it will be possible to identify the negative effects and risks generated on HSE, production and cost.

Normally, the output of this analysis is used to establish maintenance strategies since it will be determined all those assets which are critical to the system.

- Fourth pillar - Total Productive Maintenance (TPM)

This maintenance program focuses on maintaining and improving production and quality systems through keeping all assets at their best working conditions, having as a goal to achieve cero failures, cero faulty products, improve production performance and minimise the waste (Agustiady, 2016). Also, TPM is a fundamental part of the world class maintenance.

The house of TPM, consists in eight pillars which this methodology is based on. The TPM pillars consists on: autonomous maintenance, focussed maintenance, planned maintenance, quality maintenance, education & training, HSE, office TPM and developed management (Andersson et al., 2015).

The eight pillars of TPM focus in machine maintenance and in a continuous improvement which contributes to increase the overall equipment effectiveness (OEE) of the plant. OEE measures the efficiency of the equipment. In other words, it calculates the time when the equipment is producing a quality product. The OEE consists in multiply three factors (performance, availability and quality) that indicates six losses which their causes can be eliminated once they are identified (Agustiady, 2016).

Regarding the economic aspect, it is important to remember that high productivity is translated into high profitability.

- Fifth pillar - Measuring maintenance excellence results

One way of identifying progress towards maintenance excellence is by measuring results, this is the only way to know and have an accurate insight of the maintenance process, so it is important to quantify KPI's and compare with goals and previous results. Also, the benefit of benchmarking lays to know where the organisation stands in comparison with similar companies. Analysing benchmarking results can help to identify those enterprises that have the best practices and that information can be used and applied to your firm to make improvements and achieve maintenance excellence.

When performing this part, it should be consider to review and apply the section 2.4.4 Measurement of maintenance excellence, where (Djurovic et al., 2015) propose a flexible model which can be adapted to any enterprise.

- Maintenance excellence components

As it can be seen from the figure no. 14, it exists four important components that must be implemented to achieve maintenance excellence. Those components comes from (Jardine and Campbell, 2001).

The first component is maintenance fundamentals, where maintenance management is carried out and the maintenance strategies are developed. Depending the asset, is the maintenance strategy chosen, the strategies should be developed accordingly to the equipment at the plant, considering equipment reliability.

The second component is reliability management, where it is proposed to have an overview of all assets at the plant. The implementation of criticality analysis is essential when developing effective maintenance strategies. It is recommended from (Jardine and Campbell, 2001) to use reliability centred maintenance (RCM).

The third component is optimising maintenance decisions. In this part is needed the collaboration of a reliability engineer who is going to be responsible for developing the maintenance optimisation of the assets, based on the failure rates registered in the CMMS.

The fourth component is called achieving excellence. This component depends on the three previous components which need to be excelled to achieve excellence.

These four components are essential to achieve maintenance excellence. Also, they are part of a cycle process, which is always improving its performance to sustain the maintenance excellence model.

2.6.3 Discussion and conclusion of the maintenance excellence model proposed

Indeed, it doesn't exist one methodology that paves all the way to achieve maintenance excellence. Therefore, it was proposed a maintenance excellence model which is aiming to comply with all different aspects related to reliability, availability, maintainability and safety of an organisation. In addition, this perspective provides a model which handles assets in an effective way, considering a cost-effective solution without compromising the reliability and safety of the system.

The maintenance excellence model proposed was build up using the maintenance excellence models which were presented in previous sections. It was selected what was relevant from every single model from previous sections.

Due to the great complexity that exists among every single company, it does not exist one universal method for achieving maintenance excellence, and the method proposed is not the exception. Therefore, it is recommended that the method is tailored for the company who is going to apply it.

The maintenance excellence model proposed has limitations because it was not possible to apply the methodology within Statnett due to external factors. It is suggested that while the model proposed is carried out step by step, it can be also tailored by Statnett, so the model can satisfy all necessities generated by the organisation.

So, further work must be done for the proposed method, where it can be applied for a real study case within an organisation.

2.7 Value driven Maintenance & Asset Management

When analysing maintenance excellence, the economic part is quite relevant as well. It could be believed that the only way to achieve excellence within the different areas in an enterprise is by spending large amount of money in investments. But, sometimes companies have a very tight budget designated to investment or simply they cannot afford to make large investments. Through this section, it is going to be analysed an effective way of investment on current assets within the organisation. The literature used comes from (Haarman and Delahay, 2016),that book presents a methodology which is based on a economic value driver model.

2.7.1 Introduction

According to (Haarman and Delahay, 2016) many industry sectors were built after the second world war; thus, the majority of the assets are approaching to the end of their functional life due to aging. Replacing old assets for new ones is not feasible to all companies, due to the high cost that represents the renewal. Therefore, companies try to extend as much as possible the operational life of the assets.

Besides extending the operational life of an asset, other factors need to be considered. Carrying out maintenance activities to keep an acceptable availability on an old asset becomes challenging because of factors such as reliability and safety become more difficult to maintain in a tolerable level. In some cases, is not enough that an old asset performs its functions adequately; it is required that the old asset can provide the same functions and performance as a new asset, so the company can compete against the existing tough market.

In order to satisfy those demands, VDM^{XL} has created a new model which was developed with industry cooperation. Infrastructure industries were taken into account and took a relevant part on the creation of the model since this kind of industry takes more often investment and reinvestment decisions. Also, infrastructure industries are characterised for rather than having a maintenance department which is in charge of operational maintenance cost, they have an asset management organisation in charge of investment cost and capital expenditure.

2.7.2 Value of maintenance & asset management

A way to add value to an old asset is by modernising it in order to improve its functionality. One of the main goals when applying VDMXL models is to rise the competitive value of an asset by maximising its economic return.

The Economic Value Added (EVA) method is used to measure and improve companies' performance. It is defined by:

> *"Economic Value Added = sum of all future free cash flows, discounted to today"*

where the difference between income and expenditure is referred to free cash flow, which is time related. By time related is meant that it will gain value with the time, therefore future cash flows must be corrected or discounted to present-day. So, the term assigned to this is present value and according to (Haarman and Delahay, 2016) is expressed as:

$$PV = \sum\{CF_t \,/(1+r)^t\}$$

where:

PV = *present value*

CF_t = *future free cash flow in year t*

r = *discount rate*

The risk profile of a project or company is going to determine the level of discount rate which can be between 1 and 0. So, future cash flows are subtracted to present-day by means of the discount rate.

To evaluate the true value of a project and determine if it is feasible or not, the present value formula can be used, where the initial investment is taken into account. So:

$$NPV = CF_0 + \sum\{CF_t / (1 + r)^t\}$$

where:

NVP = *net present value of* CF_0

CF_0 = *initial investment in year 0*

CF_t = *future free cash flow in year t*

r = *discount rate*

According to (Haarman and Delahay, 2016), it is quite common that CF_0 will have a negative value.

By applying this formula, it will be possible to know if projects can become valuable. So, only if the NPV is positive, the company should invest in the project. Otherwise is not recommendable.

It is important to mention that EVA method can be used for industry assets, departments, projects and products as well.

2.7.3 Study case – Alois Health products

In this section, a study case taken from (Haarman and Delahay, 2016) will be reviewed. It is going be analysed whether is profitable a project where an important investment of a plant is required.

Alois Health Products plans to build a new plant. The initial investment is $ 110 million with an annual free cash flow of $ 15 million. The discount rate is 7% for such new development projects and it is considered a time of 10 years. So, the company is wondering if the project should be approved. To find out this, the net present value formula showed above will be used.

NPV $_{\text{new plant}}$ = -110,000,000 + 15,000.000 / 1.07 + 15,000,000 / 1.07^2 + 15,000,000 / 1.07^3 +

15,000,000 / 1.07^4 + 15,000,000 / 1.07^5 + 15,000,000 / 1.07^6 + 15,000,000 / 1.07^7 + 15,000,000 / 1.07^8 + 15,000,000 / 1.07^9 + 15,000,000 / 1.07^{10}

=$ - 4,646,277

Since the result of NPV is negative, the project is rejected.

After the project team evaluate different options, they came up with two new proposals.

The first one is going to have a cheaper design for the new plant, so the initial investment is reduced to $ 80 million and an annual free cash flow of $ 12 million. The second proposal consists in sponsor an American television program for a period of 10 years, with an initial investment of $ 40 million, annual free cash flow of 5.5 million and a 5% discount rate for such marketing projects. Using the NPV formula it is obtained:

NPV $_{\text{new plant 2}}$ = -80,000,000 + 12,000,000 / 1.07 + 12,000,000 / 1.07^2 + …+ 12,000,000 / 1.07^{10}

= $ 4,282,978

NPV $_{\text{sponsoring}}$ = -40,000,000 + 5,500,000 / 1.05 + 5,500,000 / 1.05^2 + …+ 5,500,000 / 1.05^{10}

= $ 2,469,542

Whereas the new plant 2 project, has a better NPV of $ 4,282,978; the sponsoring project has a NPV of $ 2, 469.542. Both project proposals have a positive outcome, thus they can be approved.

2.7.4 Maintenance & asset management value drivers

Coming next, the four value drivers in a Maintenance & Asset Management (M&AM) organisation are going to be introduced. The VDM^{XL} methodology and the four value drivers are going to prove how an organisation can create added value with existing assets.

In the following figure, the value drivers (asset utilisation, SHEQ control, cost control and capital allocation), can be found along the axes. These values are in charge of maximise income, reduce operating cost, lower capital expenditure and minimise risk.

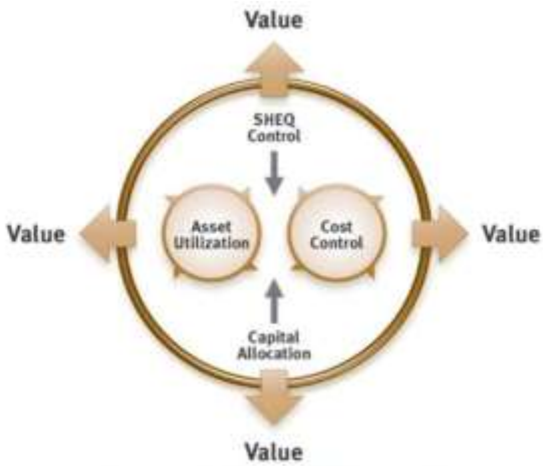


Figure 11. Maintenance & asset management value drivers (Haarman and Delahay, 2016)

According to VDM^{XL} methodology, the value M & AM drivers are:

1. Asset utilisation.

This value is responsible on maximise the income. So, asset's technical availability is going to make that possible. When the asset's availability increases, the production increases as well. Which means that it is possible to produce more, using the same number of assets and having the same fixed costs. Usually, more production translates to more sales that equals to the increment of free cash flow. In order to achieve a higher availability, an effective maintenance program is needed to avoid unwanted failures and minimise the down time.

2. SHEQ control.

The name of this value driver stands for safety, health, environment and quality control. It consists in to reduce the risk related to SHEQ. The prevention of SHEQ incidents is very relevant for the company, since all incidents represent costs and critical incidents can be devastating for the company due to their large financial loss.

3. Cost control.

It is stated in (Haarman and Delahay, 2016) that maintenance is not a cost, nevertheless it is used great amounts of money carrying out this action. The aim of this value driver is to lower maintenance costs, reduce operating costs, spare parts and tools costs and outsourced work as well. Basically, saving on maintenance budget represents free cash flow in the future.

4. Capital allocation.

This value driver focuses in reducing capital expenditures. M & AM organisations improve their assets by doing modifications on them or by replacing them, therefore managing investments can created value to the company.

Extending assets lifetime is a way to create value. Instead of reinvesting by replacing an old asset, the lifetime extension will delay the large expenditure that generates the replacing of the asset which means that the delay expenditure can generate value by interest over the years.

Spare parts inventory is classified as cost. It is assigned that classification because spare parts are just stored, and they don't generate any capital return. So, the larger the inventory is, larger the cost.

2.7.5 The VDM^{XL} formula

The formula was developed in order to have the right balance among the future value drivers, because a positive change in one of the value drivers can created a negative effect on other value driver. The VDM^{XL} formula, which comes from (Haarman and Delahay, 2016) is expressed as:

$$PV_{M\&AM} = \sum_{i=0}^{n}\{(\Delta CF_{AU,t} + \Delta CF_{CC,t} + \Delta CF_{SHEQ,t} + \Delta CF_{CA,t}) \,/\, (1+r)^{t}\}$$

where:

$PV_{M\&AM}$ = *the value potential that can be exploited with M & AM*

$\Delta CF_{AU,t}$ = *future free cash flow in year t from Asset Utilization*

$\Delta CF_{CC,t}$ = *future free cash flow in year t from Cost Control*

$\Delta CF_{SHEQ,t}$ = *future free cash flow in year t from Safety, Health, Environment & Quality Control*

$\Delta CF_{CA,t}$ = *future free cash flow in year t from Capital Allocation*

t = *the years between now and the expected remaining lifetime*

n = *expected remaining lifetime in years r*

r = *discount rate*

The formula shows that the free cash flow comes out from present-day until the last operational date of the asset, and this is calculated in each of the four value drivers. So, the present value appears by dividing future cash flows $(1+r)^t$. As it is expressed in the formula, the summations of the four value drivers corresponds to the entire potential value of the asset.

2.7.6 Value driver analysis

M & AM organisations play a big role when improving assets with the four value drivers and in order to make that happen, a strategy needs to be set up.

According to (Haarman and Delahay, 2016), four steps need to be followed in order to set a winning strategy.

1. It is important to understand the M & AM organisation functions, in order to measure its actual performance.
2. To assess the values obtained, it is recommended to do benchmarking to have an insight of the organisation and for future improvement.
3. In this step M & AM organisations need to set realistic goals which are going to create value by solving the problems found in the previous step.
4. After completing step 3, then is possible to determine the potential value of each value driver.

2.7.7 Winning a maintenance & asset management strategy

During this phase, a winning maintenance and asset management strategy is developed, implemented and adjusted accordingly to the organisation’s necessities.

Asset’s competitive position is strengthened by the developed strategy, which identifies the changes required by the maintenance and asset management organisation in order to apply the asset´s proposed value potential.

The identification of core competences comes out from the dominant value driver and maintenance & asset management professionalise the core competences, since they generate value for the company.

When the strategy will be analysed and after is validated financially, it can be implemented. So, the organisation, processes and performance management must be adjusted accordingly to the strategy.

During the phase when the strategy is implemented, it is recommended to follow, monitor and adjust the driver values which were established at the beginning in order to keep within the plan and strategy selected.

To conclude, through this section it was demonstrated how Statnett and any other organisation can create great revenue within the maintenance department. It was shown through a systematic model how value can be generated, as well as the importance of managing assets in an effective way, that instead of replacing them, upgrades can be done in order to maintain them working at an acceptable and competitive performance level.

Chapter 3

Condition Monitoring

3.1 Introduction

In the previous section it was proposed a maintenance excellence model, which has fundamental pillars for maintenance excellence. One of those pillars is condition monitoring, a topic which will be reviewed through this third chapter.

Condition monitoring is an important strategy which can guide a company to increase its operation excellence by having a constant overview of the assets health; and by that, create the advantage to act previous a failure mode is presented in the equipment.

Condition Monitoring consists on measure the actual state of a machine through a process that monitors the machine's condition and evaluates certain parameter such as: vibration, temperature, etc. to determine the actual state of the machine.

It is important to establish the parameters when the asset is operating in normal conditions and presents a normal performance. Naturally, assets' operations cause degradation in its components, thus this degradation will produce a change in the parameters established as baseline when the asset performed with normality. So, a comparison of parameters should be carried out to detect possible failures. It is mentioned in (Kaboli and Oraee, 2016) that when a significant change of the parameter is presented in the machine, this will normally lead to a failure. Therefore, condition monitoring is a powerful tool for maintenance activities because it gives the possibility to act before a failure is presented, so maintenance activities can be scheduled to prevent a costly breakdown.

Since Statnett deals mostly with electric assets in its plants, ultrasound condition monitoring will be reviewed because this condition monitoring technique is applicable for electric equipment. In addition, online condition monitoring is considered as well, due to the relevance it takes towards the smart industry which will take part in the next chapter.

