Joachim Flesjå

Smart Maintenance in Bane NOR

TPK 4590 – Safety, reliability and maintenance, master's thesis

Master's thesis in Subsea technology – operation and maintenance
Supervisor: Per Schjølberg
June 2019

Master's thesis

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

NTNU
Norwegian University of
Science and Technology

Joachim Flesjå

Smart Maintenance in Bane NOR

TPK 4590 – Safety, reliability and maintenance, master's thesis

Master's thesis in Subsea technology – operation and maintenance
Supervisor: Per Schjølberg
June 2019

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

NTNU
Norwegian University of Science and Technology

Preface

This master's thesis is conducted during the spring of 2019 in the subject TPK 4950 – safety, reliability and maintenance, master thesis at the department of mechanical and industrial engineering at the Norwegian University of Science and Technology. The course is conducted in the fourth and final semester at the two-year master's program Subsea technology – operation and maintenance at the department of Mechanical and industrial engineering. The master thesis will constitute a work scope of 30 study credits and concludes with the submission of a final report.

Based on the specialization, operation and maintenance, the candidate was interested in a thesis related to these topics. Associate Professor Per Schjølberg was the supervisor for this master thesis. Bane NOR has been the external contributor during the thesis.

This cooperation was made possible due to Per Schjølberg's broad knowledge and network within the Norwegian industry. Per Schjølberg recommended Bane NOR as a company with similar interests for smart maintenance. Through discussions with Fahad Reman in Bane NOR, the thesis, topic and scope was determined.

Acknowledgment

I want to thank my supervisor Per Schjølberg at the department of mechanical and industrial engineering at NTNU for his guidance through the master thesis. This thesis would not have been completed without his help and his guidance has been invaluable. I would also like to thank my industry partner Bane NOR for the contributions of data and interviews and a special thanks to Fahad Reman for accepting the responsibility as supervisor. I also want to thank Charles Nilsen and Anna Gjerstad for answering any questions related to Bane NORs activities.

Lastly, I want to thank my fellow students, Eirik Hove and Are Stolsmo for continued support during the 2-year master program.

Abstract

The railway sector has always been a high performing maintenance sector were maintenance and safety has had the utmost of importance. In 2014 when the national transport plan for 2014-2023 was presented, it included a big investment to increase railway activity in Norway. To better facilitate the increased activity, Bane NOR was tasked with improving the reliability of the infrastructure to a very high level.

In this digital age, Bane NOR has seen the value of implementing communication technology into maintenance, hereby creating the smart maintenance initiative. By using smart maintenance Bane NOR aims to reach world class maintenance (WCM).

Bane NOR’s strategy for maintenance management is today mainly time-based maintenance, with addition of some smart maintenance. The aim for the future is increasing the amount of smart maintenance being performed on the Norwegian railway infrastructure. To measure this improvement, the thesis provides selection of indicators that can help mapping how the increased use of smart maintenance effects the maintenance efficiency.

By presenting relevant theory about smart maintenance and WCM, together with a WCM overview for Bane NOR. The thesis analyses how Bane NOR can achieve WCM. Recommendations are given, that will help Bane NOR find concepts that will increase maintenance efficiency and allow them to achieve WCM.

Sammendrag

Jernbanesektoren har alltid hatt sikkerhet som den høyeste prioritet. I 2014 da den nye nasjonal transportplanen for 2014-2023 ble presentert, viste den store investeringer for en mer aktiv jernbane i Norge. For å kunne oppnå dette trengs en infrastruktur som ikke påvirker togtrafikken. Derfor tenkte Bane NOR innovativt for å vedlikeholde et aldrene jernbanenett og svart ble smart vedlikehold.

I dagens digitale tidsalder så Bane NOR verdien av å implementere kommunikasjonsteknologi inn i utstyr og benytte seg av dataen dette skapte. Denne dataen skulle brukes for å effektivisere vedlikeholdet i Bane NOR. Gjennom bruken av smart vedlikehold, er målet at selskapet skal oppnå vedlikehold i verdensklasse.

Dagens vedlikeholdsstrategi er hovedsakelig tidsbasert, med innslag av smart vedlikehold. Dette håper Bane NOR på å forbedre med en utvidelse av overvåking og kontroll gjennom smart vedlikehold. For å måle denne forbedringen skal det etableres et utvalg av indikatorer med hensikt å klassifisere hvordan en øking i bruken av smart vedlikehold påvirker den overordnede vedlikeholds effektiviteten.

Ved å presentere relevant teori om smart vedlikehold og vedlikehold i verdensklasse, sammen med en oversikt over vedlikehold i verdensklasse for Bane NOR, undersøker denne oppgaven hvordan Bane NOR kan oppnå vedlikehold i verdensklasse. Anbefaling er gitt, som skal hjelpe Bane NOR å identifisere konsepter som øker bruken av smart vedlikehold og tillater dem å oppnå vedlikehold i verdensklasse

Et potensielt resultat av denne masteroppgaven er videre utredelse av anbefalingene.

List of Figures:

List of Tables:

List of Formulas:

1 Introduction

In 2014, Norway's national transport plan for 2014-2023 was presented. It showed a big push towards a more active railway sector in Norway with a 2015 budget at 21 billion NOK, a significant increase compared to years before. This was called the railway reform and was the government's plan to increase profitability of the transport sector in a socioeconomic fashion[1].

As a result of the railway reform a demand for a more punctual and reliable railway was fronted. For railway operators, this meant asking themselves how this could be achieved. Smart maintenance might be the answer.

1.1 Background

The railway sector has always been a high performing maintenance sector where maintenance and safety has had the highest importance. As a part of the never-ending chase for improvement in maintenance and reliability new concepts arise, one result of this innovation was smart maintenance. Through new technology such as machine learning and big data, Bane NOR seeks to find the failures before they happen.

As a part of this digitalization process the candidate and supervisor approached Bane NOR about their interest in a collaboration. The company expressed interest in identifying procedures for how they can improve the use of smart maintenance and WCM, and this thesis aims to answer that. Successfully implementing the resulting recommendations would results in less delays in railway traffic.

This thesis aims to help Bane NOR achieve their goal of:

"Operating the infrastructure without having service disruptions for the train traffic[2]"

1.2 Problem description

The problem presented in the master thesis is articulated in collaboration between supervisor Per Schjølberg from NTNU and candidate.

1. Research and present theory on smart maintenance and WCM.
2. Research and present the use of smart maintenance in the railway industry.
3. Familiarization and presentation of smart maintenance within Bane NOR
4. Recommend improvements for smart maintenance in Bane NOR.

1.3 Objective of the Master thesis

The objective of this master thesis is to research and present theory about smart maintenance, and use this theory to recommend improvements for smart maintenance within Bane NOR. A WCM overview for Bane NOR will be presented, with the objective of mapping Bane NOR's progress towards WCM.

The findings presented in this thesis will act as objective recommendations to enhance railway availability and safety in Bane NOR.

To accomplish the main task of the master thesis several intermediate objectives needs to be completed:

- Research and present theory on smart maintenance and WCM
    - Research literature about smart maintenance
    - Research literature about WCM
    - Establish an understanding of what smart maintenance is
    - Establish an understanding of what WCM is
    - Present relevant theory on smart maintenance
    - Present relevant theory on WCM.
- Research the use of smart maintenance within railway industry
    - Research the implementation of smart maintenance on an international scale
    - Research the current state of smart maintenance within a world leader such as Germany
    - Describe the use of smart maintenance in different countries.
- Map smart maintenance within Bane NOR
    - Research the use of smart maintenance within Bane NOR
    - Conduct interviews with maintenance personnel at Bane NOR.

  - Describe the use of smart maintenance at Bane NOR
- Create a WCM overview for Bane NOR.
  - Establish Key performance indicators related to WCM.
  - Measure Bane NORs current maintenance processes in correlation with WCM.
  - Create an overview for WCM based on the current status within Bane NOR
- Presents recommendations to improve maintenance in Bane NOR.
  - Use theory presented to recommend actions to improve maintenance.
  - Recommend a selection of key performance indicators that Bane NOR can monitor.

1.4 Scope

The scope of this master thesis is to gain increased understanding of smart maintenance and document how it is used in the railway industry. The candidate aims to present a selection of recommendation to improve smart maintenance in Bane NOR. The department at Bane NOR relevant for this thesis is the smart maintenance division and therefore other divisions in Bane NOR will not be studied in this thesis. The thesis is structured on the basis that the reader has a general engineering background with an understanding of modern concepts related to maintenance.

1.5 Contributors to the Master thesis

In this master thesis there is one internal contributor and one external industrial contributor. The internal contributor is NTNU with supervisor Per Schjølberg and the external industrial contributor is Bane NOR with Fahad Reman as the main contact person. The thesis has also been guided by two Bane NOR employees; Charles Nilsen and Anna Gjerstad, providing valuable information and feedback.

1.5.1 NTNU

The Norwegian university of Science and Technology is the largest university in Norway after combining with the colleges of Aalesund, Gjøvik and Sør-Trøndelag. There are around 40,000 students in total at NTNU. Within NTNU there are 8 different faculties with different focus areas, and this master thesis is written for the department of production and quality engineering, which is a part of the faculty of engineering science[3].

1.5.2 Bane NOR

Bane NOR is a state-owned company responsible for the national railway infrastructure. With 4500 employees they are responsible for planning, development, administration, operation, maintenance, traffic management and administration for the national railway network. Bane NOR's main mission is to ensure accessible railway infrastructure and efficient and user-friendly services, including the development of hubs and goods terminals[4].

1.6 Limitations

There have been some factors limiting the scope of this thesis. These limitations include time, literature and industrial partner.

1.6.1 Time

The official start of the master thesis is 15.01.2019 and the submission date is 11.06.2019 and after the unsuccessful cooperation between a former industrial partner, the time available will be shortened. The master thesis has a time limitation of 21 work weeks, which include 40 work hours in each week totalling in 840 hours. The master thesis credits 30 study points and is the only course taken in the final semester.

1.6.2 Literature

As an NTNU student, the candidate has access to a wide range of licenses, scientific articles and books. Available literature for the master thesis will be limited to the litterateur available through the NTNU library and licences. The NTNU library and data from the industrial partners is extensive, but there might be some limitations regarding literature about certain subjects. This may limit the thesis.

In this thesis some excerpts and Figures from standards such as NS-EN 13306:2017, NS-EN 15341:2007, NS-EN 15628:2014 and NORSOK Z-008:2017 have been used. Standard.no has given the candidate permission to use this content.

«Utdrag og Figurer fra NS-EN 13306:2017, NS-EN 15341:2007, NS-EN 15628:2014 og NORSOK Z-008:2017 er gjengitt av Joachim Flesjå i masteroppgaven [Smart maintenance in Bane NOR] med tillatelse fra Standard Online AS 05/2019. Standard Online er ikke ansvarlig for eventuelle feil i gjengitt materiale, Se www.standard.no »

1.6.3 Industrial partner

Bane NOR will have limitations on how much time and resources they can contribute with. As a big company in the middle of a restructuring, there is not an abundance of time available for guidance. This will limit the thesis in some way.

1.7 Methodology

The master thesis theme of smart maintenance was decided upon in February 2019 in a meeting between the candidate and the supervisor at NTNU, Per Schjølberg. After the meeting, supervisor Per Schjølberg contacted Fahad Rehman in Bane NOR and finalized the final problem description in March of 2019.

Initially a literature study was conducted to gain knowledge of relevant information for the thesis, with a focus on smart maintenance and WCM. Some literature was collected during the course TPK4550 – Reliability, Availability, Maintainability and

Safety, Specialization Project, and a more extensive literature study was conducted for the master thesis.

To gain an overview of how smart maintenance has been used in the other countries an additional literature search focused on case studies was conducted. This was done to gain insight into other applications of smart maintenance in the railway industry.

Since the intermediate objectives include mapping present-day use of smart maintenance, an interview was conducted with maintenance personnel from Bane NOR. Charles Nilsen and Anna Gjerstad provided a good description of how smart maintenance is developed within Bane NOR.