3.2 ISO 29821:2018 Condition monitoring and diagnosis of machines - Ultrasound

The next part comes out from the International Standard (29821:2018, 2018) Condition monitoring and diagnostics of machines – Ultrasound – General guidelines, procedures and validation. It is important to mention that this new standard edition (2018) replaces previous versions such as: ISO 29821-1:2011 and ISO 29821-2:2016.

It is relevant to review the ultrasound technique since it can be used in electrical assets such as: transformers, insulators, generators, etc.

3.2.1 Introduction

Condition monitoring and diagnostics of machines standard (29821:2018, 2018) focuses in the process of monitoring a machine using ultrasound, as well as its reading and analysis of the output process.

Two different ultrasound techniques are considered, airborne (AB) and structure-borne (SB), to evaluate the normal condition of an asset and identify changes or anomalies when they are presented. The anomalies that change the normal condition of the asset present high frequency acoustic events due to factors such as: turbulent flow, ionisation events, impacts and friction; and those factors are produced by faults such as: inappropriate machine operation, leaks, lack or too much lubrication, components deterioration, and/or electrical discharges (29821:2018, 2018).

Airborne and structure-borne techniques consist on: firstly, measuring the high frequency sound generated by anomalies, and secondly, to compare that with the normal condition of the asset getting as a result some insights which will provide valuable information after an analysis is carried out. The valuable information obtained could be the current diagnostic of the asset which can be used to do a prognosis to prevent failures and apply the most cost-effective solution to avoid a breakdown.

An inspector shall be responsible of the condition monitoring program. So, to create an AB/SB program, the inspector shall have total comprehension about ultrasound and its propagation through atmosphere or through structures. All machines when working, produce ultrasonic energy in form of friction, turbulent flow, impacts and/or ionizations. So, based on that, it is possible to identify and create a parameter when monitoring a machine during performing at its ideal condition, so machine diagnosis can be carried out in order to search for anomalies (29821:2018, 2018).

Ultrasound, as a condition monitoring technique is very beneficial due to its efficient and quick way to find the current location of a machine anomaly, as well as been a non-invasively technique.

3.2.2 Principle of the airborne and structure borne method

Both methods consist in the detection of high frequency sounds that the human ear cannot detect (20 Hz to 20 kHz). Mostly of the instruments used for condition monitoring of assets recognise frequencies above 20 kHz (29821:2018, 2018).

Airborne ultrasound consists in the detection of a wave produced in the test subject (material or machine component) through the atmosphere, whereas structure-borne is produced in the test subject and detected through the same asset. Both methods can be carried out either close to the test subject or at a distance from it (29821:2018, 2018).

Ultrasound technology is very useful to condition monitoring due to the way of travelling of the sound. Whilst low-frequency sound keeps a high intensity of sound volume and travel longer, high-frequency sounds intensity decreases rapidly with the distance after their generation, this depends of the elasticity and density of the medium of propagation. So, the source that is causing the sound can be identified through the medium of propagation (29821:2018, 2018).

In the table below, it is stated the way of propagation and detection of the ultrasound techniques previously mentioned.

Table 7. Ultrasound techniques

	Ultrasound techniques	
	Airborne ultrasound	**Structure-borne ultrasound**
Propagation of the sound	Through an atmosphere (either air or gas)	Through the structure, which can be a machine or any component of a machine/system
Detection of the sound	Ultrasonic microphone	Contact module. Other sensors might be used

As it is mentioned above, for sound detection of the structure-borne ultrasound technique, other sensors besides the contact module might be used. In case that other sensors are utilised for sound detection, such as permanently mounted sensors, special mounting techniques shall be used to prevent signal attenuation or resonance, or both.

3.2.3 Application of AB and SB ultrasound within condition monitoring programs

Although ultrasound techniques are not commonly used in a typical condition monitoring program, they become quite relevant when a non-invasive indicator for failure is required, or when a pressure/vacuum leak needs to be localised without increase machine performance degradation.

Normally, in a condition monitoring program, AB and SB ultrasound inspections are carried out after a failure mode has been detected with other technology, so the ultrasound inspection is implemented to know the characteristics of the failure mode detected. For example, it is mentioned in (29821:2018, 2018) that AB and SB ultrasound can be used to assists an operator that will carry out an inspection of an enclosed electrical system using an alternate technology. The operator wants to carry out an infrared thermographic inspection on the asset previously mentioned and it is known that a hazard of an arc flash can be presented before opening the cabinet. So, AB and SB ultrasound can be used to determine if the hazard is there or not. Thus, the operator can perform the activity required in a safety way.

The table below, which comes from the standard (29821:2018, 2018) presents common examples where ultrasonic applications are used for machine condition monitoring.

Table 8. Ultrasonic application examples (29821:2018, 2018)

Machine description	Pressure or vacuum leak detection	Mechanical	Electrical
Heat exchangers	AB	-	-
Boilers	AB	-	-
Condensers	AB	-	-
Control air systems	AB	-	-
Valves	SB	-	-
Steam traps	SB	-	-
Motors	-	SB	SB
Pumps	AB	SB	SB
Gears/gear boxes	-	SB	-
Fans	-	SB	-
Compressors	AB	SB	SB
Conveyors	-	SB and AB	SB
Switchgears	-	AB and SB	AB and SB
Transformers	-	SB	AB/SB
Insulators	-	-	AB
Junction boxes	-	-	SB
Circuit breaker	-	-	SB
Turbines	AB	SB	-
Generators (utility)	AB	SB	AB/SB
Lubrication	-	SB	-
High-speed bearings	-	SB and AB	-
Low-speed bearings	-	SB and AB	-
AB: airborne; SB: structure-borne.			

3.2.4 Ultrasonic equipment

Indeed, the most common AB&SB ultrasonic equipment are portable and use batteries, thus they can be easily used in the field when is required. It also exists the non-portable AB&SB ultrasonic equipment working online which are mainly used for condition monitoring. When a irregularity occurs and is detected by the online AB&SB ultrasonic equipment, the deviation shall be handled at its origin instead of waiting for a schedule inspection (29821:2018, 2018).

Regarding online operations, the main parameter is amplitude. So, the ultrasonic equipment focuses in monitor a narrow range of applications to decrease false indications that can affect the online equipment lecture.

It is recommended in (29821:2018, 2018) that the condition monitoring system is composed by an instrument, ultrasonic transducers and headphones. Headphones are utterly important to be used to have a right lecture of the output signal and not be disturbed by other sources.

Accordingly to (29821:2018, 2018), the function of the system is characterised by the detection of acoustic energy which have a range above 20 kHz, this acoustic energy could be either airborne or structure-borne. Then, the acoustic energy will be converted (demodulate or heterodyne) into an audible signal which could be heard through the headphones and shown on a signal strength indicator. Since the signal strength is normally presented in decibels, it is referred as decibel value. The characteristic of amplitude and frequency of the original ultrasonic signal determines if the signal is either demodulated or heterodyned. The ultrasonic instrument receives and estimates the physical pressure variation which is demodulated and transformed to a unit decibel.

It is stated in the standard (29821:2018, 2018) that the threshold level of the AB&SB ultrasonic instrument is referred to a sound pressure level, *Lp*. The mathematical expression is below, where *ra* represents the amplitude ratio.

$$Lp\ dB = 20\ log_{10}\ r_a$$

The limitation of AB&SB instruments lays in the lack of threshold level standardisation. So, it exists different thresholds levels among manufacturers, even a single manufacturer can produce different instruments with different levels of sensitivity (29821:2018, 2018). Thus, the instrument sensitivity varies as well. Therefore, when reading signal strengths over time from condition monitoring applications and a comparison is done, the instruments used shall have the same sensitivity as well as the same type of dB readings.

Ultrasonic condition monitoring consists of ultrasonic transducers that transform the received signal into an amplified electrical signal. Afterwards, a main instrument amplifies again the signal which is right after demodulated or heterodyned. The principle of demodulation or heterodyne consists in transforms a non-audible signal to an audible signal for humans (29821:2018, 2018). By using devices, the inspector can use the signal, so it can be recorded and analysed to find a sound source where the anomaly can be presented in the machine.

In (29821:2018, 2018) there is an example where the benefit of the application of ultrasound is showed. Where besides a mechanical condition analysis, a signal analysis of electrical discharges is carried out. Heterodyned signals that are received from the electrical discharges are used to diagnose the condition’s severity and determine between loose or 50 Hz or 60 Hz vibrating components as can be the case of a transformer winding.

3.2.5 Airborne sensor choice

It is important to mention that sensors have limitations, thus they cannot be suitable for all applications. There are two common types of airborne sensors, wide-angle and parabolic, for ultrasonic instruments with interchangeable sensors.

- Wide-angle airborne sensors. They are used for machine condition monitoring and provide an overall assessment of the machine condition. These sensors utilise the whole machine field to compare ultrasonic signatures, thus, different components of a machine can be checked. Wide-angle airborne sensors are used for places where the access area can be very small (29821:2018, 2018).
- Parabolic sensor. These types of sensors are used for remote locations, where access can be restricted or limited, and the assets are far away, such as outdoor substations.

Parabolic sensors have a confined field of reception that can help to find out an electrical discharge in a high voltage electrical tower (29821:2018, 2018).

3.2.6 Structure-borne sensor choice

SB sensors can carry out non-invasively internal machine anomalies detections. The sensors used for SB ultrasound are:

- Hand-held contact sensors. Usually a stethoscope is used for situations where a quick scan is performed to find out the location of the anomaly in the asset (29821:2018, 2018).
- Permanently installed sensors. Whereas a hand-held contact sensor is used to get a good monitoring point in tight spaces, a permanently installed sensor are normally used in unsafe areas (29821:2018, 2018).
- Magnetically coupled sensors. These ones are more effective than the hand-held contact sensors since they remove a measurement variation which is presented with the stethoscope. For example, when inspecting an electrical transformer, a minor movement of the hand-held sensor can be related to a partial discharge inside the transformer, so a misunderstanding of an anomaly can be interpreted. Magnetically coupled sensors work perfectly in situations where long sampling time is carried out, also where many inspectors take readings of the same sampling point (29821:2018, 2018).

3.2.7 Data collection

As everything in the industry, technology provides tools that help to work in a more effective way. Ultrasonic instruments have advance with technology which can provide systems that can store data, record sound samplings and analyse the data obtained from the condition monitoring activities. It exists software, that besides they do all data management within condition monitoring, are also capable to analyse data and identify anomalies in the assets, as well as to determine further actions that should be taken (29821:2018, 2018).

3.2.8 Benefits and limitations

Ultrasound techniques for condition monitoring are very effective, either they are used as a primary or secondary condition monitoring program. Ultrasound techniques are non-invasively, that represents a great benefit when performing inspections in systems or equipment to detect anomalies. Also, AB&SB provides the possibility that no matter the location and accessibility that operators have to the assets, a condition monitoring program can be established to optimise the assets’ functionality.

The employee who is going to create a condition monitoring program should have a deep understanding of the AB&SB techniques. The practitioner who is going to use the program, requires to be experienced and good trained to apply correctly the ultrasound methods. So, that is clearly a limitation of this type of condition monitoring.

Another limitation that exists within ultrasound condition monitoring is the AB&SB instrumentation that is used currently in the industry. Threshold levels and sensitivity levels of the instruments have a great variation, not only among manufacturers, but also within a single manufacturer. Until both threshold and sensitivity levels are not standardised, that problem will still be present.

Industry 4.0 can take to further steps the ultrasound condition monitoring techniques, by implementing an online condition monitoring of the assets and providing the current health of the equipment. In addition, it exists software which can analyse the data obtained and carry out diagnosis and prognosis of the equipment, so future failures can be anticipated as well as to optimise the performance of the asset.

3.3 Applications of ultrasonic condition monitoring in power plants

Since Statnett possess a lot of power plants, it is important to analyse in which way ultrasonic condition monitoring techniques can be applied to critical assets in the power plant. Through the journal article (Bandes, 2009) some ultrasonic condition monitoring techniques are reviewed, and it is demonstrated how this kind of technology can help power plants to improve equipment availability by identifying anomalies in electrical and mechanical systems.

It exists three generic categories of ultrasonic applications in power plants such as: leak detection, mechanical inspection and electric inspection. These categories will be reviewed in the following sections.

3.3.1 Leak detection

In this category, it is included all equipment which contain pressurised systems and systems under vacuum. The loss of gasses normally take place in heat exchangers, condenser tubes, also internally through valves and steam traps.

Accordingly to (Bandes, 2009), leaks can be very costly to power plants. Therefore, in USA, the department of energy carried out a compressed air leak survey program, where the results showed that approximately 30 percent of all compressed air used in the US by industry is lost due to leaks. This represents an estimation cost that could range from 1 to 3.2 billion dollar annually (Bandes, 2009).

A software was used to handle this specific case of compressed gas. So, after gathering and analysing the data, the software calculates the cost per leak (dollar currency is used), also gives information about the type of gasses that are released to the atmosphere and how those affect the environment.

Additionally, the software keeps an overview of the leaks, by providing information about those leaks that have been repaired and those ones that haven't. Thus, it is possible to see savings costs in both money and carbon gas emissions.

The illustrations below were obtained from (Bandes, 2009) and are typical examples of annually compressed gas reports, where the results show the money saved, as well as the carbon gasses saved.

Table 9. Compressed gas report, dollar saved (Bandes, 2009)

2, 3	Year to Date	$56,227.99			Air Leaks Repaired	
4	Month	Identified leaks Cost Avoidance	Repaired Leaks Cost Avoidance	% Complete	CFM	Cost
5						
6	Aug-08	$26,743.99	$5,146.91	19%	29.8	$5,146.91
7	Jul-08	$19,853.88	$1,895.60	10%	11.0	$1,895.60
8	Jun-08	$9,630.12				

Table 10. Compressed gas report, carbon gasses saved (Bandes, 2009)

Carbon Dioxide CO_2 (lbs)		Nitrogen Oxide NO (lbs)		Sulphur Dioxide SO_2 (lbs)	
Identified Avoidance	Realized Avoidance	Identified Avoidance	Realized Avoidance	Identified Avoidance	Realized Avoidance
211199	40645	265	51	506	97
156787	14970	197	19	375	36
76050		96		182	

3.3.2 Electric emissions

Ultrasonic inspections are able to detect arcing, tracking and corona within all type of voltages (low, medium and high) that are produced in enclosed and open access equipment (Bandes, 2009).

Due to the ultrasound created by ionisation of air molecules produced when arcing, tracking and corona, ultrasonic techniques can identify the nature of an electric emission, as well as how critical can that be to the equipment (Bandes, 2009).

Software that records digital sound and do spectral analyses are provided to inspectors as great tools to identify anomalies in electric assets. So, inspections can be carried out in a safety way.

The images below , which comes from (Bandes, 2009), are examples of corona, tracking and arcing.

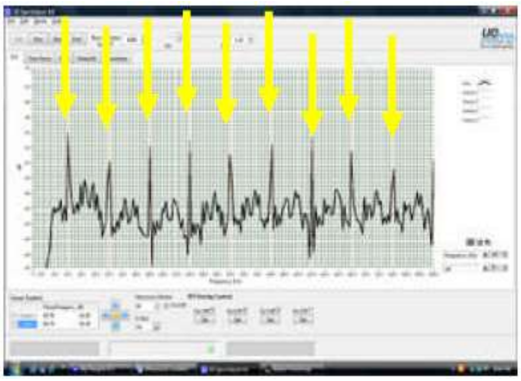


Figure 12. Example from a software analysis of corona (Bandes, 2009)

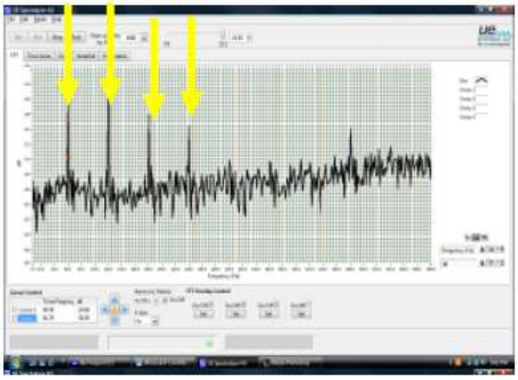


Figure 13. Example from a software analysis of tracking (Bandes, 2009)

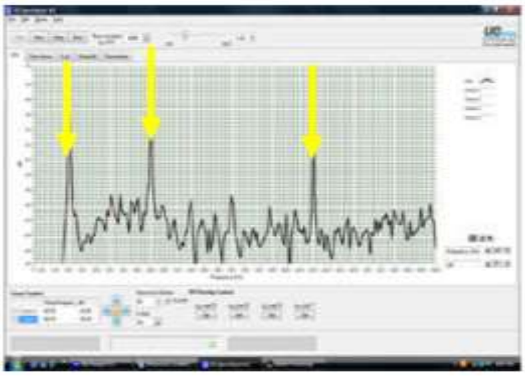


Figure 14. Example from a software analysis of arcing (Bandes, 2009)

In power plants, it is very effective to use ultrasound techniques together with infrared. A clear example of inspecting a switchgear, which comes from (Bandes, 2009), consisted in using both techniques previously mentioned. Since there were no IR ports on the closed cabinets of a switchgear which was supposed to be inspected with infrared, doors could not be opened; so, ultrasound was used to scan door seams and air vents. The inspector detected an arcing sound, so he recorded it and afterwards the cabinets were opened, then visual and infrared images were taken (the images are shown below). So, the images below present a failure condition, a flashover, which could have ended up with catastrophic consequences. But, thanks to both, ultrasonic and infrared techniques, this hazardous event was prevented.

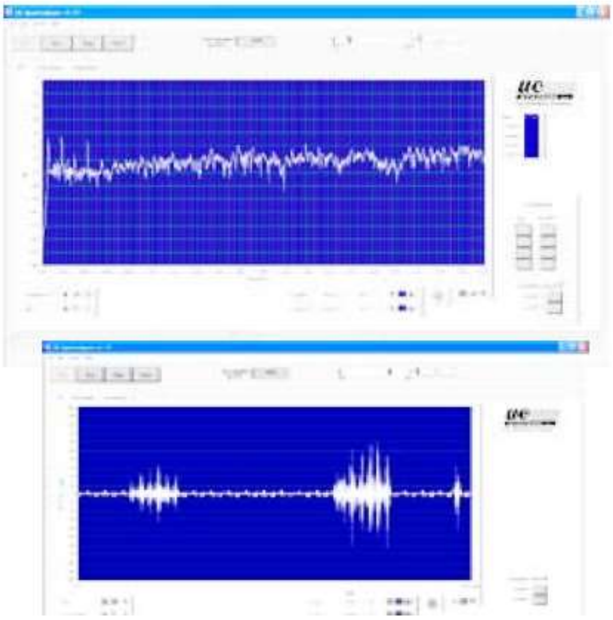


Figure 15. Spectral image and time series view of arcing (Bandes, 2009)

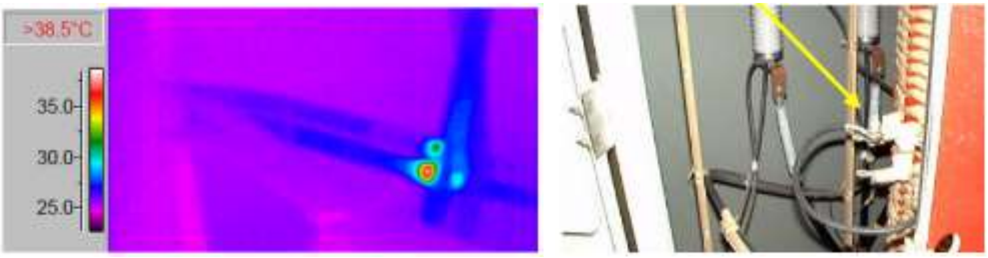


Figure 16. Visual and infrared image of switchgear(Bandes, 2009)

3.3.3 Mechanical inspection

Due to fast technology changes, ultrasonic has improved the ways it is carried out. Today, data software management can store, upload and download data which comes from assets condition monitoring and analyse it to improve asset availability. In addition, the software is able to analyse data providing insights such as trend charts, generate reports with specific criteria and set alarm levels which are used to generate work orders for assets that need corrective actions (Bandes, 2009).

In the journal article (Bandes, 2009), a mechanic inspection is carried out using ultrasound technology, where anomalies are detected in mechanical equipment to determine fault frequencies for bearings or gears. An anomaly happens when a sound sample is superior to an alarm value over baseline. So, spectral analysis was used to analyse sound samplings to get a diagnosis.

The analysis is showed in the pictures below, which comes from (Bandes, 2009), where it is possible to see the analysis of good bearing (note no harmonics) and a faulty one (note harmonics). Baseline sounds are very important because they are used to determine whether it exists a fault or not, therefore the baseline readings should be taken as stored decibel levels and recorded sound samples.

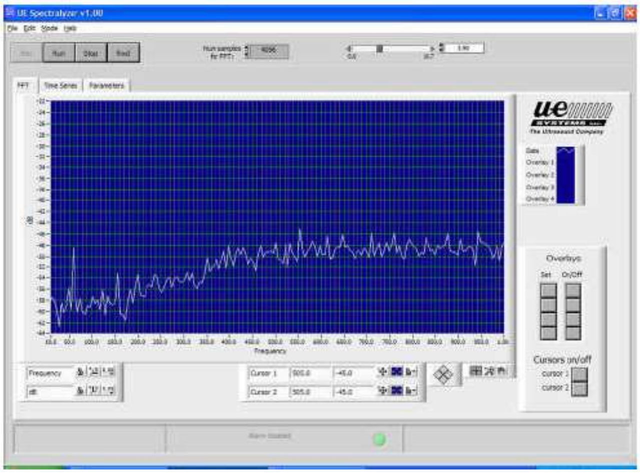


Figure 17. Good bearing with no harmonics (Bandes, 2009)

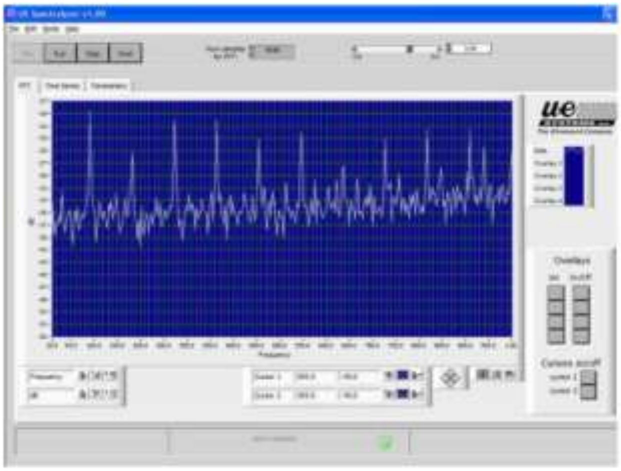


Figure 18. Faulty bearings with harmonics (Bandes, 2009)

While inspecting the bearings, the inspector perceived an unusual sound coming from a gearbox. The sound was recorded and then analysed with the spectral analysis software, where the results confirmed inspector’s suspicion and revealed that the sound came from some gear mesh harmonics. The picture below which comes from (Bandes, 2009), demonstrate the spectral analysis software of the gearbox, where the blue reading is the baseline, the green one was the sound recorded and the red one was the result obtained from the gearbox after some time, when the condition worsened and thus a corrective action was taken.

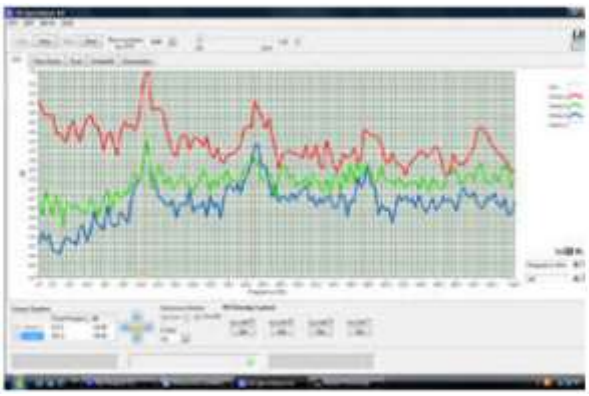


Figure 19. Spectral analysis of a gearbox (Bandes, 2009)

3.3.4 Conclusion of ultrasonic condition monitoring applications in power plants

Ultrasonic condition monitoring techniques have benefited from technology advances. Nowadays software tools are used for condition monitoring inspections in power plants. In addition, the software can record, store and analyse data providing useful insights to improve assets availability and provide safety working conditions to the workforce. Thus, both downtime and maintenance overhead can be reduced in the power plant.

It was demonstrated through the journal article (Bandes, 2009) the great advantage that represents ultrasonic condition monitoring applications in power plants. Thanks to this kind of technology, operators can perform maintenance activities in a more effective and safety way than before.

3.4 Technical condition assessment

Components in assets normally degrades after some operational time, thus the risk of failure and breakdown on assets increase as well. Therefore, the maintainability of assets is quite relevant for both, safety and economical points of view.

The purpose of a technical condition assessment is to know the current condition of an asset and obtain an accurate performance measure. The output of a technical condition assessment can be used for both fault detection and fault estimation.

Whereas diagnosis is used to identify whether a component is faulty or not, and in addition the nature of the fault, estimate its magnitude and severity; prognosis estimates the remaining useful lifetime (RUL) of the component, in other words, the remaining time before the component fails from the moment it was measured RUL(t) (Barros, 2017). So, technical condition assessment can be used for both, diagnosis and prognosis of assets.

3.4.1 Technical condition diagnosis of power transformers – Study case

In the paper (Borucki, 2012) it is presented a new methodology of an effective assessment of the technical condition of mechanical structure of the power transformer core and winding. It is used a non-invasively diagnostic method of the transformer active part by utilising a modified vibroacoustic method.

3.4.1.1 Introduction

Power transformers are critical assets in power plants and the objective of a technical condition assessment is to obtain valuable information regarding the asset's status. So, decision making can be made based on that information as well as schedule maintenance activities in a more effective way. Indeed, transformers have high reliability since they present a designed life that could last from 20 to 35 years and being provided of appropriate maintenance, they can operate for 60 years (Wang et al., 2002). But, when failures are presented on this kind of assets, its consequences can be economically catastrophic, as well as putting in risk personnel by causing explosions and fire; not to mention damage to the environment through oil leakage.

Figure 20. Catastrophic transformer failure (Borucki, 2012)

3.4.1.2 Traditional assessment methods of the technical condition of the mechanical structure of the power transformer core and windings

Transformers experience harmful factors during their lifecycle which can cause operational failures and decrease their lifetime. Accordingly to (Borucki, 2012), the most harmful factors regarding the core and windings are magnetostrictive vibrations and cellulose depolymerisation which normally cause loosening of the screws, wedges and problems with the distance insulation inserts of the squeezing beams of the active part. In the picture below, it is shown the last issue previously mentioned, which is normally presented in transformers with over 20 years of operational time. (a) shows the fallen out distance inserts of windings and (b) shows the slackened core sheets, both images are extracted from (Borucki, 2012).

a) b)

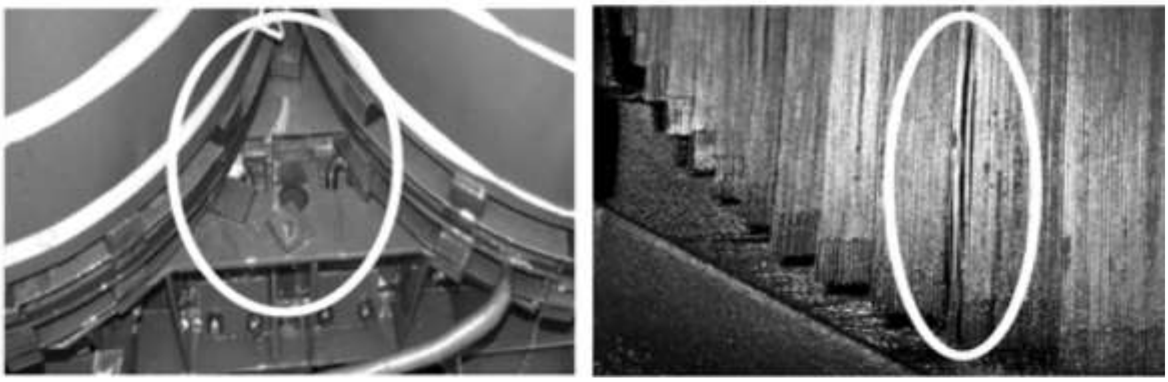


Figure 21. Pictures from an internal inspection of a transformer active part

(a) Fallen out distance inserts of windings. (b) Slackened core sheets (Borucki, 2012)

Due to the high cost that transformers represent, it is not common that power enterprises buy them often. Thus, every company that is in use of transformers try to extend the service time of this pricey asset by implementing methods that can reveal future failures to avoid expensive reparations or a total replacement of the asset.

For transformer diagnosis, different methods such as chromatographic analysis of oil dissolved gas analysis (DGA) method, measurement of magnetising currents and frequency response method (FRA); are used to assess the core and windings degree of pressing and slackening of the winding. These methods are not very effective, since they just identify cases where extreme loosening of the active part elements is presented (Borucki, 2012).

The analysis of mechanical vibrations of transformers during regular operation and analysis of acceleration rms values and amplitudes of spectrum frequency components has been carried out using the vibroacoustic method (VM). But, some difficulties are presented when applying this methodology; such as complications to apply the method when it is analysed different transformers which differ in power, it also differs external measurements of the tank and in core and winding structure technology; the degree of transformers load when carrying out the assessment, and the location of the measuring transducers on the tank which can cause an incorrect evaluation of the results obtained; just to mention some examples (Borucki, 2012).

3.4.1.3 Modified vibroacoustic method (MVM)

This method is suggested by (Borucki, 2012) and it is based on the mechanical vibration analysis of the transformer in its temporary state of work. MVM provides many benefits to the diagnosis of technical condition of the core and windings of power transformers that previous methods mentioned cannot offer.

MVM advantages:

- It can exist variation of the current load degree of the transformer when carrying out the method.
- The vibroacoustic signals detected and the type are not significant dependent of each other.
- Power and construction technology of the transformers diagnosed can vary.
- Disturbances that comes from operation of the induced oil and air circulation appliance are eliminated.
- The mounting location of measuring transducers on the tank surface of the transformer doesn’t affect the results obtained when carrying out this method.
- It is just needed to shut down the transformer for a short period (10 minutes maximum) to take proper measurements.

MVM disadvantages:

- To apply the MVM it is required to shut down the transformer for a short period and then switch it again into idle operation. Anyway, that is not a big disadvantage as could be the measurement of magnetising currents and FRA measurements, where it is required to shut down the asset for about three hours, so the methods can be carried out.

3.4.1.4 Object under study and the measurement instruments used

The object under study was a 200-kVA oil transformer which was switched into idle operation and was fed from the lower voltage (400 V). Due to the not interference on the measured vibration signal, the three-pole manual switch was used as part of switching power supply.

The nominal parameters of the transformer under study are presented in the table below. Also, the overview of the transformer under study is shown in the figure below which comes from (Borucki, 2012).

Table 11. Nominal parameters of the object tested (Borucki, 2012)

Transformer nominal parameters
Type: TZ-200/20
Power: 200 [kVA]
Primary voltage: 15750 ±5% [V]
Secondary voltage: 400 [V]
Connecting group: Yz5
Manufacture year: 1959

Figure 22. Power transformer under study (Borucki, 2012)

Two accelerometers type 4514 by Brüel and Kjær with a sensitivity of 100 mV/g were used to measure mechanical vibrations. The transducers were mounted in the symmetry axes of the two side walls, using magnetic grips, as it can be seen from the following figure. In the figure below, it is shown the location of the accelerometers (Acc 1 and Acc 2) mounted on the transformer.