To map the WCM status, the present-day status of smart maintenance and maintenance management within Bane NOR was evaluated. After this evaluation was completed by the candidate, a WCM overview was developed.

The finalizing part of the master thesis was providing recommendations that could increase the efficiency of smart maintenance in Bane NOR. This was provided on the basis of the conducted literature research and applications of smart maintenance in other countries.

1.8 Structure of Master thesis

In this master thesis the structure is as follows:

Table 1: Structure of the master thesis

Theory:	International railway:	Bane NOR:
Smart maintenance - Smart maintenance introduction [2.1] - Smart maintenance strategies [2.2] - World class maintenance [2.3]	Smart maintenance in international railway: - Benefits of implementing smart maintenance within railway [5.1] - International use of smart maintenance within railway [5.4]	Smart maintenance in Bane NOR: - Smart maintenance in Bane NOR [6.3] - Future of maintenance within Bane NOR [6.4] - World class maintenance in Bane NOR [6.5] - What should Bane NOR implement [7]
Maintenance management - Resources [3.1] - Management of Maintenance work process [3.2] - Results [3.3] - CMMS [3.4] - Smart maintenance management [3.5]	Maintenance management in international railway: - Planning and scheduling using machine learning [5.2.1]	Maintenance management in bane NOR: - Maintenance practises today [6.2]
Industry 4.0 - Evolution of Industry 4.0 [4.1] - Industry 4.0 concepts [4.2] - Industry 4.0 today [4.3] - Society 5.0 [4.4]	Industry 4.0 in international railway: - Machine learning within railway [5.2] - Big data within railway [5.3]	Industry 4.0 in Bane NOR: - What should Bane NOR implement [7]

Chapter 2 presents and discusses smart maintenance and relevant theory to smart maintenance. These theories include smart maintenance strategies and WCM. The aim of chapter 2 is to create an understanding of what smart maintenance is and build a theoretical foundation to present a recommendation for enhancing the smart maintenance at Bane NOR.

Chapter 3 focuses on presenting an introduction of maintenance management. Within this chapter the maintenance loop will be explained, as well as concepts such as CMMS and smart maintenance management. The aim of chapter 3 is to present the reader with knowledge about how maintenance is planned and how modern tools can help with this.

Chapter 4 gives a presentation of industry 4.0, with concepts related to industry 4.0. After the related subjects are presented, the current state of industry 4.0 in the industry today is presented. In the end of chapter 4 the step after industry 4.0 is presented, Society 5.0

Chapter 5 presents how industry 4.0 is being implemented in the railway industry. This chapter continues by introducing cases from other countries and how they have implemented industry 4.0 and smart maintenance concepts.

Chapter 6 introduces Bane NOR, both as a company and their smart maintenance processes. The aim of this is to show how far the development of smart maintenance has come today and the future plans for smart maintenance in Bane NOR. This allows evaluation of smart maintenance and what could be improved in Bane NOR.

A WCM overview is also presented in chapter 6. The aim of this subchapter is to indicate at what level maintenance is being performed in Bane NOR and which indicators are being used to measure the effectiveness of maintenance.

Chapter 7 gives a recommendation for implementation of smart maintenance in Bane NOR. This chapter aims to give a recommendation of how Bane NOR can improve the use of smart maintenance.

Chapter 8 presents a discussion chapter. This chapter will discuss the results presented in the thesis, by comparing the presented results to the objectives set in the beginning of the master thesis.

Chapter 9 presents a conclusion and further work chapter. The aim of this is closing of the master thesis with finishing statements and a recommendation for future work.

The remaining chapters are the reference list and appendixes.

2 Smart maintenance

This is a special time for maintenance. It is growing to become an increasingly visible activity in our society today. With more and more technical assets being produced and put into production, the need for maintenance is higher than ever. If we, as a society, are to survive we will need to successfully make society more sustainable and less energy-consuming with lower emissions of greenhouse gasses.

In chapter 2 an introduction to smart maintenance and WCM will be presented. This will include theories about smart maintenance strategies and WCM. The theory will form the theoretical basis for evaluating the present-day smart maintenance at Bane NOR.

Figure 1 shows an overview of different concepts within smart maintenance. The different concepts are all related to smart maintenance and will be presented in the thesis.

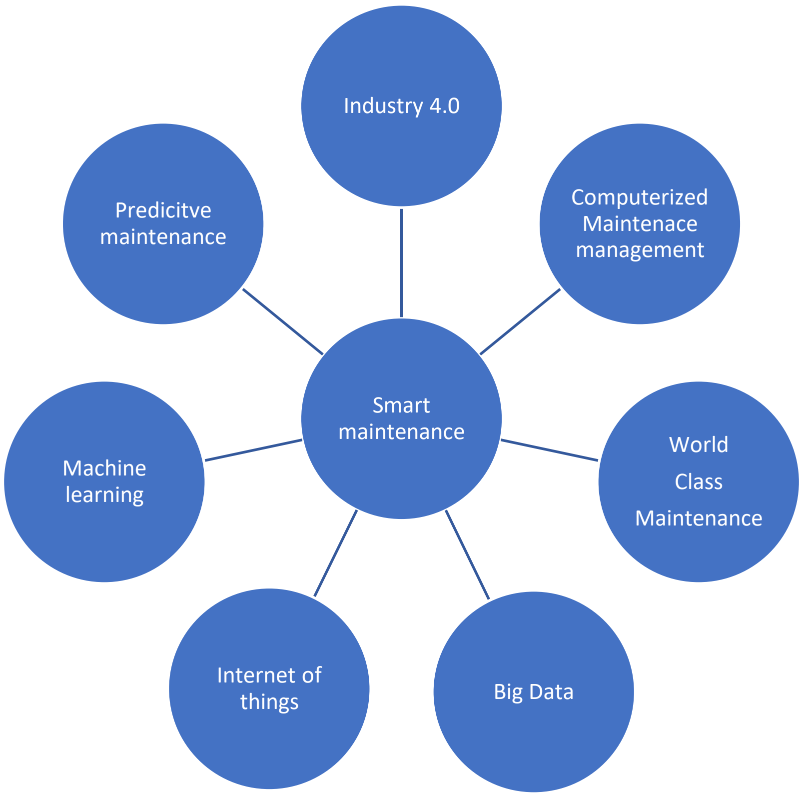


Figure 1: Smart maintenance

2.1 Smart maintenance introduction

In chapter 2.1 an introduction to smart maintenance will be presented. This includes a definition of smart maintenance and theory related to smart maintenance. In the subchapters the maintenance concepts related to smart maintenance will be presented.

Smart maintenance is the concept that correlates with industry 4.0 and maintenance 4.0. The definition of smart maintenance can be:

"*A subset of smart systems represented by self-learning and smart machines that predicts failure, makes diagnosis and triggers maintenance actions*"[5]

To give a visual overview of what smart maintenance is, figure 2 was created. Figure 2 shows the smart maintenance life cycle loop. Starting with information, mainly sensor data, that is transferred and transformed by cloud processing and sent to analysis software. The finished prediction is sent to a cloud decision support system that is based on a set of hierarchy rules that establishes what maintenance tasks that are required to be done. These tasks are sent to maintenance personnel through e.g. tablets and augmented reality (AR) glasses and show the given maintenance needs. The maintenance technicians uses this information to efficiently perform the scheduled maintenance and closes the loop[6].

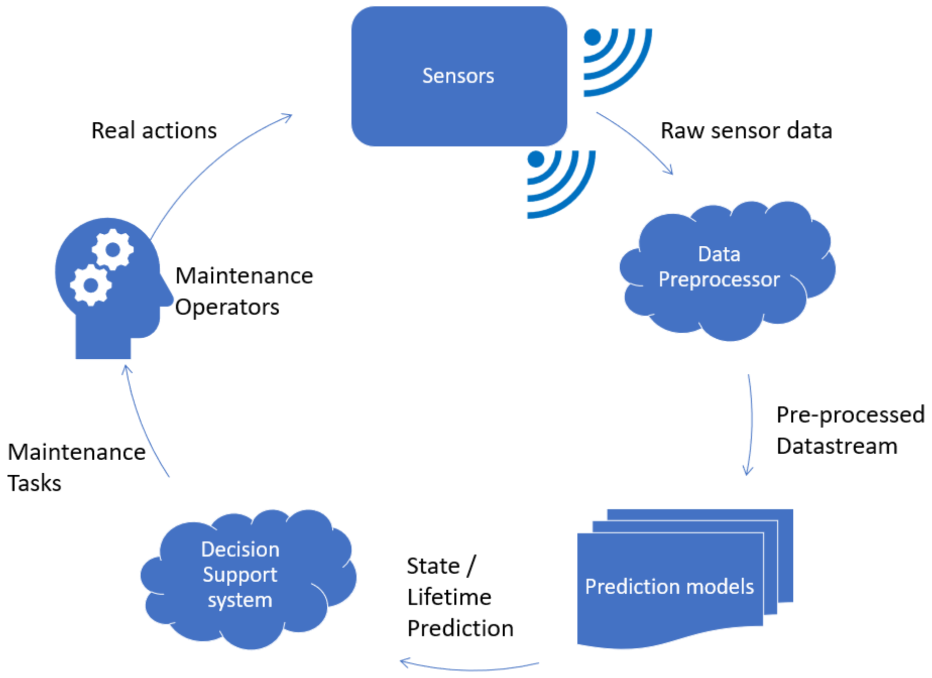


Figure 2: Smart maintenance lifecycle (adapted from [6])

To use smart maintenance, the machines themselves needs to be smart. These systems can either have smart equipment embedded or be a cyber-physical system, where the physical equipment is intertwined with data collecting components. The cyber-physical system uses computing resources for efficient data capture, processing and communication in order to monitor and control the system [7]. This is illustrated as the sensor block in the smart maintenance loop.

Figure 3 presents a diagram where the y-axis shows machine performance and uptime, and the x-axis is the evolution of maintenance. Figure 3 shows which types of maintenance strategies are classified as smart maintenance. In the diagram there are three maintenance methods that are classified as smart maintenance and three maintenance methods that are classified as basic maintenance methods. The three smart maintenance methods are predictive maintenance, proactive maintenance and self-maintenance, and the three basic maintenance methods are no maintenance, reactive maintenance and preventive maintenance. Further down in this chapter the three smart maintenance methods will be explained.

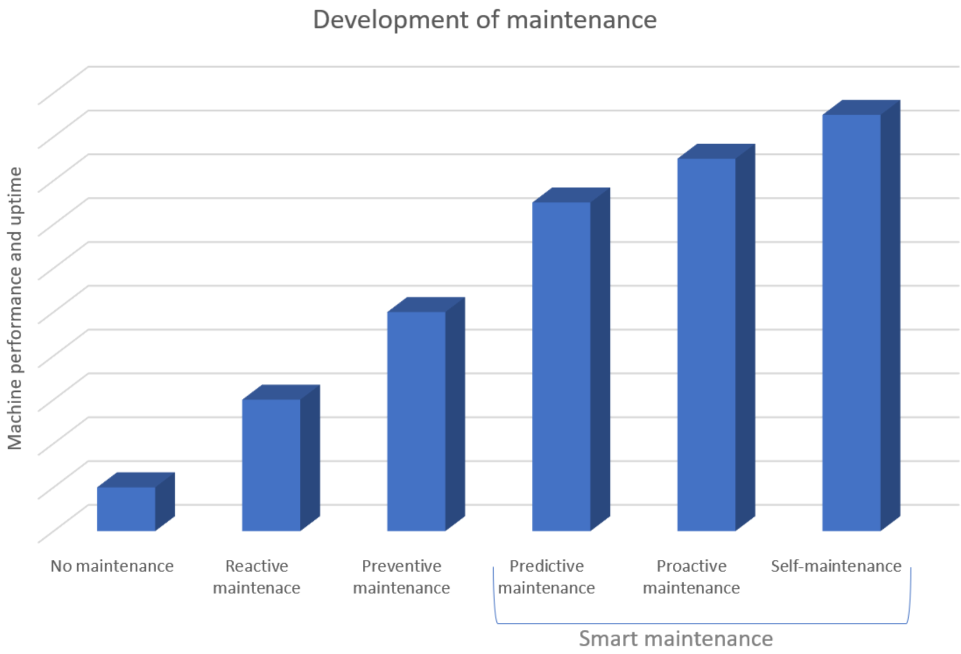


Figure 3: Development of maintenance (adapted from[8, 9])

As seen in figure 3 the first step of smart maintenance is categorized as predictive maintenance and will be a natural focus within this thesis.

Continuing forward the benefits of smart maintenance will be presented, this is to see the advantages of smart maintenance and why it may be the future of maintenance.

2.1.1 Benefits of smart maintenance

With the introduction of smart maintenance, it is important to see what the benefits are, if implemented [10]:

1. **Maximizing uptime**

Smart maintenance introduces principles to increase uptime, such as: faster service, better technical insight, maintenance only when needed and optimized logistics. Faster service is done by giving technical maintenance personnel accurate work orders. With predictive analysis it increases the insight of the asset by providing sensor data and condition analysis. Maintenance only needs to be conducted when the technical condition demands it and thus increasing uptime. Optimized logistics automatically orders spare parts when needed and decreasing the logistic and planning[11].

2. **Increased productivity**

Productivity will see a significant increase as a result of the higher uptime for the technical assets. Additional factors that contribute to increased productivity are the insights on how to maintain or repair equipment. This will increase the knowledge of the technical staff, thus increasing efficiency[10].

3. **Reduce maintenance costs**

Poorly scheduled maintenance and the resulting downtime are costly. By smartly optimizing the use of predictive maintenance (PdM), you'll reduce costs for components and labour[10].

4. **Extend equipment lifetime**

With an increased amount of data available, concepts such design for maintenance and 3D design will help providing a better basis for maintenance, thus increasing the equipment's lifetime[11].

5. **Ensure compliance**

The automatic reporting and follow up procedures provided by smart maintenance solutions help maintenance personnel to comply with maintenance related standards[10].

6. **Enhance safety and cut energy consumption and CO2 emissions**

Monitoring and fixing problems before a failure occurs increases the safety in the workplace for technical employees. Moreover, advanced tools can help cut energy consumption while reducing CO2 emissions for the whole value chain[10].

These benefits are all good reasons for implementing smart maintenance, but with these benefits there is also some challenges that affect smart maintenance. These challenges are not universal for every industry, and the presented problems are related to the railway industry.

2.1.2 Current challenges with smart maintenance

To help understand these challenges they need to be identified. These challenges include culture/organization, knowledge, poor data quality, unreliable correlations and insufficient lead time[12].

Culture and organization:

One of the biggest challenges is a non-technical challenge. In a report by the Dutch institute of WCM named smart moves for smart maintenance, this was identified[11]. The report showed that culture and organizational challenges was the hardest to innovate and change. Today's challenges include the lack of a fact-based culture, conservatism when it comes to new technology, reservations in sharing expertise and the lack of a long-term perspective. With a lack of cooperation between innovation, purchasing and service/maintenance results in lost benefits by not realizing the potential[11].

As a measure to change the culture is to initiate a change in mindset from the top and down, leading by example. The companies that solves these challenges are companies with the right mindset, valuing experimentation, speed, with a distributed leading structure and fostering collaboration[11].

Knowledge:

Another big challenge is knowledge[11]. Smart maintenance is a new and advanced concept that requires new knowledge, a challenge with older maintenance personnel. Knowledge based challenges that appear consist of; lack of knowledge about big data analytics, limited experience with sensor technology, a lack of experience using PdM, insufficient time and experience in systematic evaluation of degradation models, lack of experience in smart maintenance management and lack of knowledge about 3D design[11].

To resolve this challenge a push from human resources is needed, making courses widely available to increase the amount of knowledge within a company.

Poor data quality:

The concept is very new within the railway sector and this offers some challenges. Existing data and data history are not rich enough to predict the failure of specific subcomponents. Since machine learning models perform better with more specific historic data, the limited historic data poses a challenge[12]. In the future this problem will become less and less relevant due to the collection of data, thereby increasing the amount of historic failure data.

Unreliable correlations:

Prediction models is based on revelling correlations between sensor data and previous failures. With a limited data history, it will be challenging to develop an accurate prediction model[12]. To enhance the accuracy of the predictions a close cooperation between senior technical staff and analytic experts is required. This is something that Bane NOR has seen the value of and cherishes the knowledge of both sides.

Insufficient lead time:

One of the most important aspect of conducting predictive maintenance is the lead time between finding and verifying the failure, to the time where it can be repaired. Predictions sometime give insufficient time between failure alert and component failure. Making introducing prediction models into maintenance processes even more challenging[12]. This problem will diminish over time with more accurate sensors and better analytical tools that can detect failures sooner. By detecting failures earlier, one has increased lead time and hereby reducing the problem.

In smart maintenance today there are some technical challenges, but the main challenges remain non-technical in culture/organization and knowledge. Only by focusing on humans and putting them first can smart maintenance succeed.

Now when the benefits and current challenges have been presented, the thesis will present the smart maintenance methods defined in figure 3.

2.2 Smart maintenance strategies

The goal of chapter 2.2 is to present the relevant maintenance strategies from predictive maintenance to self-maintenance. After this chapter the reader should have a good understanding of the smart maintenance strategies.

Subchapters include predictive maintenance, proactive maintenance and self-maintenance. Figure 4 will give an overview of maintenance strategies and how they relate to each other. This figure is adapted from a Figure in NS-EN 13306:2017. Maintenance is defined as:

“*Combination of all technical, administrative and manager actions during life cycle of an item intended to retain in, or restore it to, a state in which it can perform the required function*”[13].

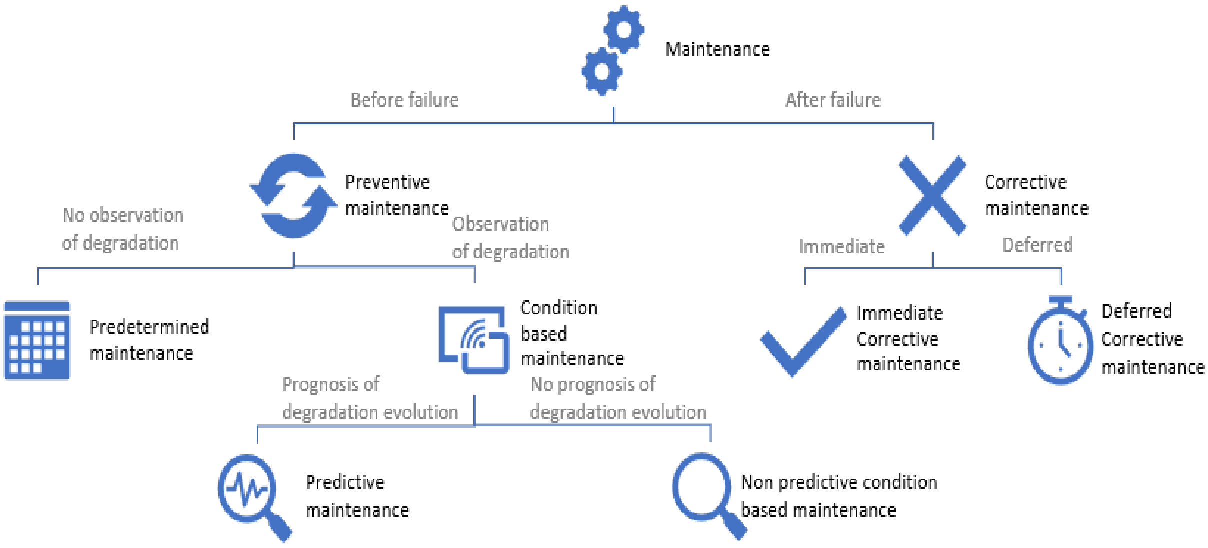


Figure 4: Maintenance methods, with correlations (adapted from[13])

In figure 4 the different maintenance strategies is illustrated within the categories they belong, as well as the actions required to proceed with the given strategy. e.g. predictive maintenance is where the observations of degradation are used together with analysis to make a prognosis of the degradation evolution. This prognosis is acted upon and the maintenance is performed before a failure occurs. In this thesis the candidate will have a focus on predictive maintenance since it is the first step within smart maintenance.

2.2.1 Predictive maintenance

Predictive maintenance is the first maintenance strategy classified as smart maintenance. In figure 5 the steps of smart maintenance are presented.

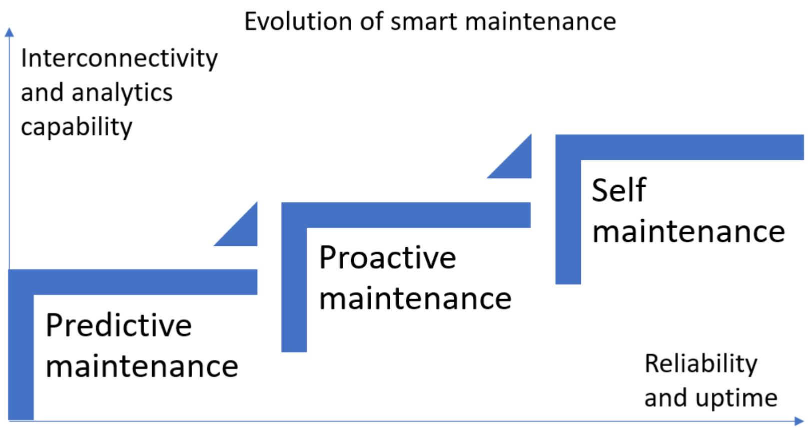


Figure 5: Evolution of smart maintenance

Predictive maintenance (PdM) is a subcategory maintenance strategy under preventive maintenance category. In NS-EN 13306:2017 PdM 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"[13].

Evolution of PdM:

The development of PdM evolves in line with data capture technology from a range of sources with different data formats. The challenge is to handle great amounts of data and have the ability to use this data. By viewing predictive maintenance in the light of smart maintenance, the use of concepts such as machine learning and Big Data are highly relevant[14]. In figure 6, the evolution of predictive maintenance is shown on the basis of Big Data compared to Reliability. The result of increased data availability and better statistical analysis, results in a high performing maintenance strategy[14].

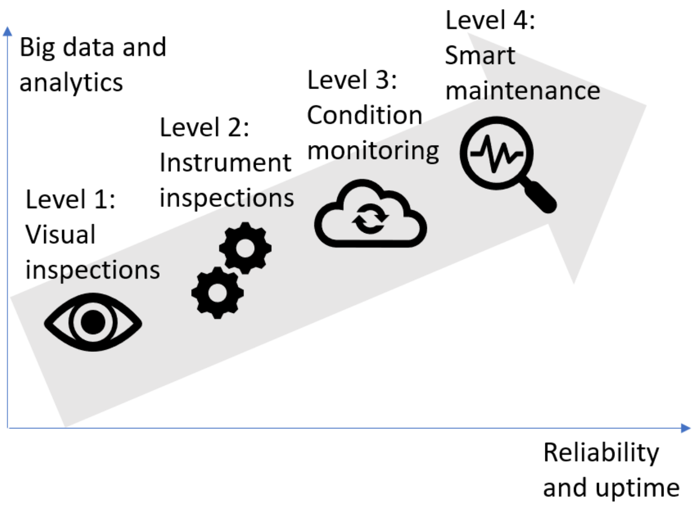


Figure 6: Evolution to smart maintenance (adapted from [14])

Level 1 *Visual inspections:* Periodic physical inspections; decisions are based solely on inspector's expertise[14].

Level 2 *Instrument inspections:* Periodic inspections; conclusions are based on a combination of the inspector's expertise and instrument read-outs[14].

Level 3 *Real-time Condition monitoring:* Continuous real-time monitoring of assets, with alerts given based on pre-established rules and criticality levels[14].