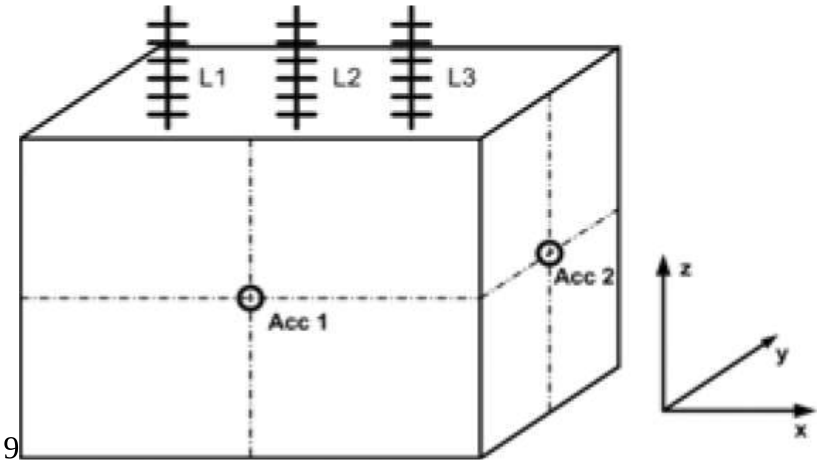


Figure 23. Accelerometer locations on the unit under study (Borucki, 2012)

The signals received from Acc 1 and Acc 2 where transferred to the measuring case of PULSE Dyn-XI, type 3050 system by Brüel and Kjær.

It was installed a packed pulse-time data recorder in a computer to register the vibroacoustic signals measured during switching the transformer into idle operation. The time-frequency evaluation of the vibrations obtained was applied based on the software Pulse LabShop ver. 13.5.

3.4.1.5 MVM experiment applied on the transformer and the results obtained

The experiment consisted in the application of the MVM on a transformer. Four different cases where carried out, including the registration of mechanical vibrations. The different cases are described below.

- First case. It was analysed the vibroacoustic signals during switching the transformer into idle operation. In this case, no failure or mechanical defects are presented, since the core and windings were tightened by the manufacturer.
- Second case. It was presented what is called from (Borucki, 2012) a first degree of mechanical defect on the active part which consists in having loosen screws that were pressing the upper yoke, as it is shown in the figure below.

Figure 24. Transformer presenting a first degree mechanical defect of the active part (Borucki, 2012)

- Third case. The experiment was carried out on the transformer which presented a second degree of mechanical defect on the active part that consists in having loosen screws that were pressing the upper and lower yoke beams, as it is shown in the figure below.

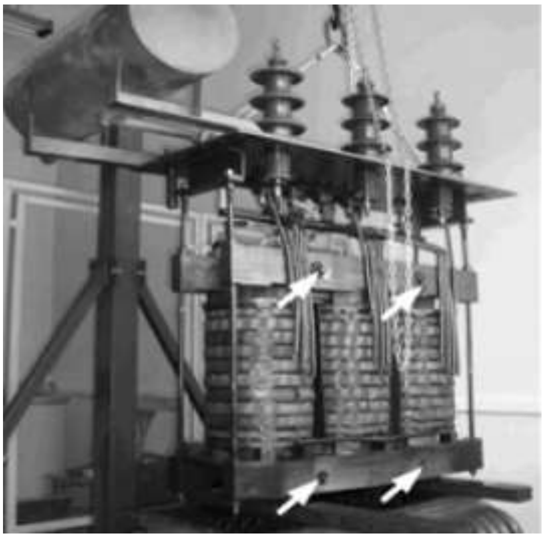


Figure 25. Transformer presenting a second-degree mechanical defect of the active part (Borucki, 2012)

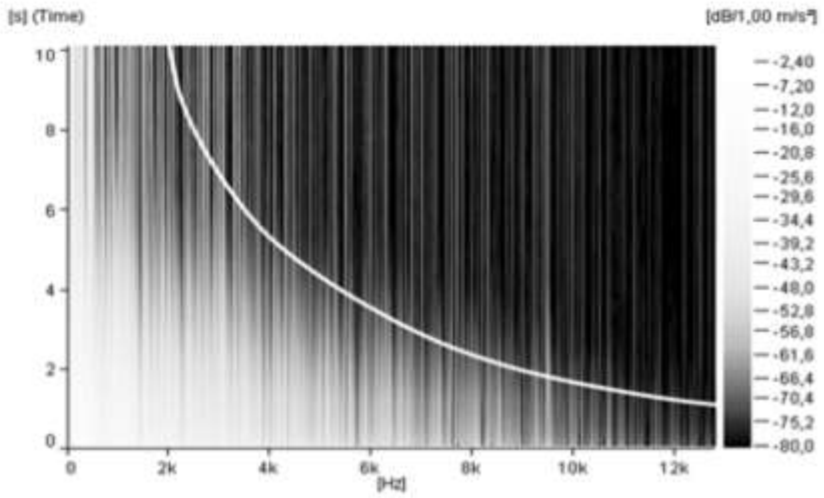
- Fourth case. A third degree of mechanical defect of the active part was presented in this case, which consisted in having loosen the windings of every phase (three phases) of the average voltage side and core defects. The image below shows the third degree of mechanical defect.

Figure 26. Transformer presenting a third degree mechanical defect of the active part (Borucki, 2012)

The short-time Fourier transform (STFT) was used to measure the vibroacoustic signals of the transformer. Also, STFT was used to determine 2D spectrograms of the root-mean-square-value (rms) of vibration acceleration. The mechanical vibrations were measured from the moment of switching the transformer until idle operation t= 10s, and the analysis of the frequency band was from 0 to 12 800 Hz (Borucki, 2012).

Regarding the first case, it is shown in the figures below the 2D spectrograms analysis of the rms values of vibration acceleration of the transformer, where the signals measured are practically located in the entire determined range, from 0 to 12 800 Hz. Since this case presents no failure or mechanical defect, it denotes a proper technical condition of a mechanical structure of the active part of the transformer. The results obtained from the analysis are used as a baseline for further comparative analysis of the other cases (Borucki, 2012).

a)



b)

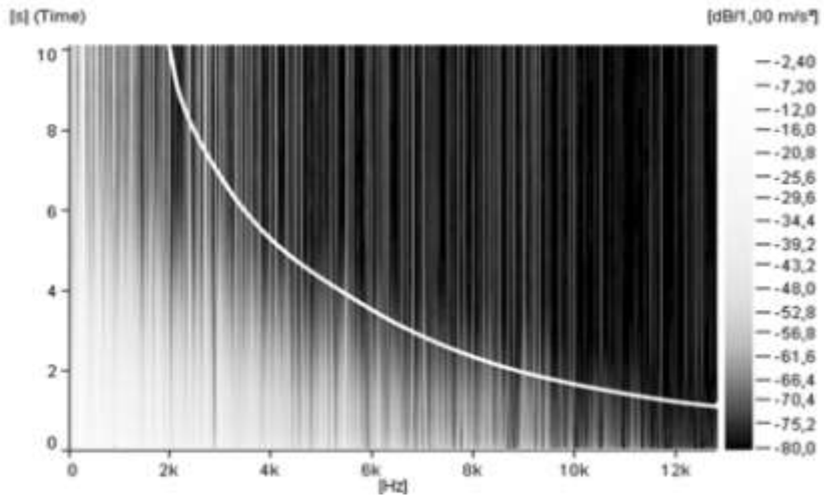
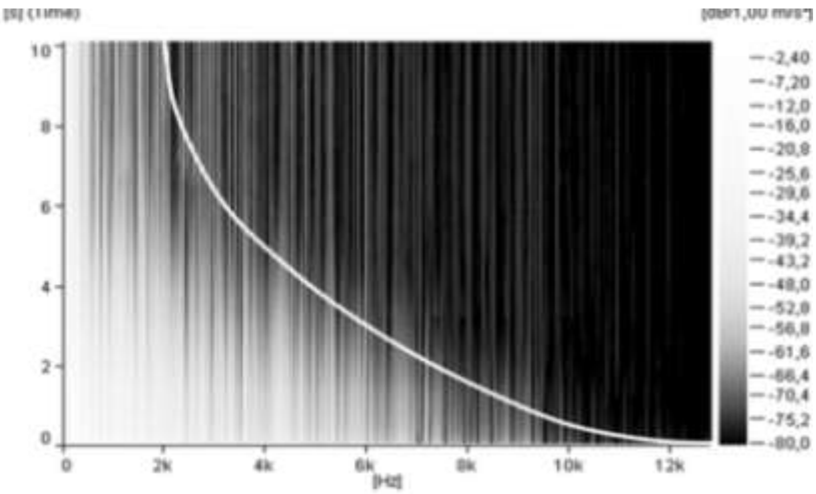


Figure 27. 2D spectrograms of the rms value of vibration acceleration of a transformer without a failure or defect. (a) Acc1; (b) Acc2 (Borucki, 2012)

Regarding the second case, where a first degree of mechanical defect of the active part of the transformer is presented, it shows at liberty an extension of the upper sheet packets and the intention of changing the magnetic circuit of the transformer simulates a slight mechanical defect on the core. The figures below show the 2D spectrograms analysis of the rms values of vibration acceleration of the transformer, where it can be seen that the frequency of the mechanical vibration registered is mainly located in the band from 0 to 10 000 Hz, whereas on the first case, where no defect is presented, the signals measured are located in the band from 0 to 12 800 Hz (Borucki, 2012).



b)

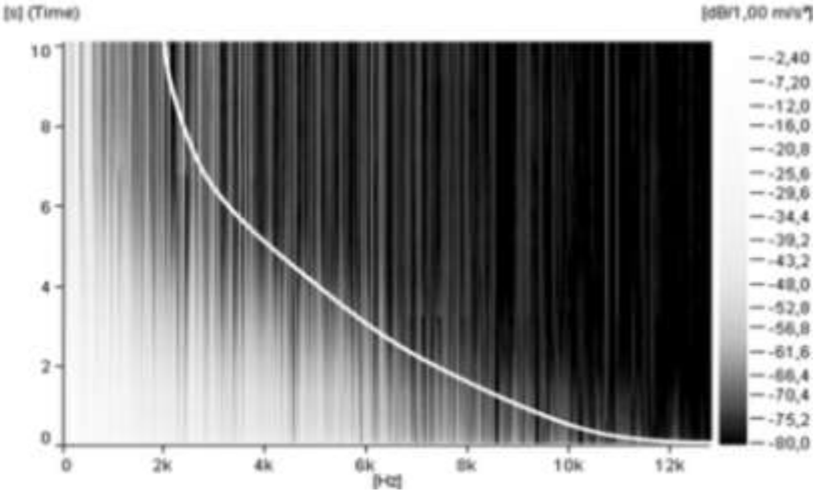
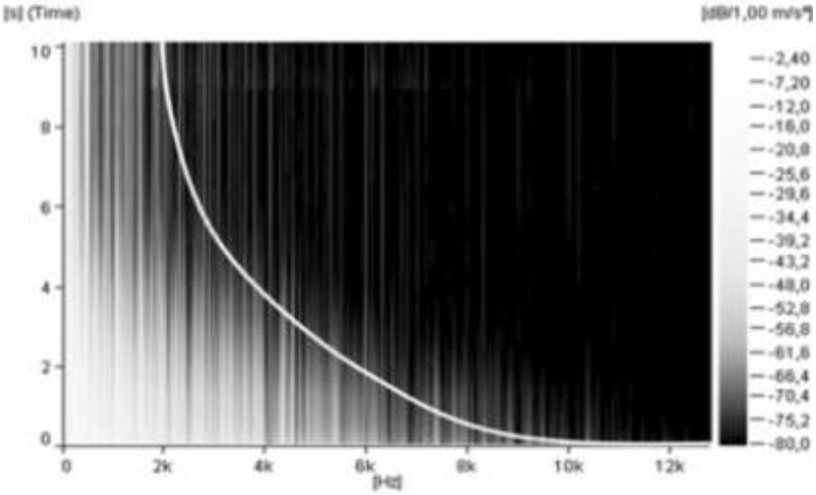


Figure 28. 2D spectrogram of the rms value of vibration acceleration of a transformer with a modelled first-degree defect of the active part. (a) Acc1; (b) Acc2(Borucki, 2012)

The technical condition of the unit tested, presenting a first degree of mechanical defect, is characterised by a narrower frequency range from 9 000 Hz and a disappearance of vibrations in frequencies above.

Regarding the third case, where a second degree of mechanical defect of the active part of the transformer is presented, it is observed in the 2D spectrograms analysis of the rms values of vibration acceleration of the transformer a disappearance of vibrations in the frequencies between 8 000 and 12 8000 Hz, which means that mostly of the mechanical vibrations are located from 0 to 8 000 Hz. When comparing, the 2D spectrograms analysis where a second degree of mechanical defect of the active part is presented, against previous spectrograms, it can be seen that in the third case experiment the vibrations registered have a narrower frequency band (Borucki, 2012). The figures of the 2D spectrograms analysis registered with accelerometer Acc1 and Acc2 are shown below.

a)



b)

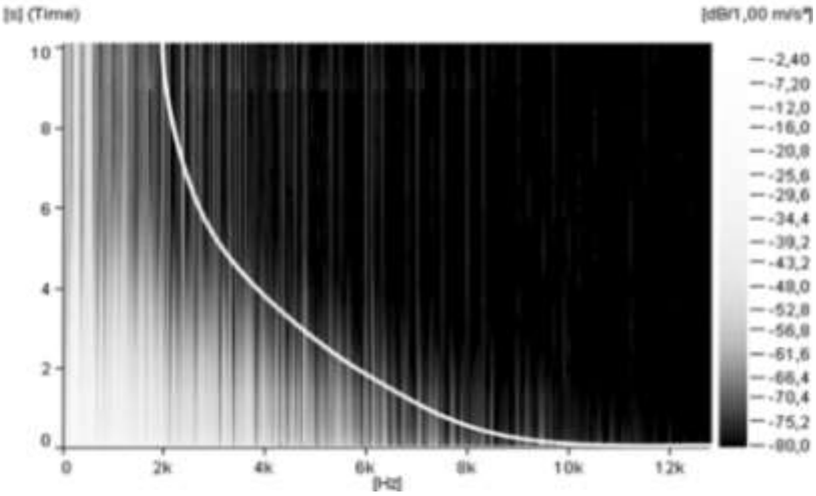


Figure 29. 2D spectrogram of the rms value of vibration acceleration of a transformer with a modelled second-degree defect of the active part. (a) Acc1; (b) Acc2 (Borucki, 2012)

Regarding the forth case, it is presented a third degree of mechanical defect of the active part of the transformer which simulates a simultaneous mechanical defect of the core and windings by expanding the windings and removing specified distance inserts (Borucki, 2012). Below it is shown the 2D spectrograms analysis of the rms values of vibration acceleration of the transformer, where the vibroacoustic signals that are registered are mainly presented in a very narrow range, from 0 to 5000 Hz; after that frequency range, the signals disappear (Borucki, 2012).