Level 4 *Smart maintenance:* Continuous real-time monitoring of assets, with alerts sett based on predictive techniques, such as regression analysis[14].

P-F Curve

When talking about predictive maintenance it's essential to talk about potential-to-failure curve (p-f curve), the degradation curves that depict the condition over time for an asset. In a p-f curve the functional failure is the point when the asset no longer performs it's intended function. Figure 7 shows an example of an p-f curve.

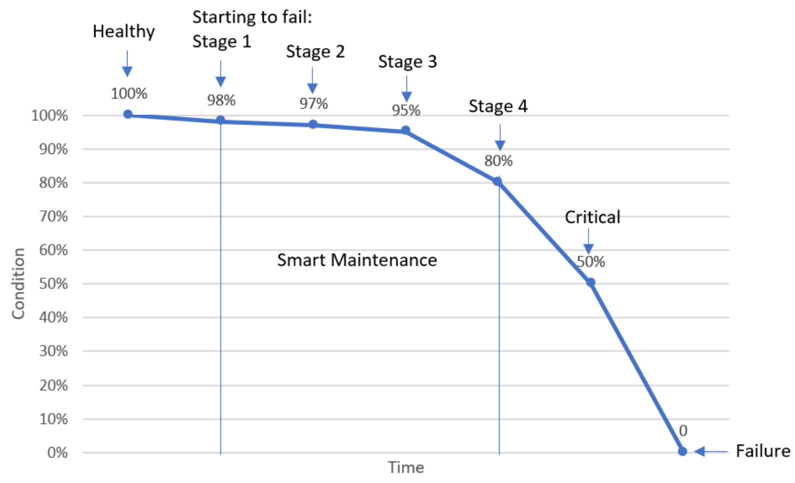


Figure 7: P-f curve

In figure 7 four different stages of wear has been identified. These will be described under[15]:

- **Stage 1:** Microscopic level of damage but the asset is still operational, and the risk of catastrophic failure is low. The recommendation is to continue monitoring at this stage at a normal control interval. Most sensors cannot detect this type of wear.
- **Stage 2:** When reaching this stage, the damage is visible to the naked eye and the damage is detectable to some monitoring techniques. With stage 2 deterioration it's recommended to schedule repairs in the next normal preventative maintenance interval. The risk for catastrophic failure is low/moderate in this stage.
- **Stage 3:** The damage has grown substantially in all dimensions as well as in multiple locations. Depending on mileage and load repairs might be needed within a month. Most types of monitoring techniques can detect this stage of deterioration. The risk for catastrophic failure is high when reaching stage 3.
- **Stage 4:** The damage in stage 4 is now audible and visible to nearby humans. When reaching this stage of deterioration, it's recommended to schedule maintenance immediately after detecting the damage. The risk of catastrophic failure is very high.

These four stages give a representation of how deterioration develops and how it increases the potential for failure. It is important to note that p-f curves are specific to each technical asset.

As well as the stages of deterioration, figure 7 shows a smart maintenance interval. This interval represents the time interval where smart maintenance can be utilized. PdM, as the first step in smart maintenance, requires a certain lead time between identification and verification of a fault, to the correction of the fault.

In figure 7 the two stages that are detectable and usable with PdM are stage 2 and stage 3. Both stages are detectable by sensors and gives a sufficient amount of lead time. If deterioration is in stage 1 or stage 4, PdM is not recommended. In stage 1 most sensors cannot detect the fault, resulting in unreliable predictions. In stage 4 the fault is easily identifiable, but the lead time will be to low to use PdM effectively.

Now that the theoretical basis for PdM has been presented, the application of PdM will be presented.

2.2.1.1 Predictive maintenance today

The aim of this chapter is to describe how PdM is being implemented within the German industry today. This will give insight into how the development of PdM has been and what the lies in store for PdM in the future.

In a report produced by Roland Berger, German companies was asked how they were tackling PdM and what their future goals for PdM was [16]. This report showed that big parts of the engineering industry in Germany was tackling PdM and wanted to continue with the development.

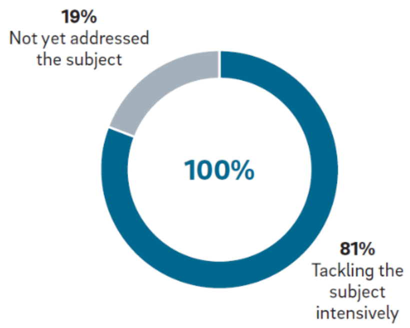


Figure 8: Getting to grips with PdM [16]

Figure 8 shows that 81% of engineering within German industry is focused on the development of predictive maintenance. But, for the future development of PdM, only 40% of the companies questioned in the report says that mastering PdM is of great importance for the future of the companies[16]. This shows a that most companies are hoping for improvements but tackling PdM is not central for their survival.

As PdM is developing, what do companies believe PdM can improve? The survey pinpointed that enhanced performance is the main benefit of PdM and cost reduction as a secondary benefit. In figure 9 both the cost reducing measures and performance enhancing measures are illustrated.

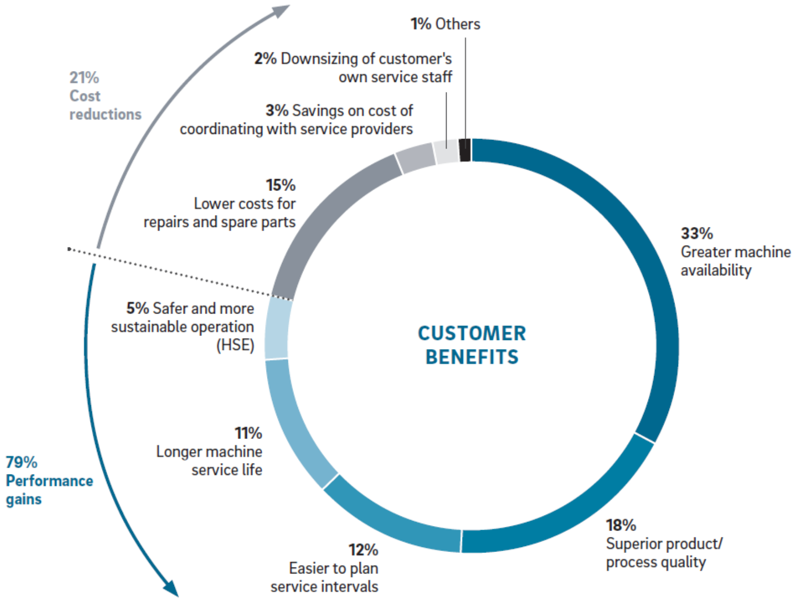


Figure 9: The benefit categories and their importance[16]

As illustrated in figure 9, only 21% of companies surveyed sees cost reductions as the primary benefit of PdM, versus 79% for increased performance. The major contributors to enhanced performance mentioned by the companies are greater machine availability, superior product/ process quality, easier planning and longer machine service life. This shows that the industry believes that machine heavy companies will be the main benefactors in implementation of PdM.

But how has the companies experience been utilizing PdM and its benefits? In the German industry 4.0 index, PdM is mentioned as one of the first applications of industry 4.0. In figure 10 different companies answered the questions; have they had any experience with PdM? and if they have, how was that experience?

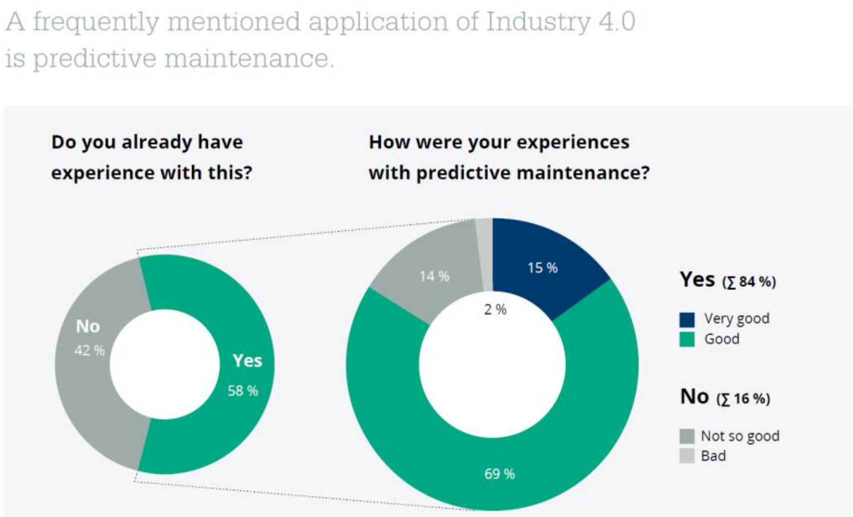


Figure 10: Application of PdM [17]

The question reviled that a majority of companies surveyed, 58%, have had experience with PdM, but even more interesting was the question how their experience with PdM have been. It reviled that 84% have had a positive interaction with PdM. Showing two things, that the industry is implementing PdM and that it works.

By comparing the results from the German industry 4.0 index and the Roland Berger report, one can see that PdM has entered an important role within German industry and companies are benefiting from it. Now that the current state of PdM has been mapped, the future of PdM will be described.

2.2.1.2 Future of predictive maintenance

The future of PdM for companies is uncertain. When questioned where the future market for PdM would be, the industry pointed towards mainly mechanical engineering. Since the German industry is very heavily based on the “traditional” manufacturing processes it’s natural that the industry sees this as the main future for PdM.

After questioning both software and engineering businesses the consensus was that mainly mechanical engineering would be the main benefactor in the future. The believed future breakdown of the market for PdM is presented in figure 11.

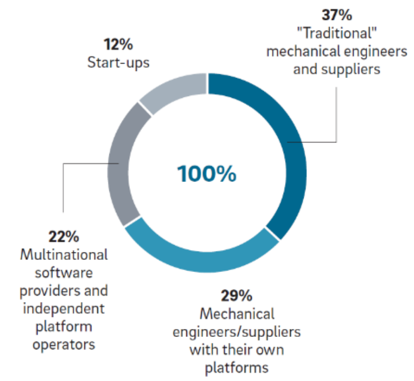


Figure 11 shows that 56% of German industrial companies think that the future benefactors of PdM is within mechanical engineering. Meaning that companies that benefit from performance gains will be the main benefactors in the future.

Figure 11: Future breakdown of PdM [16]

The German industry 4.0 index also supports this statement as shown in figure 12. The main reason companies try PdM is maintenance of their own machinery, with the main goal of increased asset performance.

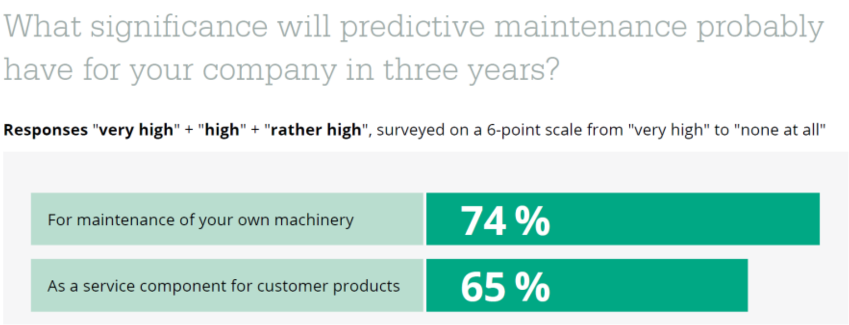
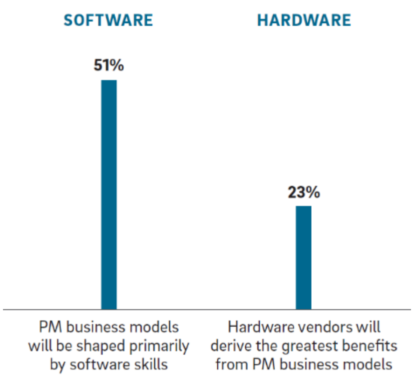


Figure 12: Significance of PdM in the future[17]

This shows that the main benefiting companies today, will be the main benefiting companies in the future, with increased performance as the main benefit.



But where does PdM have the most to gain? According to figure 13, 51% of correspondents say that software is where value has yet to be created. This means that IT businesses with the correct competence can push to develop better software to better the use of PdM.

Figure 13: Future value of predictive maintenance [16]

As seen by the statistics presented in this chapter, PdM is concept with a great deal of interest from the German industry. Both software developers and traditional industry will benefit from the rise of PdM. With this focus on development comes the application of PdM to other sectors of industry e.g. the transportation sector. The concepts used to predict failures within production industry is fully applicable to the railway sector. Correlation between getting data from mechanical components onboard trains and on tracks closely resembles the data gathered from industrial machines.

Now that the first step of smart maintenance has been presented in great detail, the two next steps will be described.

2.2.2 Proactive Maintenance

Proactive Maintenance is defined I as:

"*Proactive maintenance is a preventive maintenance strategy that works to correct the root causes of failure and avoid breakdowns caused by underlying equipment conditions*"[18].

In general terms, proactive maintenance encompasses any tasks used to predict or prevent equipment failure. Proactive maintenance seeks to prevent or to fix the failure from the source after it identifies the root cause. An example of proactive maintenance is the human body and heart diseases. For proactive maintenance, the diseases maintenance would involve cholesterol and blood pressure monitoring along with diet control. As a comparison PdM would use EKG or ultrasonic technology to detect heart disease and maybe installing a device for continues monitoring.[8] By comparing proactive maintenance and PdM , the differences that come to light is that proactive maintenance aims to prevent the failure before it happens and PdM aims to predict when the failure will happen.

To further enhance proactive maintenance's strategy to correct root causes is the cooperation between maintenance, operations and design departments. By feeding failure information and improvement suggestions back to the design departments, improvements on machines can be done and the failure could be prevented proactively[8].

2.2.3 Self-Maintenance

Self-maintenance is an advanced maintenance concept where archiving near zero downtime is the focus. Self-maintenance can be referred to as a system that has the ability of recovering its main functions when failure occurs or is about to occur. The requirements of a self-maintenance system are defined as capabilities of perception of sensory data, fault diagnosis, fault classification, failure prediction, repair planning and repair execution[19].

A self-maintenance system features several different concepts to increase uptime, and are expected to be able to monitor, diagnose and repair themselves with a small amount of human interaction. With a self-trigger within the machines, the machine will self-monitor, self-diagnose and self-trigger service request with detailed and clear maintenance requirements. The maintenance task will still be performed by a maintenance crew, but the no gap integration of machine, maintenance schedule, dispatch system and inventory management system will minimize maintenance costs to the greatest extent and raise customer satisfaction tot the highest level[8]. This will reduce the cost, improve quality and minimize downtime.

Self-maintenance systems are a long way in the future due to its advanced techniques and technology.

Now after smart maintenance have been explained, WCM will be explained.

2.3 World Class maintenance

In chapter 2.3 an introduction to WCM will be given. Subchapter 2.3.1 will present an introduction into WCM and chapter 2.3.2 will describe the steps needed to achieve WCM. In subchapter 2.3.3 relevant key performance indicators (KPI) will be presented as a measure of how efficient the maintenance organization is. The KPIs together with the steps needed to achieve WCM will form the basis for if a company achieves WCM.

2.3.1 World class maintenance introduction

WCM can be defined as:

"World class maintenance is an integrated approach to perform asset maintenance comprehensible for all participants in an industrial organization[20]"

WCM doesn't have a unified definition, but experts refer to WCM as the transition from preventive maintenance to smart maintenance. Others define that WCM is achieved through measuring of KPIs for maintenance[20]. The common denominator for WCM is that to attain WCM level the companies have to show best practises and the ability to produce bottom line results[21].

The fundamentals of WCM can be divided into 5 pillars[22]:

1. **Improving equipment effectiveness:**

Looking for big losses, and the causes for these losses. Then improving the equipment to be more effective. To achieve WCM, the overall equipment efficiency should be over 85 %[20].

2. **Involving operators in daily maintenance**

Involve the operators in maintenance activities such as planning and partnership. This will facilitate interdisciplinary learning between technical and analysis and give maintenance personnel a great understanding of the equipment.

3. **Improving maintenance efficiency and effectiveness**

To improve on maintenance with the use of smart maintenance, optimizing planning and scheduling. Focus on optimizing the whole maintenance department, not only on the maintenance being performed.

4. **Educating and training personnel**

By educating personnel to a higher level, operators will gain increased insight on what maintenance could be done, and this will give a better partnership between operations and maintenance. Also, education supervisors in the use optimization tools will give a company increased resource usage.

5. **Designing and managing equipment for maintenance prevention.**

Use previous knowledge of failures and maintenance problems to improve the equipment. By gathering suggestions from operators and maintenance technicians the equipment can be optimized in the design phase and lowering the life cycle cost.

These 5 WCM pillars will guide a company and set a basis for good business practices and increase the partnership within a company.

In figure 14 the different stages from no maintenance to world class. By using the 5 pillars one can hope to reach the top of the pyramid and be a part of top 10% of companies in maintenance efficiency. Figure 14 is made to illustrate the different stages of WCM.

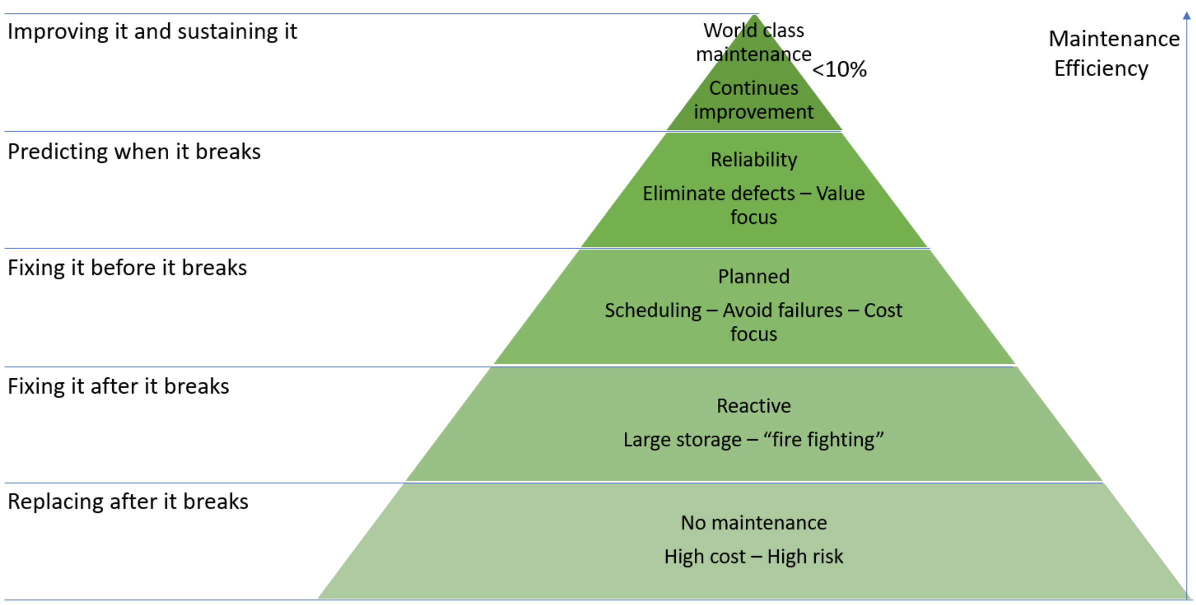


Figure 14: WCM pyramid

To reach the top companies need not only advanced tools, but a healthy company culture and processes to continuously improve.

With a brief introduction to WCM, the future trends will be described. In a report published by SINTEF in 2009 (Meland, Schjølberg, Vatn, Rødseth) three different future trends was identified[21].

1- The Company’s culture is moving towards a learned maintenance organization. By understanding how the employee’s behaviour and motivation affects the maintenance function, and if it’s possible to facilitate a learned maintenance organization.

2- Advanced technology within information technology and condition monitoring will in the future be used to help with decision making. This is the result of better commercial exploitation of technology where the cost of technology will be reduced, and the usability will increase.

3- The development of new processes within the company which hasn’t existed before. Due to better usage of communication technology, access to more maintenance specialists through globalization and demands for machines without design flaws and an alliance between different suppliers and customers will be essential.

2.3.2 Steps towards world class maintenance

Table 2 represents how an organization can move from basic to world class as a maintenance organization. Illustrating the maintenance status of a company by assessing which maintenance concepts and maintenance technics are implemented.

By assessing the maintenance proficient of an organization, one needs to evaluate the different aspects stated in table 2. To give a better understanding of table 2 each of the columns will be explained.

Table 2 will be used to map Bane NOR level of maintenance proficiency later in the thesis.

Table 2: Mapping and management of maintenance status within an organization(adapted from [21])

	Scale	*Focus*	*Organization*	*Digital tools*	*Readiness*	*Competence*	*Methodology*
World Class	Competitiveness	Core maintenance	Optimal maintenance organization	Tools for optimization	Process improvement	Improvement expertise	Optimization of intervals and spare parts
Approaching the top	PLI	Condition based maintenance	Process oriented	Dashboard prediction	Ahead of the problem	Analysis competence	RCM
Well underway	Overall equipment efficiency	5 S Trained by operator	Separation of 1. line maintenance	Condition measuring/ analysis	Pit Stop	Process competence inter disciplinary	FMEA
Put in system	Stop time registration	Preventive program	Separating maintenance from core	EDB based maintenance system	Tools Spare parts Procedures	Machine competence	Trouble shooting
Basic	Maintenance budget	Repair	Traditional maintenance department	Maintenance board, manual workorders	Fire extinguishing	Subject competence	Own experience

Scale:

Scale measures a company's ability to do the correct amount of maintenance hereby focusing on the economic aspect. To reach WCM within scale a company needs to be competitive and strive for improvement by lowering cost to a minimum.

Focus:

Focus is a measure of how a company approaches maintenance. To reach WCM a company needs to focus on core maintenance, using smart maintenance strategies to improve the efficiency of maintenance.

Organization:

Organization is a measure of how a company distributes the need for maintenance. An optimal maintenance organization will be able to plan and perform maintenance in the optimal maintenance interval.

Digital tools:

Digital tools measure how effective a company's usage of digital tools is. To reach a WCM level within digital tools a company needs to use smart maintenance together with digital tools that automatically optimize processes, such as automatic maintenance planning and scheduling.

Readiness:

Readiness is a measure of how a company are prepared for failures and problems. To reach a WCM level within readiness a company not only needs to stay ahead of the problems but also have the ability to improve processes after they have been completed. This could be done by applying improvements identified through smart maintenance to similar maintenance actions in the future.

Competence:

Competence evaluates the level of training the personnel within the company possesses. A WCM level within competence is having personnel with the ability to continuously improve the efficiency. Personnel will not only have the ability analyse data, but also know how to improve processes based on the completed analysis.

To define the level of competence needed, one can refer to NS-EN 15628:2014. In this standard a world class competence would be defined as a A.6 competence for technicians, B.8 for maintenance supervisor/engineer and a C.5 maintenance manager. A A.6 competence for technicians requires the personnel to ensure the quality of the maintenance tasks. Maintenance supervisors/engineer with a B.8 requires personnel to use the engineering knowledge and the organizational tools to improve maintenance tasks and plant efficiency in terms of availability and reliability. A C.5 maintenance manager will have the competence to ensure right management and continues improvement of maintenance[23].

Methodology:

Methodology measures how a company works towards optimizing. On a WCM level a company will work towards always having an optimal maintenance interval together with an optimized spare part inventory.

Table 2 describes the mapping of maintenance for a company, but to verify the actual level there needs to be a standard for comparison. This standard is KPIs set by NS-EN 15341.

2.3.3 Key Performance indicators

In this subchapter a short description of key performance indicators will be given, as well as indicators related to WCM.