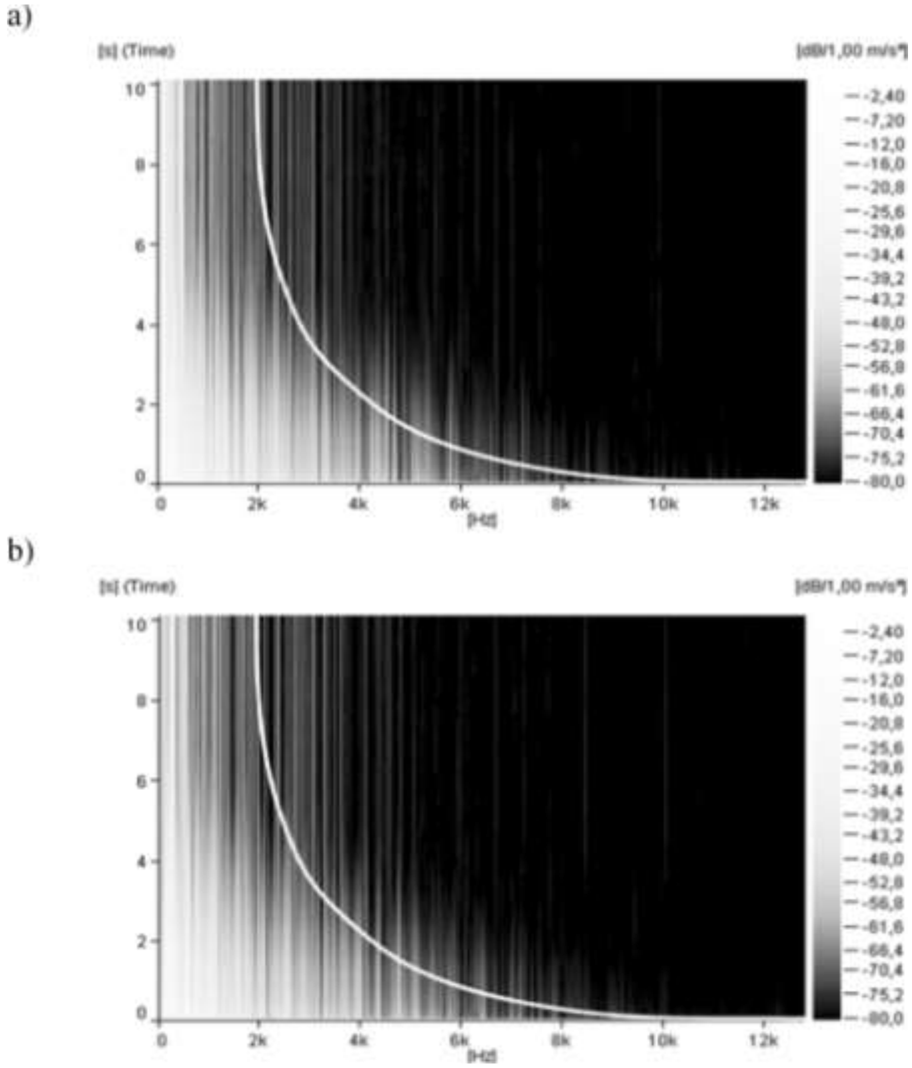


Figure 30. 2D spectrogram of the rms value of vibration acceleration of a transformer with a modelled third-degree defect of the active part. (a) Acc1; (b) Acc2 (Borucki, 2012)

3.4.1.6 Conclusion of the technical condition assessment

It was used the MVM for the assessment of the technical condition of a power transformer core and windings where it was demonstrated that the method proposed in (Borucki, 2012) provides an effective non-invasive assessment of the technical condition of the mechanical structure of the transformer's active parts.

The results obtained from the MVM can be seen on the 2D spectrograms of the rms value of vibration acceleration of the transformer, where the mechanical vibrations were measured from switching the transformer until idle operation. These 2D spectrograms represent the vibroacoustic parameters of the technical condition of the transformer's core and windings.

The 2D spectrograms show time-frequency images in the band range from 0 to 12 800 Hz. When the unit tested presented no failure or mechanical defects (regular operation), it was possible to see a wide frequency band (from 0 to 12 800 Hz). When the transformer presented mechanical defects, the 2D spectrograms images showed significant differences in the frequency band, since the frequency range became narrower in comparison with the 2D spectrogram of the transformer on regular operation; in addition, some images presented noncontinuity, or a clear disappearance of the mechanical vibrations measured. Normally, this could be seen in the range of upper band of the mechanical vibrations signals evaluated.

Through this section was demonstrated the importance of a technical condition assessment, where a failure of a critical asset was presented and the reasons of that failure where identified, in addition the consequence that can be expected if a worst-case scenario of the failure of the asset is presented.

The following sections of this thesis will be presented technologies which are available nowadays and help the workforce to work more effective, since it exists tools that can facilitate procedures and provide valuable information at demand. For example, great advantages can be found within PdM 4.0, where technical assessment can be benefited from, since this technology can make possible to analyse the current condition of an asset 24/7, so personnel will be aware of the deterioration of every single critical component of the asset and by having this valuable information available, failures will be avoided which is going to represent higher reliability on assets, higher production, higher profitability and lower maintenance costs.

3.5 Online monitoring systems

This part is going to analyse online monitoring systems and their characteristics. Today, multiple possibilities exist for online monitoring systems, thus it is important to review those different options. Having a deep understanding of online systems is essential to establish predictive maintenance solutions.

Accordingly to (Kennedy, 2014), online monitoring provides solutions that walk-around inspections cannot. In addition, online monitoring is a great tool that can help companies to succeed on challenges within safety, equipment accessibility, equipment complexity and labour constraints. Thus, it is important to review how online monitoring can be applied to each of those industry challenges.

- Safety. Online monitoring systems are safer than walk-around inspections, since the inspector is able to monitor the assets without been present in a risky area where assets can be located (Kennedy, 2014).
- Equipment accessibility. Assets that are difficult to approach, either because they are hard-to-reach or because they are situated in a remote area, are suitable for online monitoring. By using an online monitoring system, inspectors will be able to save time when carrying out an asset's inspection (Kennedy, 2014).
- Equipment complexity. Due to technology, assets become more complex, smart and efficient; therefore they are in the need for efficient maintenance such as PdM, where data collection and analysis are vital to carry out in an effective way the PdM strategy (Kennedy, 2014).
- Labour constraints. Online monitoring systems becomes quite useful when there are not enough inspectors or personnel to carry out walk-around inspections. In countries like

USA, labour costs are high, therefore remote work and online monitoring systems are more common to use in the industry (Kennedy, 2014).

3.5.1 Benefits of online versus walk-around monitoring

Under the right conditions, online monitoring can help to operate efficiently a plant, cut down costs of operational processes and extend asset life.

A big part of a walking-around inspection consists on gather data from all assets that are monitored (Kennedy, 2014). Not only this activity can be time consuming for an inspector, but it is important to consider that some assets can be situated on remote places or in high risk areas. So, an online monitoring can facilitate the inspection activity since the inspector can have access to the data collection on demand wherever is suitable for him/her.

Walking-around inspections are normally scheduled, which means that in case of a fault detection, this will be noticed until a walk-around inspection is carried out and by then a simple failure could have developed into a catastrophic failure for the equipment that could be highly expensive to repair for the company. In contrast, an online system can detect early a fault in the equipment, so the personnel can act within seconds after the failure is registered, diagnose the asset and take the right actions for reparation. Thus, unnecessary high cost for reparations can be avoided.

Sometimes operators are forced to use assets although they have some flaws that are known. In those cases, an online monitoring system can provide operators the current state of the operating equipment. So, in case a failure mode is developing, the operator will be noticed by the online system and address the failure before it becomes critical to the equipment.

When the online condition monitoring system is installed in the plant, the system should be scalable, which means that is able to accommodate additional sensors and handle greater amounts of data volume (Kennedy, 2014). This is quite necessary since the industry develops, so new requirements and updates will be needed for the online system, therefore it is important that the system can support those changes and don't be forced to purchase a new software system.

3.5.2 Understanding the cost factor

According to (Kennedy, 2014), it is recommended to have both online and walk-around condition monitoring systems due to economic factors. Normally, is not practical to have all equipment connected to an online monitoring system, therefore the most important and critical assets should be selected, so they can be monitored online. Then, after some time, online monitoring can be applied to other assets when walk-around inspections don't satisfy the necessities.

When implementing online condition monitoring systems, several costs such as: infrastructure, training, outsourced monitoring, extended warranties and IT department must be considered. Indeed, it is not affordable for every company to implement this technology due to its high costs. Accordingly to (Kennedy, 2014), regarding costs, 40% goes to sensors and cable, 30% goes to installation labour and the last 30% goes to the monitoring system itself. It is also mentioned that wireless devices reduce the cost of installation since cables are not used, but on the contrary, those devices operate with batteries therefore they must be included when maintaining the system.

After the online condition monitoring system is on place and working, simple maintenance will be needed to keep it working. Just to point out some typical maintenance activities related to that system could be sensor calibration, sensor and wires could be damage, and change of batteries to devices that use them (Kennedy, 2014).

3.5.3 Calculating the value

Once the online condition monitoring system is on place, the true value will be noticeable by reducing downtime, avoiding costly reparations and providing workers of safe working environments.

It is mentioned in (Kennedy, 2014) that although is expensive to implement an online condition monitoring system, after some time the system will recompense its high cost providing the benefits mentioned above. In addition, to schedule maintenance activities becomes more accurate by knowing the current asset status.

3.5.4 Standardisation advantages

All data that comes out from the online condition monitoring should be standardised in the way it is collected, stored and presented (Kennedy, 2014). It is important to have consistency in the way data is handled to create a reliable history of assets and have a wide knowledge base that can support decision making.

3.5.5 Conclusion of online monitoring systems

All companies are different from each other and therefore the online condition monitoring system should be tailored according to the maintenance necessities of the company.

To decide, whether is right or not for the plant to implement an online condition monitoring system, it is important to know the advantages and disadvantages that the system provides.

Indeed, great maintenance solutions that makes more efficient the workload of the personnel is offered by an online condition monitoring system. In addition, provides a constant monitoring without the necessity of wasting time, either, to commute to a remote location or doing the walk-around inspections to collect the data obtained from the assets.

It is expensive to install an online condition monitoring system; therefore, this solution can be unreachable for many companies. Due to the solutions that the system provides such as avoiding both, inspections in high risk locations and catastrophic failures to equipment, just to mention some examples; it is worth it to invest in this kind of technology, not only for the great benefits that provides, but also to drive the company towards PdM solutions because online condition monitoring system is an essential part of the PdM technology.

3.6 Discussion and conclusion of condition monitoring

Condition monitoring has the benefit of knowing the health of critical assets and in which way its components are degrading while those assets are working. This information is very valuable for the maintenance crew, since they could plan in some better way the different maintenance activities that needs to be carried out. In addition, by knowing the current state of the equipment, it is possible to extend its availability and depending of the failure detected, it will be decided to let the equipment safely run to failure (which means that it won't create catastrophic consequences) or take a preventive action to minimise the damage that a failure can cause.

Since Statnett handles mainly electric equipment in its plants, the ultrasound condition monitoring technique was reviewed. Thanks to technological advances, this kind of technique provides great benefits as carrying out non-invasively inspections. Also, it exists the possibility to perform inspections on site, by walking-around inspections; or remotely, by online inspections. The biggest limitation of the ultrasound condition monitoring resides in the airborne and structure-borne instruments, which lack of threshold level of standardisation that cause different levels of sensitivity among instruments. Thus, if the same instruments are used when performing the condition monitoring activities, this limitation won't be problematic.

Although the implementation of an online condition monitoring can be pricey for an enterprise, it is highly recommended to implement this method because technological changes are coming, and they provide great benefits to all those who make use of them. For instance, an online condition monitoring provides a safer working environment to those workers who needed to execute a walking-around inspection in highly risky areas.

In addition, an online condition monitoring besides informing the current state of the equipment, it is crucial when moving towards PdM. So, online condition monitoring can be empowered with industry 4.0 and new digital technologies which are changing the way maintenance is carried out nowadays, by performing activities in a more efficient way than before.

The next chapter is about how industry 4.0, smart maintenance and new digital technologies that can be applied in the industry. Not only maintenance is getting smart, but also the whole organisation changes the way they work by utilising technological advances which represents the future of how organisations will be performing.

Chapter 4

Predictive maintenance (PdM) and smart maintenance (PdM 4.0)

4.1 Introduction

In previous chapters has been presented how Statnett or any other company can achieve maintenance excellence, thus maintenance operation. Also, it was introduced condition monitoring techniques which can be useful for an electric power plant, by making working procedures easier, safer and more efficient.

In this fourth chapter, it will be examined how condition monitoring techniques can be part of a predictive maintenance program. In addition, it will be reviewed the fourth industrial revolution, also called Industry 4.0, which enables new digital technologies such as Internet of Things (IoT), that take maintenance activities to a superior level.

Industry 4.0 and all innovations that come from that concept, make possible what is called smart maintenance, a type of maintenance that combines maintenance strategies and high technology to deliver a new and very effective way to work within the maintenance field.

4.2 Industry 4.0

The concept of industry 4.0 was born in Germany, by the EU Commission and the German National Government. The goal of this concept was to create a strategy that could increase EU's financial sector, industrial sector and the IT sector for the European Union by 2020 (Wernicke, 2015).

The term of industry 4.0 stands for the fourth industrial revolution, which is characterised by digitalisation. In addition, industry 4.0 enables different digital technologies such as the Internet of Things (IoT) and Big Data, just to mention some digital technologies.

Enterprises that want to be part of the fourth industrial revolution must do large investments, in both, equipment and personnel who must be trained to handle industry 4.0. New digital technology, sensors, smart devices and software are going to be needed, not to mention the experts, such as data scientists and reliability engineers who are going to enable those technologies to innovate and make the organisation more efficient. Although industry 4.0 is expected to be expensive at the beginning, this kind of technology will justify its expense in a short time (Mulders et al., 2017)

According to (Geissbauer et al., 2016), to enable industry 4.0 within a company, the organisation must develop a robust organisational structure where decisions taken are going to be based on valuable insights which comes from data analytic systems

The maintenance field is going to be benefited by industry 4.0, since its application is going to deliver great advantages because it will empower maintenance strategies, such as PdM.

4.3 Internet of Things

IoT has revolutionised the world by enabling an advance digitalisation of all things, increased connectivity and breakthrough in big data gathering and analytics capabilities. Regarding factories, internet technologies have been implemented in the field of smart objects to increase efficiency and let the products control their own process (Lasi et al., 2014). The combination of both, smart systems and internet-based solutions, are what symbolise industry 4.0.

It is called Internet of Things when an item or device has an internet connectivity, which makes possible the interaction with other items or devices. The interaction can be with systems, machines, components or people on a global scale. For example, in case of an industry, this level of connectivity can increase the reliability and availability of equipment or increase operation efficiency or improve maintenance performance.

It is crucial for IoT to have available internet everywhere and always functioning. IoT still been a quite new technology that requires time to mature and become accessible for everyone, so it can be used in a great scale. Anyways, it exists many applications that use this new technology nowadays.

When the use of internet became popular, the creation of services on the internet increased. Mostly of the internet services where designed to satisfy the necessities of people, such as: e-mail, instant messaging, video-calls and social media were created for the interaction of person-to-person and now with new digital technologies such as IoT, internet services can make possible the interaction between person-machine, machine-machine and machine-person.

IoT is turning normal devices into smart devices, allowing them to interconnect with each other through the internet. It also transforms the daily life of people by making different tasks easier for users, also can monitor in real-time actual condition and operation efficiency of smart systems.

Regarding industry, IoT has an immense potential due to generation of data created at every single stage of a product lifecycle, from the design phase to manufacturing, testing, distribution and usage. Each of these stages is going to create a digital trace that further on will be collected, processed and analysed, and the result will be valuable information and insights from the product lifecycle. IoT can also provide more automation in the industry by wireless connection of sensors and equipment, which can have a machine-machine interaction and do all process automatically(Mukhopadhyay and Suryadevara, 2014).

4.4 Predictive maintenance

To have a deep understanding of predictive maintenance, it is necessary to review its definition and as well definitions related to PdM accordingly to the standard EN 13306.

- Predictive maintenance is defined as: *"condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item"(13306:2010, 2010).*

- Condition based maintenance: *"preventive maintenance which include a combination of condition monitoring and/or inspections and/or testing, analysis and the ensuring maintenance actions"(13306:2010, 2010).*

Since the very beginning of maintenance activities, people has been doing predictive maintenance. Over time, levels of maturity in PdM have evolved together with technology. The maturity levels of PdM will be reviewed accordingly to (Mulders et al., 2017)

A simple way of carrying out PdM is when a technician performs visual inspections - Level 1 of maturity. Based on his knowledge, experience and intuition, he decides when is the best time to shut down certain part of equipment, so maintenance can be carried out (Mulders et al., 2017).

The next level of maturity - Level 2 - in PdM consists in using periodic instrument inspections. Regular monitoring of machinery will provide its actual condition and operation efficiency. Different techniques are used to carry out this action, such as: vibration monitoring, thermography, tribology, visual inspections, ultrasonic, etc. The implementation of those techniques will increase inspector's expertise (Mulders et al., 2017).