Key Performance indicators represent the ability to evaluate and measure the effectiveness of the maintenance being done. In Standard NS-EN 15341:2007 KPIs is used to[24]:

a) Measure the status
b) Compare (internal and external benchmarks)
c) Diagnose (analysis of strength and weaknesses)
d) Identify objectives and define targets to be reached
e) Plan improvement actions
f) Continuously measure changes over time

A central part of achieving WCM will be the implementation of KPIs to measure the continues improvement.

In standard NS-EN 15341:2007 different KPIs are identified and divide into three different categories; Economy (E), Technology (T) and Organization (O). These KPIs are also divide into three different levels where level 1 is organization, level 2 is systems and level 3 is equipment.

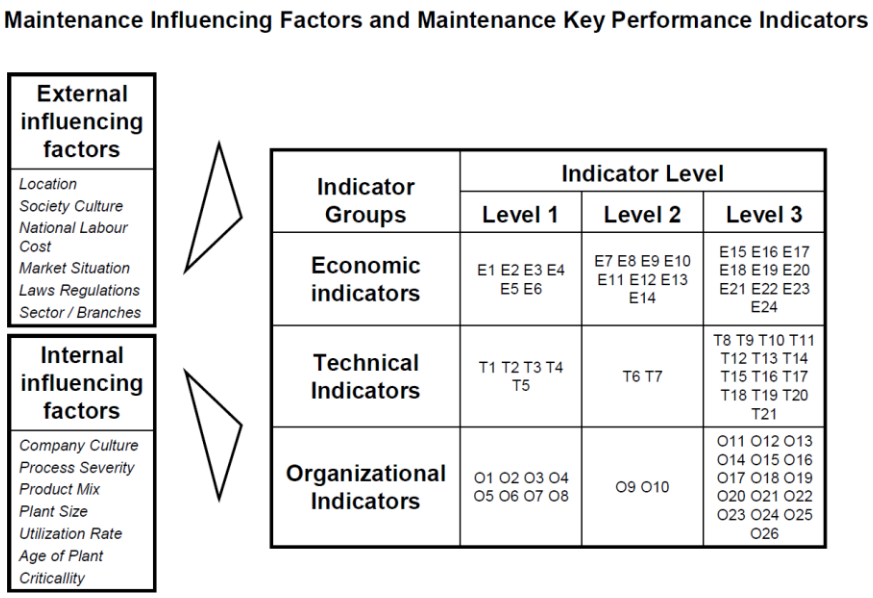


Figure 15: KPIs classification in NS-EN 15341:2007

In figure 15 it is shown that in the choosing of KPIs there are both external and internal influencing factors, where external factors are factors that isn't controlled by the company. Examples of KPIs from NS-EN 15341:2007 is presented in formulas 1:

Equations 1: Key Performance Indicators

(E1) $$\frac{Total\ Mainteance\ Cost}{Assets\ Replacment\ Cost} \quad X100$$

(E16) $$\frac{Preventive\ mainteance\ cost}{Total\ maintenance\ Cost} \quad X100$$

(T1) $$\frac{Total\ Operating\ time}{Total\ Operating\ time + Downtime\ due\ to\ maintenance} \quad X100$$

(T6) $$\frac{Total\ operating\ time}{Total\ operating\ time + Downtime\ related\ to\ failures} \quad X100$$

(O5) $$\frac{Planned\ and\ scheduled\ maintenance\ man-hours}{Total\ maintenance\ personnel\ man-hours} \quad X100$$

(O16) $$\frac{Corrective\ maintenance\ man-hours}{Total\ maintenance\ man-hours} \quad X100$$

2.3.3.1 Future of KPIs

Figure 15 is an old classification for KPIs, from a time where communication technology was not widely used. Because of this, a new organization of the KPIs is being established. This new organization will better relate each KPI to their designated section.

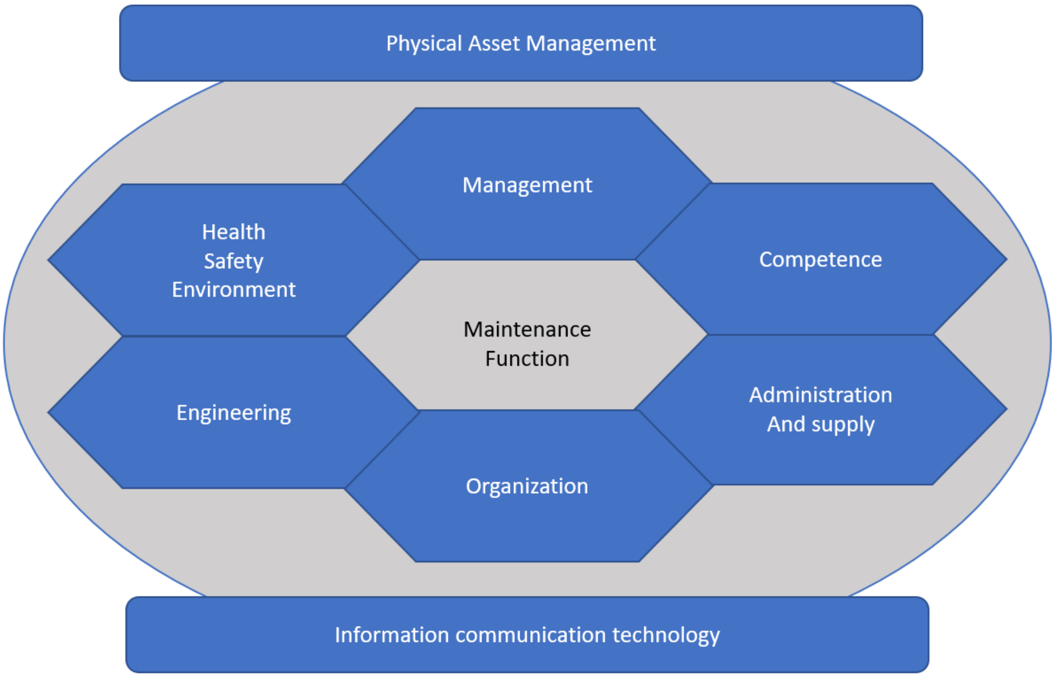


Figure 16: New KPI standard[25]

An example of the new categorization is shown under:

Management:

(O22) $$\frac{Number\ of\ work\ orders\ performed\ as\ scheduled}{Total\ number\ of\ scheduled\ work\ orders}$$ X100

Competence:

(E21) $$\frac{Cost\ of\ training\ for\ maintenance}{Number\ of\ maintenance\ personnel}$$ Unit of value/ person

Administration and supply:

(O26) $$\frac{Number\ of\ sapre\ parts\ supplied\ by\ the\ warehouse\ as\ requested}{Total\ number\ of\ spare\ parts\ required\ by\ mainteance}$$ X100

Organization:

(O8) $$\frac{Man - hours\ used\ for\ continuous\ improvment}{Total\ number\ of\ spare\ parts\ required\ by\ mainteance}$$ X100

Engineering:

(T10) $$\frac{Condition\ based\ maintenance\ time\ causing\ downtime}{Total\ downtime\ related\ to\ maintenance}$$ X100

Health, safety and environment:

(T5) $$\frac{Number\ of\ injuries\ for\ people\ due\ to\ maintenance}{Working\ time}$$

With a recategorization of the NS-EN 15341, it will become easier to gain oversight by having the different categories directly linked to actual indicator. In addition to better categorization, communications technology will have a central part in the gathering of data, making KPIs easier to use.

This overview is not established as a certified standard yet but will be an improvement on the older model.

2.3.4 Key Performance Indicators for WCM

To measure if a company has reached WCM level, a selection of KPIs will be presented. These KPIs aims to provide a basis for measuring improvements towards WCM.

KPIs should be chosen on the basis of the company's focus, i.e. if the main focus is improving economic aspects, technical aspects or organizational aspects. If company wants to achieve WCM they should monitor a selection of KPIs within different categories, not only focus on one aspect. This will increase the performance of the maintenance organization as a whole[24].

To identify the KPIs related to the objective of thesis, an evaluation of KPIs from NS-EN 15341:2007 was done. The KPIs presented in equations 2 will affect how smart maintenance is implemented and measure how effective the maintenance is. Under the seven chosen KPIs are presented:

Equations 2: WCM related KPIs

(E5) $$\frac{Total\ Mainteace\ Cost + unavailability\ cost\ related\ to\ maintenance}{Total\ maintenance\ Cost} \quad X100$$

(E17) $$\frac{Condition\ based\ mainteace\ cost}{Total\ maintenance\ Cost} \quad X100$$

(T1) $$\frac{Total\ Operating\ time}{Total\ Operating\ time + Downtime\ due\ to\ maintenance} \quad X100$$

(T8) $$\frac{Preventive\ maintenance\ time\ causing\ downtime}{Total\ downtime\ related\ to\ maintenace} \quad X100$$

(O5) $$\frac{Planned\ and\ scheduled\ maintenance\ man - hours}{Total\ maintenance\ personnel\ man - hours} \quad X100$$

(O17) $$\frac{Immediate\ Corrective\ maintenance\ man - hours}{Total\ maintenance\ man - hours} \quad X100$$

(O22) $$\frac{Number\ of\ work\ orders\ performed\ as\ scheduled}{Total\ number\ of\ scheduled\ work\ orders} \quad X100$$

The presented KPIs will help provide a guide for improvements within the three aspects of economic, technical and organizational.

An example of the use of indicators can be found in table 3. A study was conducted on what maintenance level the Norwegian oil and gas industry operated on. This table is applicable to the railway industry as a comparison. Table 3 shows the correlation between typical range, recommendations and WCM range.

Table 3: WCM indicators[20]

WCM indicators	Typical range	World class range	Norwegian industry practice	Recommended for Norwegian industry for WCM
PM to CM ratio	3:1 - 5:1	6:1	3:1	5:1
Maintenance Schedule Compliance	35% - 95%	>90%	Not Found	90% - 95%
Equipment Availability	65% - 99%	>97%	89,8 %	> 90%
% of PM or PdM to Total Hours	20% - 50%	50%	30,9%	>40%
Maintenance Planning	35% - 95%	>80%	58,3%	>90%
Reactive maintenance hours out of Total hours	5% - 50%	<10%	23,7%	<5%
Work-order Coverage	60% - 100%	95%	Not found	95% - 100%
Overall Equipment efficiency	20% - 85%	>85%	72,7%	>90%

Chapter 2 has now presented relevant theories related to the problem description for the thesis. This will include theories about smart maintenance strategies and WCM. The theory will form the basis for the evaluation of smart maintenance at Bane NOR and the WCM overview for Bane NOR.

3 Maintenance management

In chapter 3 a description of maintenance management centered around the maintenance management loop will be given. Subchapters relate to the maintenance management loop, such as resources, management of maintenance work process and results. After a description of the maintenance loop is completed, the thesis will present the concepts of computerized maintenance management system and smart maintenance management.

Maintenance management is what brings all the maintenance activities under the same management to administrate and give overview. It's defined in NS-EN 13306:2017 as:

"All activities of the management that determine the maintenance objectives, strategies, and the responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, improvements of methods in the organisation including economical aspects"[13].

To give an overview of what maintenance management is, figure 17 shows the connection between resources, management of maintenance work process and the results. The goal of this model is to produce products at low risk for health, safety and environment (HSE) and with high production performance. Under figure 17, the different parts of the maintenance management loop will be explained in greater detail.