A higher level of maturity in PdM - Level 3 - is achieved when using real-time condition monitoring and data is used for making predictions. Maintenance staff is able to improve decisions when great amounts of data are used, the increment of data makes more reliable the decisions taken getting as a result improvement in maintenance performance (Mulders et al., 2017).

The last level of maturity - Level 4 - is reached when new digital technologies are applied to PdM, such as Big Data and Machine Learning. Nowadays, the world is digitalised, so every single activity creates a digital trace. Therefore, it has been an exponential growth with the data that can be used for PdM (Mulders et al., 2017).

The table below shows the different levels in PdM previously mentioned.

Table 12. PdM levels of maturity (Mulders et al., 2017)

PdM – Levels of maturity	
Level 1	Visual inspections: periodic physical inspections; conclusions are based solely on inspector's expertise
Level 2	Instrumented inspections: periodic inspections; conclusions are based on a combination of inspector's expertise and instrument read-outs.
Level 3	Real-time condition monitoring: continuous real-time monitoring of assets, which alerts given based on pre-established rules or critical levels
Level 4	PdM 4.0: consists in continuous real-time monitoring of assets with alerts sent, based on predictive techniques, such as regression analysis.

4.5 Predictive maintenance 4.0

It is named PdM 4.0 since this type of maintenance utilises new technologies such as: Internet of Things (IoT), Big Data and industry 4.0.

A certain level of reliability is achieved when using real-time condition monitoring, but unforeseeable and inexplicable failures will still appear. Applying Big Data analytics will solve those failures. So, PdM 4.0 predicts future failures in assets and uses advanced analytic techniques on Big Data, such as machine learning or artificial intelligence, (data about technical condition, usage, environment, maintenance history and anything associated with the performance of the asset) to provide the most effective preventive measure (Mulders et al., 2017).

A great challenge that factories are facing is to obtain useful and quality data, data that is going to be used for decision making. To obtain quality data, factories must structure their data for correct use. When useful data is identified, artificial intelligence helps to analyse it. Machine Learning, as an application of artificial intelligence, uses algorithms that are self-learning. So, those algorithms perform series of trials of a set of training data, and thus construct their own model. Big amounts of new data are going to be used to enhance that model and improve its predictive skills.

To improve PdM, Machine Learning basically will use historical maintenance data (must be quality data) and failure history to create self-learning algorithms. Then the algorithm is going to detect patterns and signals in the data that associate with failure. If the algorithm can detect such patterns, then it is going to be able to predict an increased likelihood of failure and will give an early warning, before the failure occurs.

The benefits of PdM 4.0 are:

- Failures which were not predictable before, will be predictable(Mulders, 2017).
- By using analytic techniques like Machine Learning, failures and accidents can be anticipated(Mulders, 2017).
- Assets' lifetime will be extended(Mulders, 2017).

When implementing PdM 4.0, companies should also focus in different organizational aspects to be able to implement successfully PdM 4.0; not only a technological change in the assets is needed, but a digital culture and management must be considered as well. Thus, only companies which encourage digital culture and are capable of change, can be successful when implementing PdM 4.0.

Some difficulties that may arise for a company which wants to implement PdM 4.0 are to have the right skills and knowledge in the house. New people will be needed to put PdM 4.0 in place, the recruitment of reliability engineers in PdM and data scientist is crucial.

Other important aspect that must be considered is the commitment of the leadership from the top. It is vital to create an environment where new ways of working with new technology can take place, as well as an organizational culture that stimulates cross-functional cooperation between workers and a company which is comfortable with data-driven decision making.

In (Mulders et al., 2017), it is recommended several steps which will help to gradually build up the PdM for some assets:

- Asset value ranking & feasibility study: Identify assets which are feasible to implement PdM 4.0 to increase their reliability. Normally high-critical or medium-critical assets are going to justify the necessary investments (Mulders et al., 2017).
- Asset selection for PdM 4.0: Be selective when choosing assets. Then, assign those assets in pilot-projects (Mulders et al., 2017).
- Reliability modelling: The right direction into this model is reveal by using root-cause analysis (RCA) and failure mode effects analysis (FMEA) per asset type. So, it is important to know which data has to be monitored in order to obtain useful information to carry out RCA and FMEA (Mulders et al., 2017).
- PdM 4.0 algorithm design: It will require data scientist to make a self-learning logarithm which will be applied on big data sets. The algorithm will determine the quality of the predictions (Mulders et al., 2017).
- Real-time performance monitoring: At this point the implementation of PdM 4.0 is working. The algorithm that was designed in previous step monitors and shows the performance of all those assets which have sensors embedded (Mulders et al., 2017).
- Failure prediction (early warning): Future failures will be predicted based on the algorithm created and actions such as shutting down a machine will be taken (Mulders et al., 2017).
- Preventive task prediction: When PdM 4.0 has reach a high level, the algorithm besides predicting a future failure, it will also take actions on that future failure and suggest the best action to avoid it. Possibly, it may send out the corresponding working order (Mulders et al., 2017).

So, now moving out from PdM 4.0 asset implementation to enterprise implementation, it is suggested in (Mulders et al., 2017) six steps, which are designed for companies to become a front-runner within PdM 4.0:

1. First step. The plan starts by engaging and encouraging leadership in the whole transformation process. Then, make an evaluation to know where the current PdM of the company is, and set targets for the next five years accordingly to a strategy.
2. Second step. Select some assets which can be used for PdM 4.0 pilot to proof the concept and demonstrate business value. Then use the pilot program for other assets.
3. Third step. A pilot project will show the capabilities needed to succeed. Learn from the pilot project and develop a strategy for implementing new technologies.
4. Fourth step. After putting PdM 4.0 in place, the success will depend on skills and knowledge from the staff. It is important to consider that besides having reliability engineers and data scientists, the working environment will determine the effectiveness of the strategy.
5. Fifth step. Extend PdM 4.0 across the assets and develop the infrastructure needed to become data-driven in the decision-making.
6. Sixth step. Finally, to keep a constant development in PdM 4.0, collaboration with external partners and suppliers is necessary. Sharing information, data and models with partners will contribute to become more mature in PdM 4.0.

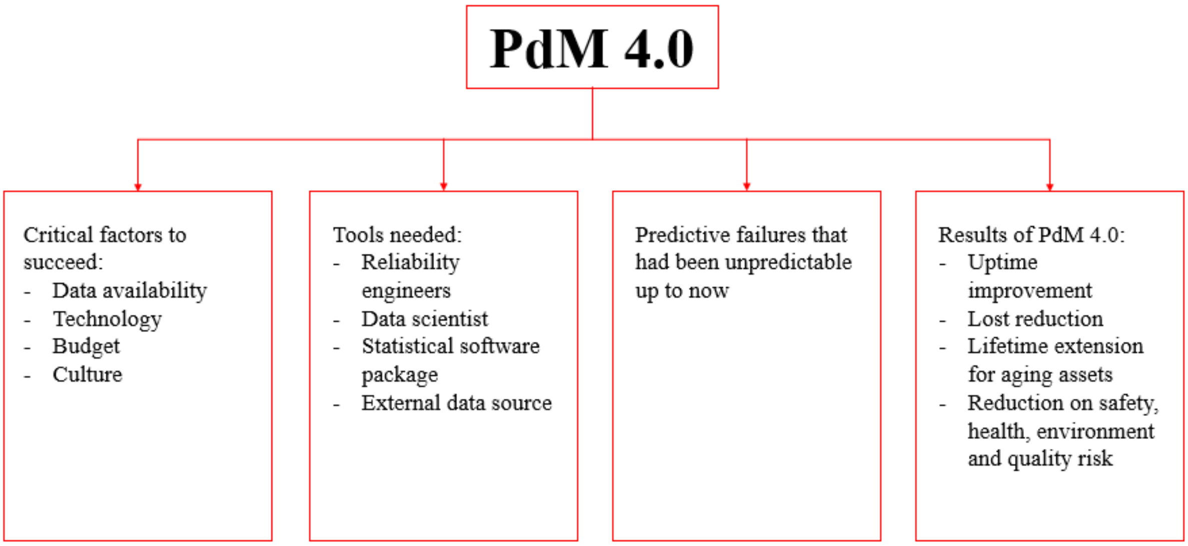


Figure 31. PdM 4.0 overview

4.6 Study case - Making maintenance smarter, PdM and the digital supply network

For this section, it was reviewed the article (Coleman et al., 2017) where smart maintenance is introduce, analysing its capabilities and the technology used which makes more effective maintenance strategies. It also focuses on how predictive maintenance can be implemented at early stages and the benefits that it provides.

4.6.1 Introduction

Normally, different maintenance techniques have been developed and used to identify failure modes at early stages with the finality of avoiding them, thus downtime in the factory can be reduced. Nowadays, new connected technologies are capable of optimising maintenance tasks such as preventing asset failure and extending its useful life.

It is known that corrective maintenance is very expensive for a maintenance organisation, therefore maintenance policies try to schedule in the best way possible the maintenance activities. Nevertheless, it can be challenging to determine the maintenance intervals on an asset, because it exists two facts that are equally important, downtimes that the asset creates whilst been maintained and the risk of lost production due to breakdown of the asset.

Accordingly to the article (Coleman et al., 2017) a maintenance program fall into four categories, where reactive maintenance delivers a <50% Overall Equipment Effectiveness (OEE), planned maintenance 50%-75% OEE, proactive maintenance 75%-90% and predictive maintenance >90%.

Predictive maintenance (PdM) has been applied from the very beginning where maintenance activities were carried out and during the years PdM techniques have evolve thanks to technology. Today, PdM is very advanced due to Industry 4.0 that makes assets smart through their digitalisation and the usage of new digital technologies such as Internet of Things (IoT), Big Data, Machine Learning, etc.

Nowadays, companies are able to invest in digital technologies since they are more available and with lower cost than a few years ago (Coleman et al., 2017), where only large enterprises could afford that.

The combination of digital technologies and the growth of the digital supply network (DSN) have made accessible for PdM to be developed in a large range within all sizes of organisations. DSN is a supply chain which is a dynamic, interconnected system that evolves over time integrating information from different sources and locations i.e. production and distribution, having as an output a virtual word which resembles the physical world (Coleman et al., 2017). So, DSN is the digital conversion of a supply chain.

This kind of PdM is capable of predict future failures by applying Machine Learning technology on the gathered data which has been collected over all those smart machines (assets or machines embedded with sensors connected to the internet) that use the IoT, so the downtime will decrease whereas the asset efficiency will increase.

Machine learning technology consists on using maintenance data and failure history to create self-learning algorithms that detects patterns associated with failure modes. So, this technology can predict a failure before it occurs. Hereby PdM is the most efficient maintenance strategy currently.

4.6.2 PdM and the Physical-Digital-Physical Loop

Through new digital technologies, organisations gain the advantage of having access to real-time data of their assets, having the opportunity to monitor them and see their current condition and performance. When organisations begin to apply PdM it must be considered how is going to be the implementation, development and so on. Digital technologies applied to PdM are going to generate valuable insights which will be crucial when it comes to decision making, thus goals and objectives become feasible to the organisation.

The Physical-Digital-Physical Loop consist on integrate information from different sources, making it digital and create and ongoing cycle (Coleman et al., 2017). In this way, real-time access to data and analytics is conducted to a repetitive and cyclical flow of information and procedures between the physical and digital worlds. This cycle consists in three steps: Firstly, information from different sources is taken from the physical world and digitised; this is the phase from physical to digital. Secondly, the data created from the first step is shared and analysed, so it will generate meaningful outputs; this is the phase digital to digital. Finally, the outputs from the second step are going to be applied to the physical world and by that the loop is closed.

The figure below describes the three-step process previously mentioned. The figure comes from the article (Coleman et al., 2017).

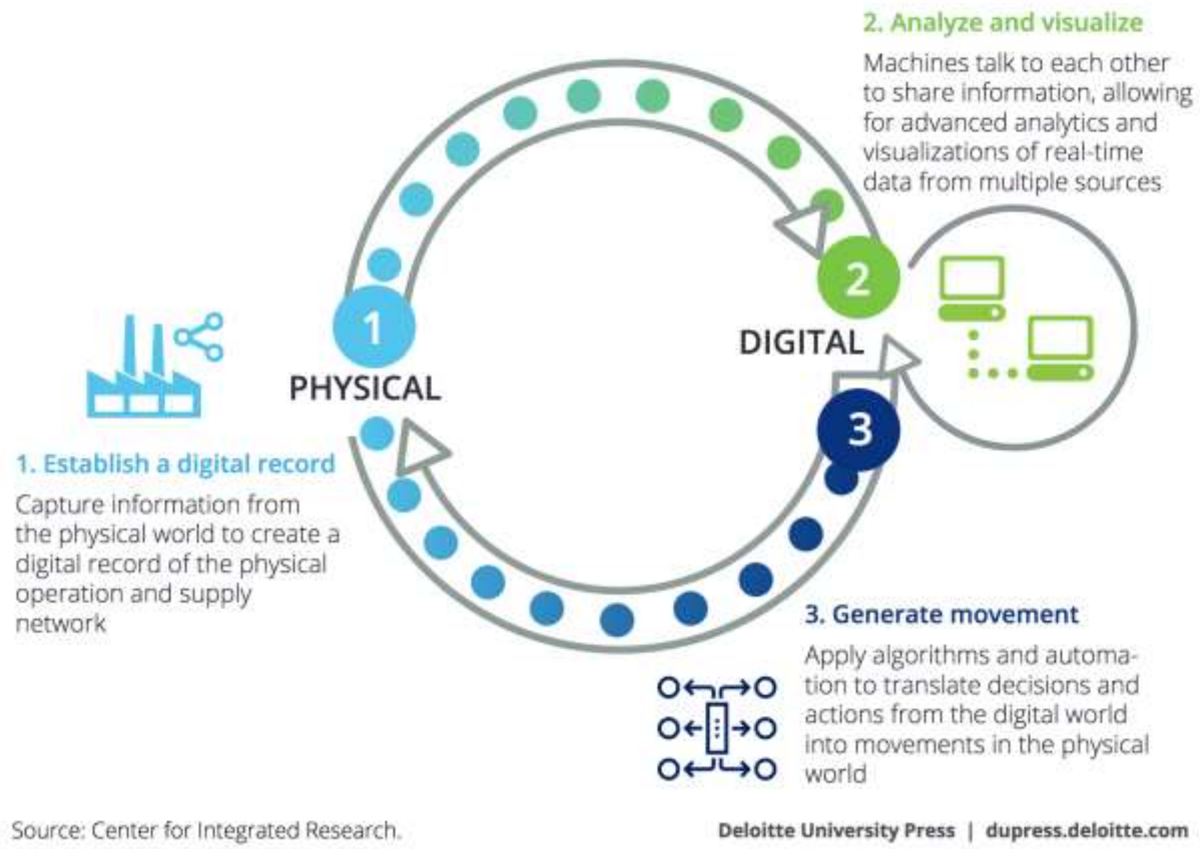


Figure 32. The physical-to-digital-to-physical loop (Coleman et al., 2017)

This process provides to organisations the opportunity of not just be informed by the data, but to utilise the data and take actions in advance. Accordingly to (Coleman et al., 2017), organisations can work more efficiently using the process described, also they to create new business models, just as DSN.

By applying this process to PdM, companies are going to gain a deeper knowledge on their assets, understand better their functionality, do better diagnostics and have more accurate prognosis to avoid breakdowns by developing better maintenance programs.

4.6.3 Managing trade-offs Current asset maintenance strategies

This section is about the benefits and challenges of the different maintenance strategies that organisations use nowadays.

In the previous section, PdM maintenance has come through as the best maintenance strategy that is currently available for enterprises, but the reality is that the best maintenance strategy must be tailored according to the plant, as well as considering the repair needed in the asset. So, every type of maintenance has its pros and cons, which should be analysed thoroughly and after that, a combination of strategies that complement each other could be the best option for a company. Therefore, the following part will review different maintenance strategies.

Reactive maintenance: Allowing parts to run to failure.