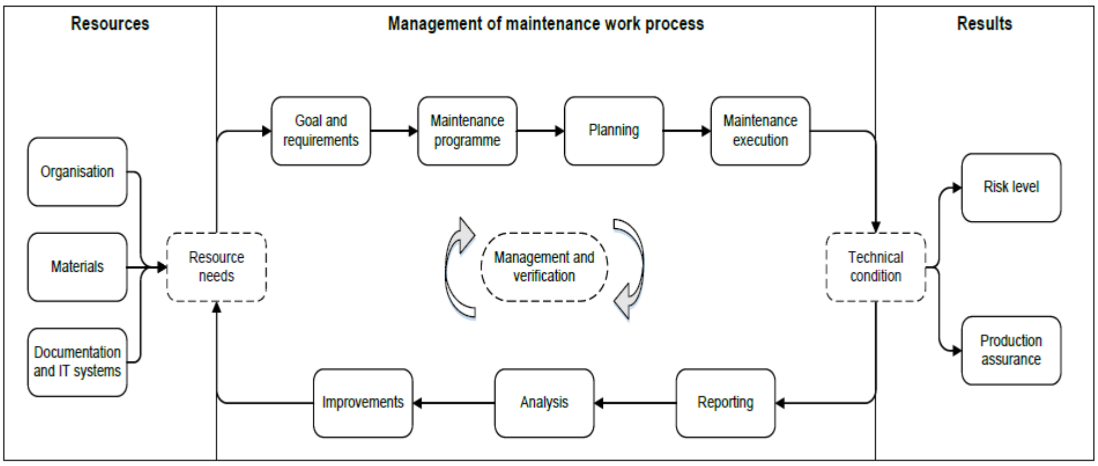


Figure 17: Maintenance management[26]

The overview is divided into 3 sub chapters; Resources, Management of maintenance work process and results and is derived from standard NORSOK Z-008:2017[26].

3.1 Resources

Organisation:

The organisation resource consists of the people, their training, competence and roles/responsibilities. These people will consist of[26]:

- Maintenance personnel with specific experience from different systems and equipment on a senior level.
- Maintenance planners and maintenance supervisors.
- Maintenance engineers.

Materials:

Material resources include consumables, spare parts and tools required to carry out maintenance. This will typically involve that the spare part availability shall be optimized based on demand, consequence of failure, repair time and cost, and linked to maintenance planning activity[26].

Documentation:

Documentation in this context includes all documentation required to carry out maintenance in an efficient way.

- Maintenance data are organized in a database, such as SAP, where technical information, plans and historic performance are readily available for users and decision makers.
- The documentation needs to be controlled, updated and made available to relevant users.

3.2 Management of Maintenance work process

Goals and requirements:

Goals is established to commit the organisation to realisable level of performance. The goals should focus on ambition level for these parameters[26]:

- Risk, production and cost.
- Regulations
- Improvement of overall maintenance process.

Maintenance programme:

Failure modes, failure mechanisms and failure causes that can have a significant effect on safety and production shall be identified and the risk determined in order to establish a maintenance program. This activity includes[26]:

- Performing consequence classification for functions. The consequence class is inherited by the equipment relevant for the function.
- Technical barriers shall be identified, reliability requirements defined for the functions and a testing program to maintain the functionality shall be developed.

Planning:

"Maintenance planning can be defined as the preparatory work to make work orders ready to execute"[27]. The result of this maintenance planning is a maintenance plan, which is defined by NS-EN 13306 as:

"*structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance"[28].*

Planning also consist of budgeting, long term planning, day to day planning and prioritising. Maintenance planning will typically involve:

Maintenance Execution:

Execution includes preparations, work permits, carrying out work and reporting mandatory information on the work order. The maintenance shall be executed in a safe and cost-effective manner and in line with the given regulations and requirements. After the maintenance is completed the condition of the system and equipment shall be reported and a risk assessment for shall be conducted as a basis for operational priorities[26].

Reporting:

Reporting involves the collection and quality assurance of maintenance data and presenting these to relevant departments and management in the form of defined indicators[26].

- To present these maintenance data a set of key performance indicators to monitor and follow up performance

Analysis and Improvements:

This activity involves carrying out analysis of historical maintenance data, and unwanted incidents related to maintenance. Some of these analyses might be trend analysis and root cause failure analysis. Further the information should be evaluated and implement actions suggested based on the conducted analysis[26].

Management and verification:

The key to effective maintenance is a well-organized management team taking responsibilities in implementing the principles planned and verifying the results. The team shall ensure that the work processes are followed. The leaders for the maintenance will be tasked with defining roles and responsibilities and qualification requirements for the actual maintenance. Key performance indicators shall be identified, and leaders will act upon deviations from the set goals, and the leaders shall also plan audits for the organisations, suppliers and contractors[26].

3.3 Results

Risk Level:

The risk level is a result of the operation and maintenance work done to the asset. Risk can be measured as HSE performance, technical barrier element reliability status or related indicators[26].

Production assurance:

Production assurance is a result of the activities implemented to achieve and maintain a performance that is at its optimum in terms of the overall economy and at the same time consists with applicable framework conditions. An indicator of this would be the archived production availability[26].

Cost:

Cost is related to cost of preventive and corrective work, spare parts and consumables, lost production during planning and execution of the maintenance function.

3.4 CMMS

An essential part of modern maintenance management is a Computerized Maintenance Management Systems (CMMS). A CMMS is a software program designed to assist planning, management and administrative functions required for effective maintenance and repairs. Categories include production, planning and reporting work orders. According to a journal by Phillip Tretten and Ramin Karim[29], a CMMS is not only a control tool of maintenance, but also, it is to ensure high quality of outputs by utilizing appropriate maintenance activates over time.

The use of CMMS can create many advantages for a company. One of the greatest benefits is to remove manual paperwork and to monitor system activities leading to improved production. It is noteworthy that the functionality of a CMMS is the ability to collect and store customized information in the required form, as requested by users[30]. As a system the CMMS doesn't assist in maintenance decisions but will provide customized information to managers of operations systems to effectively provide the relevant information and influence the maintenance planning positively. Advantages of implementation of a CMMS system can be[31]:

- Maintaining optimum equipment performance by reducing downtimes and resulting in a longer-lasting machinery.
- Achieve a higher level of planned maintenance activities that allow more efficient use of personal resources
- Influence enablers that better anticipate inventory management and purchase of spare parts for removing the deficiency and minimizing existing stocks.

- Maintain optimum performance of the device by reducing downtimes and resulting in a longer lifetime of the equipment.

3.5 Smart maintenance management

Smart maintenance management is the next step for maintenance management and a next generation CMMS. By combining a CMMS with the benefits of smart maintenance, a company can gain increased control of assets and increase efficiency[32].

To make a next-gen CMMS the digital advances need to be incorporated in a user-friendly interface, here by easing the transition into a digitalized maintenance management concept. A smart maintenance management system is based on minimal human inference by using sensor data to create prediction models, decision support system to prepare a work order and then maintenance personnel performing the maintenance.

By providing a CMMS with condition data it gives the CMMS more data to make a more accurate plan[33]. A smart maintenance system will need this data and a historic failure data base to schedule maintenance as accurately as possible.

Combing the smart maintenance lifecycle in figure 2 and the maintenance management loop in figure 17 there would lower the need for human interaction.

Resources:

A smart maintenance management system would automatically order the needed spare parts, hereby reducing the need for warehouse storage[34]. This would also include human resources, by scheduling maintenance personnel to their optimal maintenance task. i.e. if a maintenance case demands a special technical qualification it is automatically matched to an employee with said qualification[34].

Management of maintenance work process:

A smart maintenance management system would provide assistance with planning, reporting and conducting maintenance. Within planning smart maintenance would use predictive models to classify criticality and factor this into the scheduling of maintenance[34]. Together with a decision support system which automatically plans the maintenance action to take, there would be a drastic reduction in the need for human planning and logistics. After the maintenance personnel has performed the given maintenance task, the reporting would automatically be completed, and the improvements would automatically be implemented for the next maintenance task.

Results:

With the benefits of smart maintenance such as sensor data the results of the maintenance can be digitally documented[34]. By continues condition monitoring the effect of the performed maintenance can easily be documented, by comparing the before and after condition of the asset. This will verify the technical condition of the asset after the maintenance is performed and reducing the risk level and providing production assurance.

3.5.1 Sensor management

Sensor management is a subchapter of smart maintenance management focusing on optimizing sensor data. Sensor management can be defined as:

"*Sensor management aims to optimize a configuration of sensors, with the goal of improving operational availability for a given system[35]"*

In figure 18 a concept for sensor management is presented, developed by Jon martin Fordal, Harald Rødseth and Per Schjølberg.

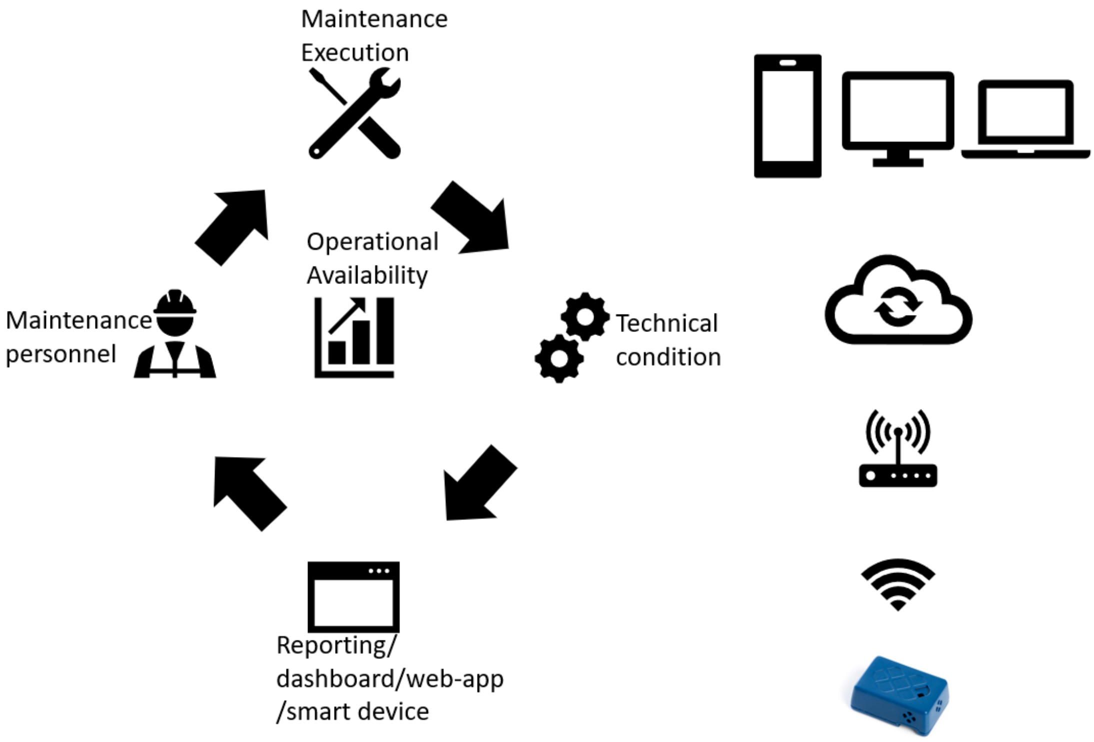


Figure 18: Sensor management (adapted from[35])

The concept focuses on increased operational availability by evaluating data gathered from wireless sensors. The article proposed a process where condition data, historical data and trends was stored on a cloud and directly linked to the maintenance personnel's smart devices. With a system of set alarm functions based on control limits, the system would notify maintenance personnel initiating maintenance execution. After the maintenance was performed, new readings from the sensors would be compared to historic data to measure the maintenance effect.

This process focuses on a simpler process than the smart maintenance lifecycle in figure 2, but this type of sensor management is significantly cheaper and easier to implement. The concept will be a great benefit to start with on the road to smart maintenance and smart maintenance management. By giving maintenance personnel experience with modern sensor technology, it will help personnel ease into increasingly digitalized maintenance.

4 Industry 4.0

This chapter aims to present the next industrial revolution, industry 4.0. The chapter will also provide insight into which aspects are related to the railway industry and theory about these aspects.

4.1 Evolution of Industry 4.0

Industry 4.0 is a result of the 3 first industrial revolutions; mechanization, mass production and automation. The next step is industry 4.0 and emphasises software and computing becoming an integral part of industry. Industry 4.0 (also termed I40) is a strategic initiative from the German government through the ministry of Education and Research and the ministry for Economic Affairs and Energy. This report defined industry 4.0 as:

> "*It aims to drive digital manufacturing forward by increasing digitisation and the interconnection of products, value chains and business models. It also aims to support research, the networking of industry partners and standardisation"*[36]

In figure 19, the 4 stages of the industrial revolutions are presented.