- This type of maintenance strategy takes places right after a component or equipment has broken down. Therefore, the useful life of the component or equipment is maximised, since the component is used until the end of its useful life (Coleman et al., 2017).
- Technologically speaking, reactive maintenance is behind of all other maintenance strategies. Whilst this type of maintenance strategy waits until a failure has occurred, other types of maintenance strategies utilise technology in order to prevent failures in the asset (Coleman et al., 2017).
- Reactive maintenance can result very costly for the company. Allowing components to be utilised to their very limits can be the root cause of other failures and create great damage to other components in the equipment. For example, excessive overheat or vibration, can cause other components failures. So, it exists the risk of address incorrectly the failure and to constantly repair the symptom, instead of what is causing that symptom to happen (Coleman et al., 2017).
- Maintenance activities should consider the best cost-effective strategy. Reactive maintenance can be expensive and increase unplanned downtime. So, reactive maintenance is acceptable when an asset or machine uses cheap, reliable or redundant parts (Coleman et al., 2017).

Planned maintenance: Preventing problems before they occur.

- This type of planned maintenance strategy replaces at determined intervals parts or components before they fail. So, the probability of having equipment failures and costly reparations decreases as well as unplanned downtime (Coleman et al., 2017).
- Parts or components of equipment are replaced while they still having an acceptable performance. The challenge is to know at what point the replacement should be done in order to avoid its rupture and utilise it as long as possible (Coleman et al., 2017).

- Planned maintenance strategy could be more cost-effective than the previous strategy mentioned. Additionally, planned downtime and spare parts inventory will increase.
- Proactive maintenance: Treating the root cause, not the symptom (Coleman et al., 2017).
- The implementation of more data driven, analytical approach is what characterises this type of maintenance. Proactive maintenance consists in diagnose, locate and direct the problems that can cause equipment breakdowns (Coleman et al., 2017).
- It uses techniques such as monitoring machinery lubrication, misalignment, temperature conditions, etc. It is supported by condition monitoring techniques, among others. Thus, lifespan of parts or components is longer (Coleman et al., 2017).
- It is more cost-effective than previous maintenance strategies mentioned above. It reduces downtime, planned and unplanned maintenance, also the spare part inventory decreases (Coleman et al., 2017).
- Proactive maintenance is ideal for large equipment that operates in demanding and aggressive conditions (Coleman et al., 2017).

Although maintenance strategies require a lot of training and time to excel its operations, when maintenance strategies are applied correctly, they can deliver great benefits to the organisation.

4.6.4 Breaking the trade-offs. The era of PdM begins

From all maintenance strategies mentioned above, PdM is the one that breaks the tread-offs, because it gives enterprises the possibility of utilise components or parts of equipment to the limit, in other words, this strategy maximises the lifetime of parts or components of assets; also decreases both planned and unplanned downtime that can be translate into lower costs (Coleman et al., 2017).

Data which comes from equipment with embedded sensors that are connected to the internet, play an important role to PdM because that data is analysed, so useful insights comes out from the analysis which are used to predict equipment failures and plan maintenance activities to avoid the failures. Therefore, PdM is a highly accurate strategy.

4.6.5 Why now? The rise of PdM and its place in DSN

Although PdM has existed for a long period, its accessibility was limited due to high costs and the technology used wasn’t advanced as nowadays.

Today, the IoT gives the possibility to connect assets to the internet and by that, the maintenance force can gather data using diverse systems such as CMMS and use the information to identify root causes that before were complicated to notice. Also, analytic capabilities have grown and been more sophisticated with the years, allowing companies to analyse better the data gathered and create quality data which can be useful to do prognosis to the equipment (Coleman et al., 2017).

DSN shares some of the capabilities that PdM have, such as the utilisation of data to inform and support decision making, by knowing the current condition of the equipment and create strength collaboration over the network to efficiently maintain the assets.

Accordingly to (Coleman et al., 2017), the five characteristics of the digital supply network are:

1. "Always-on" agility. Having physical assets connected to the internet enables this characteristic due to the constant flow of data and other systems. This allows to see the current condition of the asset and its changing condition.
2. Connected community. Thanks to the connectivity to the internet of assets and systems, communication and collaboration among suppliers, customers and partners is possible. This facilitate organisations to predict analysis more precise.
3. Intelligent optimisation. Decision making, and the use of machinery is supported by intelligent optimisation that combines humans, machines, data-driven analytics, predictive insights and proactive actions.
4. End-to-end transparency. This is achieved when IoT is present throughout the production process. So, the supply network is completely visible and available on demand.
5. Holistic decision making. The approach of maintaining assets is supported by the accurate election of the analytics and algorithms that uses the collected data to create an output.

4.6.6 Understanding how connectivity drives the PdM process

After recognising from which assets is the origin of the data, the data is available throughout the network, either on site or cloud data storage. At that point, data is analysed by analytic tools with predictive algorithms, having as a result information about when and which part of an asset is likely to fail. Thanks to the communication within the network, the maintenance personnel gets this valuable information through data visualisation; then, they can perform the maintenance activity required to avoid the failure, knowing exactly what to replace and at what time.

The figure below comes from (Coleman et al., 2017) and shows the PdM process described previously.

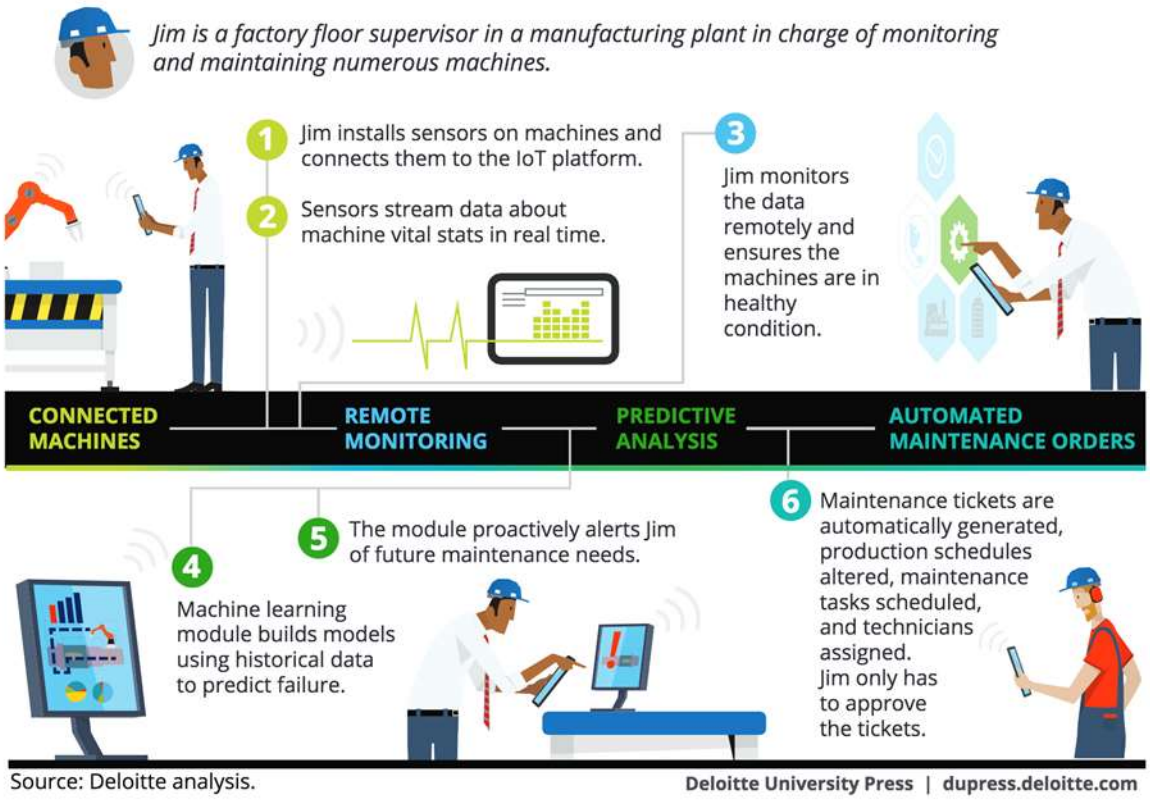


Figure 33. The PdM process (Coleman et al., 2017)

4.6.7 The impact of PdM on the smart factory

According to (Coleman et al., 2017), PdM capabilities influence and create value in two typical business objectives for manufacturing companies, business operations and business growth. Whereas digital technologies can be used to cut costs either on increasing productivity or reducing risk, PdM increases operational efficiency using the same digital technologies by allowing maintenance managers to have a real-time overview of the current state of the assets, so routine machine inspections and unplanned downtime are optimised with PdM. Other benefit of PdM is the spare part storehouse reduction, since it will be possible to predict failures and which part is likely to fail, so spare parts management can be organised more efficiently.

4.6.8 Improving the efficiency of business operation

It is stated in (Coleman et al., 2017), that digital technologies give PdM the ability to identify the most essential challenge of maintenance which resides on: "*the right part in the right place, at the right time*". It is also mentioned that the time used to plan maintenance activities can be reduced by 20-50 percent, grow assets availability by 10-20 percent and reduce the total maintenance costs by 5-10 percent.

The article (Coleman et al., 2017) talks about an example of a large chemical manufacturer that uses IoT technology and applies predictive asset analytics. This company implemented predictive capabilities for one asset class (extruders) in a pilot program, having as result 80 percent cut of unplanned downtime and an estimation of $300,000 cost savings per asset. Due to the good results of the pilot, the company expanded PdM capabilities to other critical assets.

Another example mentioned in (Coleman et al., 2017)is a train operator called Trenitalia, where 1,600 trains needed to be taken out to service for both regular scheduled maintenance and unexpected failures. This situation brought a lot of problems to the company, which reacted having as a solution a three-year maintenance improvement action that consisted with the implementation of hundreds of on-board sensors. The data emitted from the sensors was storage in a private cloud in almost real-time, where it was analysed and after provided insights as part's failures, such as brake pads. Having this information available, Trenitalia optimised the brake pads lifetime and the spare parts storage room. That solution came with great benefits as downtime reduction by 5-8 percent and an estimated 8-10 percent of savings on annual maintenance spend, that is translated to $100 million per year.

4.6.9 Growing the business

PdM not only benefits the maintenance department delivering higher asset efficiency or cutting maintenance costs, but also helps the business growth as well (Coleman et al., 2017).

When the maintenance strategy works as is supposed to, the production can increase since the assets are working at an acceptable level. On the contrary, when equipment doesn't operate as is supposed to, it can affect the quality of the delivered product. Therefore, PdM can help to guarantee product's quality which gives a good impression of the company's product and customers' satisfaction.

4.6.10 Exploring the technologies that enable PdM

To understand the process of how PdM works, it will be reviewed each of those technologies that enables it.

- Sensors and networks

These ones are embedded into the assets and make possible the interaction between the physical and the digital world by creating the data that afterwards is stored and analysed. Sensors are capable to transfer information from assets such as temperature and vibration. Other type of sources like CMMS, programmable logic controller (PLC), enterprise resource planning (ERP) system, among others can provide valuable data.

Networks as Wi-Fi and Bluetooth are used to transfer data to the cloud or where data is stored. Nowadays, bandwidth and storage are accessible to enterprises, so it makes possible to transmit great amounts of data and to storage it. This capability permits the DSN to have an overview of assets and production network, enabling the end-to-end transparency (Coleman et al., 2017).

- Data integration and augmented intelligence

After data is gathered and stored, the next step is to be analysed using advanced analytics and predictive algorithms. To predict part failures using gathered data, requires more than just collected data. Machine Learning techniques or augmented intelligence (AI) are capable of predict failures utilising top level solutions for unstructured data (Coleman et al., 2017). These technologies analyse thoroughly the big amounts of data, removing information that is irrelevant and just using what is necessary. Whereas PdM rely on finding the thresholds which accurate indicate the failure in a pilot program, machine learning works actively improving these thresholds by adjusting them accordingly to the outcomes generated of every prediction. It is crucial for PdM to create and use the right algorithms to function effectively.

Years ago, specialist such as statisticians or computer scientists were needed to use the tools mentioned previously and organisations may not have had expertise or resources needed to carry out such activities. But nowadays these tools are more common among the industry, its use has been simplified and became more friendly for the users (Coleman et al., 2017). This means that machine operators or maintenance technicians can use the insights generated by the assets to perform the maintenance activity needed.

- Augmented behaviour

After data has been analysed and valuable insights are generated, this information can be translated into actions for both maintenance personnel and machines that can operate autonomously.

For the maintenance personnel, augmented behaviour becomes very useful, for example at the time when a technician is performing a maintenance activity, this person will have the opportunity to use this type of technology that can provide him/her the ability of see or review a maintenance manual or get help from expert advice. This is possible because this technology is built up step-by-step instructions that help the operator to solve the task as well as solve problems that can arise, it works like on-demand training.

For machines, it will be cases that they can operate autonomously. For example, after PdM maintenance makes a prediction, a work order is generated in the company's CMMS system, afterwards the spare parts needed to carry out the maintenance activity can be requested and purchased and finally the unplanned downtime can be prioritised. The maintenance manager will be able to see all this process and it just going to be needed his/her approbation in the work flow and assign a technician.

The picture below shows the technologies that make PdM a reality, the picture was extracted from (Coleman et al., 2017).

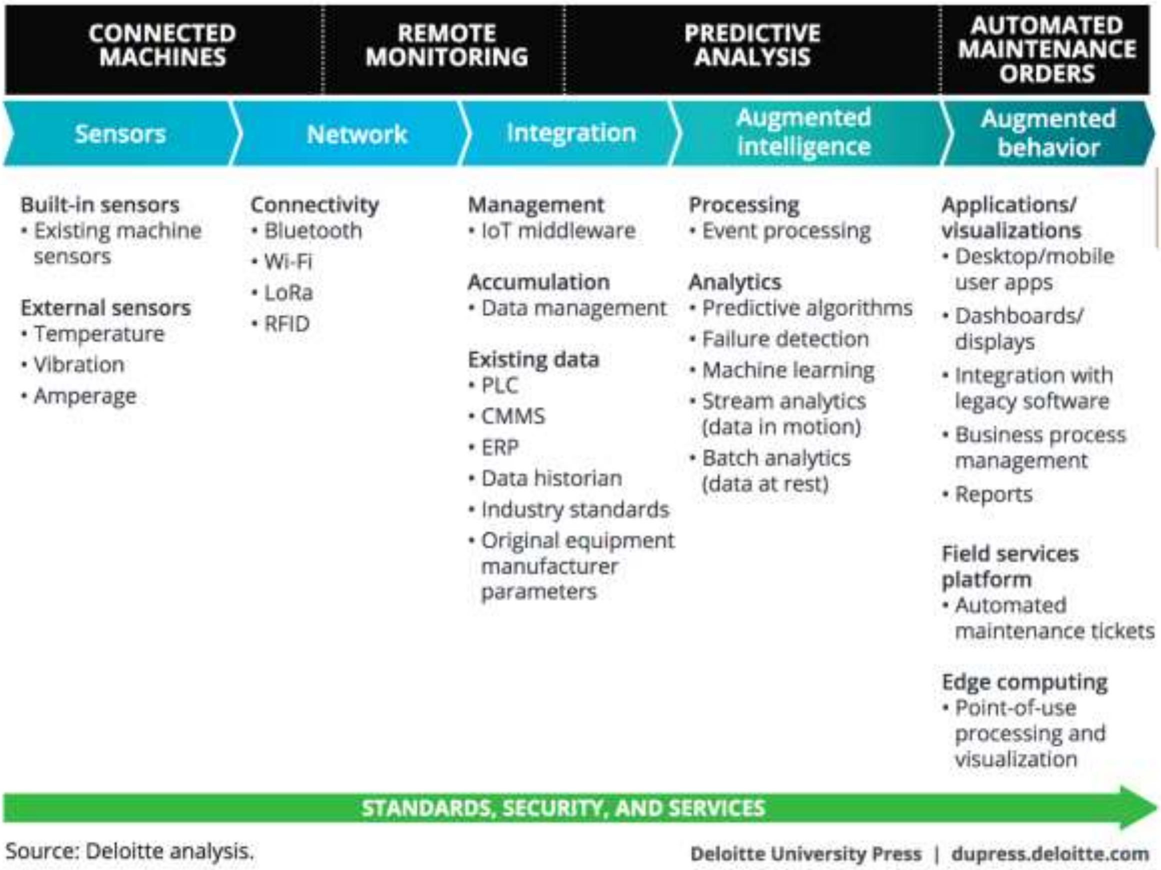


Figure 34. Technologies that drive PdM (Coleman et al., 2017)

4.6.11 Laying the foundation. Building the capabilities for PdM

Adopting and implementing new digital technologies in a company, such as PdM, can be challenging since it can create greater costs and more technical support than before. A change in the organisation and process is crucial when implementing PdM, also accordingly to (Coleman et al., 2017), enterprises should take into account five aspects which will lay the foundation on PdM:

1. Security. Connecting assets to IoT can make them vulnerable towards hackers, therefore it should be considered to protect access to critical equipment and extend cybersecurity to safeguard the connected assets (Coleman et al., 2017).
2. New skills and organisational approaches. PdM implementation and performance differs a lot from traditional maintenance activities, thus new skills will be needed. A recommended working team, data scientists and reliability engineers, is suggested in the article in order to develop algorithms used to predict failures (Coleman et al., 2017).
3. Equipment upgrades. Many companies still have old assets working although they may have some difficulties, like to obtain spare parts. In order to implement PdM, assets replacement must be taken into account or upgrade the old asset by embedding sensors

on it; anyways, this can represent a big investment for the company (Coleman et al., 2017).

4. Data management. The first thing an organisation must achieve regarding data management is to gather quality and useful data that is going to be used to predict failures. At the beginning of the gathering process, big efforts must be done to clean all data collected and to trace to events in order facilitate an effective analysis, to finally end up with the right data. Afterwards, the right data can be used in multiple assets and locations, be stored, analysed and obtain valuable information regarding as failure prediction. Data management is utterly important for the PdM success because the right algorithms and software tools are going to determine the effectiveness of PdM (Coleman et al., 2017).
5. Technology. Mostly of the technology used in PdM is quite new and could be complicated to apply that for the first time. Therefore, it is recommended to create pilot programs to practice, test and learn from it before is roll out to the rest of the plant. It is crucial for organisations to set up the right foundations to enable PdM. It will require to have the right people and investment in technology to succeed in PdM (Coleman et al., 2017).

4.6.12 Building organisational capabilities

These capabilities are very important to PdM and they should be in place to ensure the PdM process. The development of a decision-making framework is necessary to the organisation when making use of gathered and analysed data, because decisions will be supported on the data outputs, instead of being supported by operators or maintenance workforce intuition and experience.

In order to structure the decision-making framework process, it is suggested in the article (Coleman et al., 2017) some stages:

- Stage one: Set up a performance management framework.

To ensure what you are doing is right, it is important to understand in what way things are done so it will be known what to expect and what you are going to achieve. The part of what you do should be control and managed on the daily basis (Coleman et al., 2017).

- Stage two: Set up a process to identify and capture value.

Value quantification is way to know if the process is progressing towards the established goals. Also, it is recommended to overlook the process performance and the resource allocation (Coleman et al., 2017).

- Stage three: Shift from reactive to proactive decision making based on real-time informational analytics.

It will be needed the creation of a place where asset information is going to be managed. This will facilitate the approach and handling of information from various sources (Coleman et al., 2017).

4.6.13 Assessing organisational needs

Companies should address to their own necessities, this means for example that the level of assets reliability changes from enterprise to enterprise. The following part are questions extracted directly from the article (Coleman et al., 2017). Whether an organisation is wondering about the maturity of their maintenance program or assess their mission requirements, some questions should be answered:

- *Business strategy*

  What could be the value of PdM across our enterprise?

  How reliable do our assets need to be? What are our availability targets?

- *Maintenance strategy*

  How do we determine when it's time to replace an asset rather than maintain it?

  What data do we already have that are not being used effectively?

  Have we selected an analytics tool that can handle the data types and volumes needed?

  Have we identified the critical assets in our production system?

  Are there some critical assets that would benefit from a PdM pilot?

- *Maintenance process*

  Do we have the right spare parts in the right place at the right time?

  Are our processes well documented, accessible and useful?

  Do we have the right tools for the job?

  Do our technicians have the right skills to perform the work required?

Maintenance strategy and processes should be equal involve with the technology that enables them, so the maintenance organisation can operates successfully when executing a project, no matter the size of it (Coleman et al., 2017).

4.6.14 Taking the next steps toward PdM

To succeed in PdM, organisational and operational foundations should be in place before adopting this strategy. Several challenges will appear and therefore not every enterprise is ready to take PdM strategy before putting in order their current situation and prepare the company for the organisational changes that need to be done. It is recommended by (Coleman et al., 2017) to take structured steps when moving towards PdM, such as preventive and proactive maintenance strategies, while building the capabilities required for PdM.

Accordingly to (Coleman et al., 2017), enterprises should take the following steps toward PdM:

- Start small. Pilot PdM is recommended in the beginning, this can be applied when preventative and proactive maintenance are in place. Not more than two assets are recommended to apply the pilot. Also, to create predictive algorithms, the assets used should fail and be as well elemental to operations. Starting small limits the risk in case of failure and helps the organisation to test the strategy, technologies and processes (Coleman et al., 2017).
- Scale fast. Right after the pilot program is operating and delivering good results, PdM will be ready to be applied from two assets to the entire factory. That means that due to the factory connectivity to the IoT, DSN can be expanded to a wider network. This process will reveal problems within the organisation. For example, although the factory has the required technology in place, a lack of personnel training could arise (Coleman et al., 2017).
- Build a plan before getting started. In previous sections, decision-making framework was mentioned and it is relevant at this point because it will identify possible problems and will be a big factor on the way to success (Coleman et al., 2017). It is important to quantify the progression and milestones achieved to have an overview of the process and track its growth.

These steps are going to make possible for enterprises to gain all the benefits that PdM provides. Nowadays, technology makes PdM a reality, so it is up to enterprises to make the required organisational changes to make this happen.

Chapter 5

Discussion and Conclusion

5.1 Discussion

At the beginning of this Master's thesis, some objectives where defined. So, in this section it will be reviewed whether those objectives were accomplished through the thesis.

It is important to point out that Statnett is an industry collaborator of this thesis, so at the very beginning of this thesis work it was considered to apply and evaluate the models that are presented on this thesis utilising real data from Statnett, but unfortunately, due to external factors and constrains it was not possible to test any model neither use real data. Therefore, it was selected relevant study cases where some of the models presented were applied in real cases.

Several literature resources were reviewed for the elaboration of this thesis and it was selected the must relevant ones accordingly to the content and the date when they were published. So, among the selected ones, it was build the theoretical framework of this thesis.

For the topic of maintenance excellence, several models were reviewed. It was found that it doesn't exists a generic model or methodology which can be applied within an organisation in order to achieve maintenance excellence. Therefore, it was selected the most relevant models, which were analysed. Based on that, it was built and proposed a maintenance excellence model, where important aspects related to RAMS were considered. Unfortunately, due to external factors, the maintenance excellence model proposed in this thesis wasn't tested within Statnett, so that objective wasn't accomplished. Further work should be implemented, which consists in the application of the proposed maintenance excellence model within an organisation, so after implementing the model, an accurate evaluation can be made.

The condition monitoring techniques that were reviewed through this thesis, where selected considering its relevance within Statnett's electric power plants. So, the literature utilised includes relevant study cases where the condition monitoring techniques were applied within electric power plants. Also, it was analysed how the condition monitoring techniques that were considered could be applied on predictive maintenance programs. It was found that with the technological advances presented nowadays it is possible not only integrate condition monitoring techniques to predictive maintenance programs, but even take that further by utilising industry 4.0 on those condition monitoring techniques.

In the last part of this Master's thesis, it was studied the impact of industry 4.0 to the maintenance field. It was found that innovative solutions can benefit the way that maintenance is carried out. Also, relevant study cases were presented, and it was analysed how other companies implemented new digital technologies to their organisation. Through those study cases, it was analysed step by step the implementation process needed to use industry 4.0 and modernise a company.

5.2 Conclusion

Through this master thesis, three main topics were developed: maintenance excellence, condition monitoring and smart maintenance. Where all of the topics aim to excel maintenance strategies and performances in order to create effective working procedures for Statnett by providing safety working environments.

A maintenance excellence model was proposed, which provides a solid maintenance foundation that can support and sustain in an effective way the right maintenance strategy. In addition, the model proposed was developed considering a RAMS approach.

It was found that the best maintenance strategy for Statnett, shall be tailored exclusively for each of its plants, where critical assets are prioritised, thus the strategy that utilises the last technological advances should be implemented, PdM 4.0, because this strategy can handle complex equipment by offering innovative and effective maintenance solutions. For the rest of the assets, a combination of strategies is suggested, where it can exist the possibility that for not critical assets that are easy and cheap to repair, some corrective actions should be taken.

Nowadays, companies are trying to deal with their technical assets in order to keep them performing in an optimal level and sometimes an effective maintenance program is not enough to achieve competitive results that the tough market demands. Therefore, condition monitoring techniques where presented, such as ultrasound. This technique is quite effective when inspecting electric assets in power plants. Also, a technical condition assessment of a transformer was reviewed. In order to carry out a technical condition assessment, the use of condition monitoring techniques is used. Technical condition assessment and condition monitoring techniques provides valuable insights about the asset under study, since both diagnosis and prognosis can be applied when collecting information out of those processes.

Due to operation and time, the degradation of an asset is inevitable, so the great difficulty lies on predicting its failure. Modern techniques are used nowadays, thus online condition monitoring techniques are introduced in this thesis by analysing the capabilities of the technique, as well as envision the future usage of the technique.

Industry is developing faster than before, and the fourth industrial revolution, called industry 4.0 is a reality today. This new revolution uses new digital technologies that changes the way industries work by connecting smart devices to the IoT. Those smart devices create data which is collected and stored in a cloud, then the data is structured and analysed by data scientist using Machine Learning technology to provide valuable insights that can be used when it comes to decision making.

When industry 4.0 is combined with predictive maintenance, it is created what is called PdM 4.0 or smart maintenance. This kind of maintenance uses insights such as failure modes and failure rates, to predict and avoid failures that could be very expensive to the company.

Therefore, PdM 4.0 focuses on reducing downtime and increasing operational efficiency and ensuring product’s quality. Besides investments within technology are needed to implement the smart maintenance, also the organisational structure should be considered, therefore through the thesis it is reviewed how Statnett can be prepared its whole enterprise towards the future and become a data driven organisation.

After all, technology is changing the maintenance industry and this tendency will continue for a while, therefore is highly recommended that Statnett begins to move towards the future and start to build the foundation for PdM 4.0. Large investments will be required, but they will be justified since great revenue for the company is going to be created by the maintenance department.

Bibliography

2017. Maintenance is a journey, not destination, says SNSI. Manama.

13306:2010, N.-E. 2010. Maintenance terminology.

29821:2018, I. 2018. *Condition monitoring and diagnostics of machines - Ultrasound - General guidelines, procedures and validation* [Online]. Available: http://www.standard.no/nettbutikk/sokeresultater/?search=ISO+29821 [Accessed 2018-04-27 2018].

AGUSTIADY, T. K. 2016. Total productive maintenance : strategies and implementation guide. *In:* CUDNEY, E. A. (ed.). CRC Press.

ANDERSSON, R., MANFREDSSON, P. & LANTZ, B. 2015. Total productive maintenance in support processes: an enabler for operation excellence. *Total Quality Management & Business Excellence,* 26**,** 1-14.

BANDES, A. 2009. Ultrasonic Condition Monitoring in Power Plants. *Asme Power Conference 2009***,** 345-351.

BARROS, A. 2017. Condition Monitoring and Maintenance Optimisation Compendium.

BORUCKI, S. 2012. Diagnosis of Technical Condition of Power Transformers Based on the Analysis of Vibroacoustic Signals Measured in Transient Operating Conditions. *Power Delivery, IEEE Transactions on,* 27**,** 670-676.

CAMPBELL, J. D., JARDINE, A. K. & MCGLYNN, J. 2016. *Asset management excellence: optimizing equipment life-cycle decisions*, CRC Press.

COLEMAN, C., DAMODARAN, S., CHANDRAMOULI, M. & DEUEL, E. 2017. *Making maintenance smarter* [Online]. Available: https://www2.deloitte.com/content/dam/insights/us/articles/3828_Making-maintenance-smarter/DUP_Making-maintenance-smarter.pdf [Accessed March 9 2018].

DJUROVIC, D., BULATOVIC, M., SOKOVIC, M. & STOIC, A. 2015. MEASUREMENT OF MAINTENANCE EXCELLENCE. *Teh. Vjesn.,* 22**,** 1263-1268.

DUNN, R. L. 2001. Foundations for maintenance excellence. (cover story). *Plant Engineering,* 55**,** 62.

FARR, R. 2009. An enterprise approach to reliability - Ash Grove's Maintenance Excellence Process (MEP).

GEISSBAUER, R., VEDSO, J. & SCHRAUF, S. 2016. *Industry 4.0 Building the digital enterprise* [Online]. Available: https://www.pwc.com/gx/en/industries/industries-4.0/landing-page/industry-4.0-building-your-digital-enterprise-april-2016.pdf [Accessed 2018.06.06 2018].

HAARMAN, M. & DELAHAY, G. 2016. *Value Driven Maintenance & Asset management,* Amstelveen, Mainnovation.

INSTITUTE, T. M. E. 2010. The reliability pyramid.

JARDINE, A. K. S. & CAMPBELL, J. D. 2001. *Maintenance excellence : optimizing equipment life-cycle decisions,* New York, Marcel Dekker.

KABOLI, S. & ORAEE, H. 2016. *Condition Monitoring*, IGI Global.

KENNEDY, S. 2014. *Is an online monitoring system right for you? What you should know* [Online]. Available: https://www.plantservices.com/assets/Media/promo/special-report/thinking-about-remote-monitoring.pdf?submissionGuid=9a134655-408b-4c6a-92a1-a19429bb18e9 [Accessed 2018-04-02 2018].

LABIB, A. 2010. Maintenance strategies: a systematic Approach for selection of the right strategies. *In:* KIRITSIS, D., EMMANOUILIDIS, C., KORONIOS, A. & MATHEW, J. (eds.) *Engineering Asset Lifecycle Management: Proceedings of the 4th World*

Congress on Engineering Asset Management (WCEAM 2009), 28-30 September 2009. London: Springer London.

LASI, H., FETTKE, P., KEMPER, H.-G., FELD, T. & HOFFMANN, M. 2014. Industry 4.0. *The International Journal of WIRTSCHAFTSINFORMATIK,* 6**,** 239-242.

MUKHOPADHYAY, S. C. & SURYADEVARA, N. K. 2014. *Internet of Things : Challenges and Opportunities (Smart Sensors, Measurement and Instrumentation),* Springer.

MULDERS, M., HAARMAN, M. & VASSILIADIS, C. 2017. *Predictive Maintenance 4.0 Predict the unpredictable* [Online]. Available: https://www.pwc.nl/nl/assets/documents/pwc-predictive-maintenance-4-0.pdf [Accessed 2018.06.06 2018].

MULDERS, M., HAARMAN, MARK 2017. Predictive Maintenance 4.0 Predict the unpredictable. *www.pwc.nl*.

RAUSAND, M. 2013. *Risk Assessment: Theory, Methods, and Applications*, United States: John Wiley & Sons Inc.

WANG, M., VANDERMAAR, A. J. & SRIVASTAVA, K. D. 2002. Review of condition assessment of power transformers in service. *Electrical Insulation Magazine, IEEE,* 18**,** 12-25.

WERNICKE, I. 2015. Achieving Sustainable Economic Growth from the European Point of View. *Journal of Economic Development, Management, I T, Finance, and Marketing,* 7**,** 1-23.

Z-008:2017, N. 2017. *Risk based maintenance and consequence classification* [Online]. Available: http://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=956000 [Accessed 2018-06-04 2018].