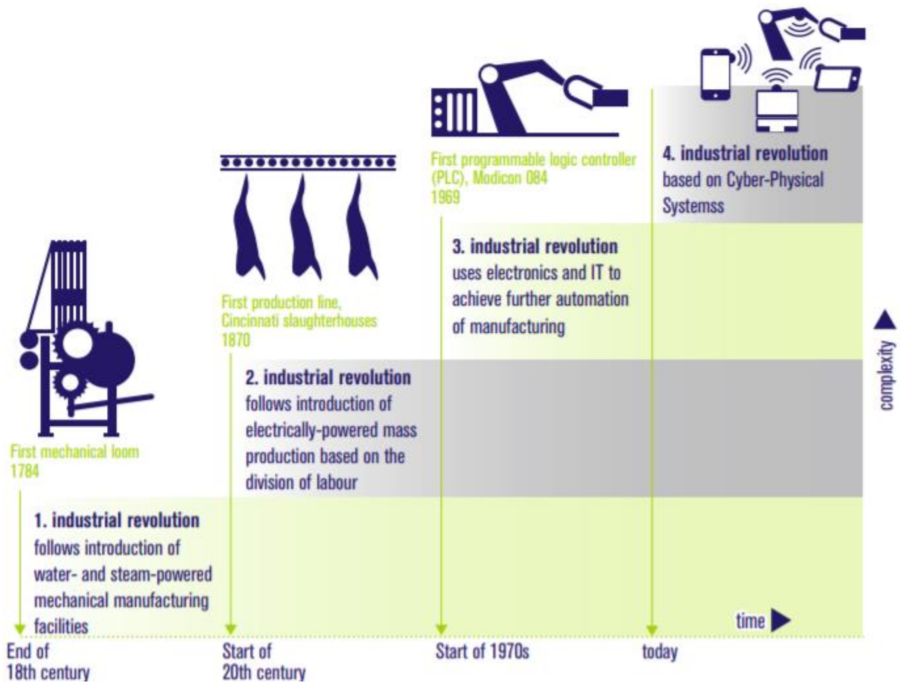


Figure 19: Industrial revolutions[37]

As seen in figure 19 the evolution of industry started with new technology. And today this new technology is the interconnectivity between devices, called Cyber Physical Systems (CPS). Under the term CPS and industry 4.0 there is different concepts, and these will be explained in chapter 4.2.

4.2 Industry 4.0 concepts

In chapter 4.2 the industry 4.0 concepts will be described. As seen in figure 19 4th industrial revolution is defined as Cyber Physical Systems (CPS). This encapsulates the core of industry 4.0, the combination of Internet of things (IoT), Big Data, machine learning and internet of service (IoS). The combination of these new technological concepts formed the new industrial revolution. In the sub chapters these concepts will be explained.

4.2.1 Cyber Physical Systems

CPS is a term used to described systems that can communicate together and is able to form a digital model of itself. CPS can be defined as:

"*Cyber Physical Systems (CPS) are automated systems that enable connection of the operations of the physical reality with computing and communication infrastructures*"[37].

This separates CPS from traditional embedded systems (e.g. smartphones, cars, household appliances) which are designed to be stand alone, since the focus of CPS is the communication between the devices. CPS gives these standalone systems the ability to work together.

As an example, a sensor sends data regarding the state of the tracks. This information is sent to cloud processing and the finished analysis is sent down to the control center. The analysis revealed that the track had sustained damage and the system generates a work order for the given part of the track. Maintenance personnel receive the work order on their digital device and proceeds to correct the damage, hereby allowing train to run without interruptions.

Figure 20 shows an example of how CPS information could be used in railway maintenance.

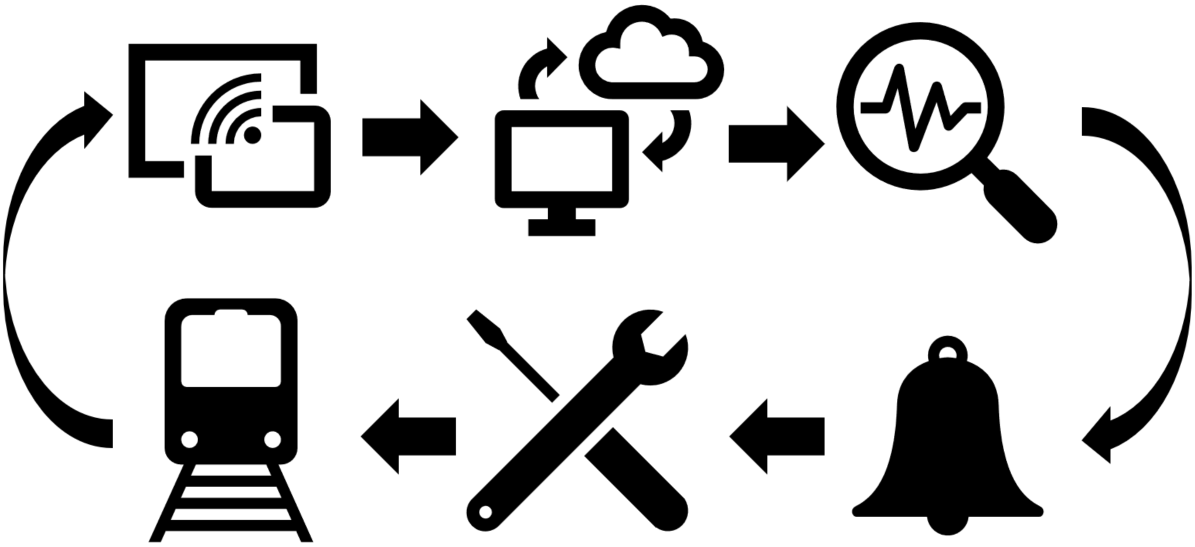


Figure 20: Signalling process for railway maintenance

This is example is given to introduce the use of CPS into railway and how they could work. By linking sensors, cloud processing, control centers and digital devices the total amount of time need to conduct the maintenance is greatly reduced.

CPS is also relatable to maintenance by introducing remote diagnostics, the systems is able to help service personnel by sending information of what tools and spare parts to bring. With advanced CPS features, the system itself can order spare parts and help with the corresponding communication infrastructure.

4.2.2 Internet of Things

Internet of Things (IoT) encapsulates the idea that even the smallest object shall have circuits that allow the sending and receiving of messages over the internet. The evolution of the internet opened the possibility for an infinite number of devices connected to the internet with the ability to communicate. The embedding of more and smaller unites in components of production systems gives access to new types of data. This data is not only associated with production or operations but also information about the environment [38].

With the ever expansion of smart devices, the possibilities are endless. Industry 4.0 is a data driven industry concept, and how is the data collected? Through IoT. With assets imbedded with sensors the data capture will be increased by having the ability to monitor data in real time [39].

Having an IoT framework with real-time data analysis increases the accuracy of failure data and condition data. Having a machine be able to document its own condition and in the same time documents failure data, makes the implementation of PdM easier. With a bigger and denser data collection from assets, prediction models will be able to compare historic failure data to real-time data faster, resulting in a better model[40].

The railway industry will also benefit from the implementation of IoT[41]:

- Flexibility of maintenance intervals because the condition and risk is understood.
- Enhanced planning, with streamlined supply chain management
- Improved utilization of assets (e.g. more mileage with fewer cars)

As an example, trains would require less time in the depot for maintenance, resulting in more mileage with fewer cars. Faults can be remotely identified, hereby making maintenance faster and more efficient. By remotely identifying faults, the supply chain can be enhanced by having only to order the necessary spare parts and lower the storage to a minimum[41]. These benefits are only a small part of the benefits that can be achieved with the implementation of IoT in the railway industry.

In figure 21 this worldwide network of connected objects e.g. (sensors, smart devices, cell phone, actuators) is illustrated. Data is communicated between devices on the train up to the cloud and within internal train system. This data enhances both control and safety for the train, by having more data to describe the situation on and around the train.

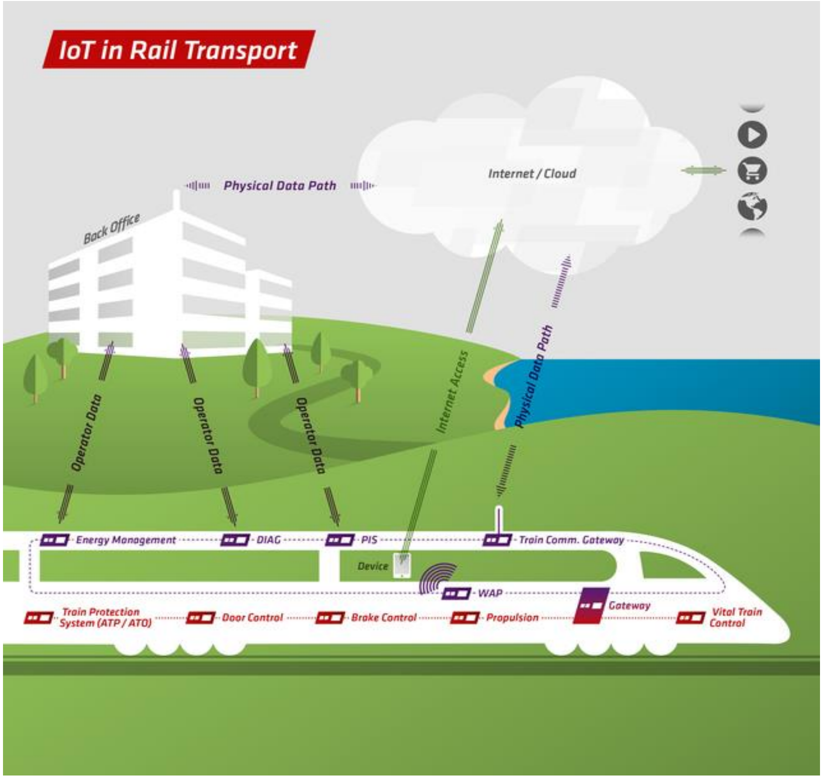


Figure 21: IoT in rail Transport[42]

IoT within railway transport faces additional challenges than stationary production systems. The high speed of a rapidly moving train together with long distances, rough terrain and tunnels create a challenging environment for real-time data transfer. To solve this challenge, the development of increased accessibility of wireless connections such as 4G has eased the communication between connected devices[42].

4.2.3 Internet of Service

Internet of service (IoS) is a concept where a system can go online to use services as useful in its domain. This requires that services are developed with a focus on interoperability, i.e. that the service is structed in a way it can easily be used by other systems[33].

IoS is combination of two other concepts, WEB 2.0 and Service-oriented architecture (SOA). WEB 2.0 is based on 4 aspects, interactivity, social networks, tagging and web services. WEB 2.0 allows the internet to be dynamic communication between a server and the web browser together with software that allows machine access to services online. SOA is a way of designing and building a set of Information Technology (IT) applications where application components and Web Services make their functions available on the same access channel of mutual use. These two concepts build the foundation of interactivity between physical systems and services provided on the internet[43].

4.2.4 Big Data

Big data is the term coined for the massive amount of available data created by IoT. Big data will be the new frontier for collecting and analysing data, by turning it into usable information. The evolution of big data started with past data analytics techniques, a reduction in storage costs, and the increased potential for collecting data due to technological progress[44].

Finding an agreed upon defining for big data is difficult due to the varying definitions in literature, but there is a consensus in the handling of a big volume of data at high speed coming from different sources. Gartner (2012) defines Big data as:

"Big data is high-volume, high velocity and/or high variety information assets that demand cost-effective, innovative forms of information that enable enhanced insight, decision making, and process automation[45]"

The concept of the 3 Vs: Volume, Velocity and Variety[44] and are presented in figure 22.

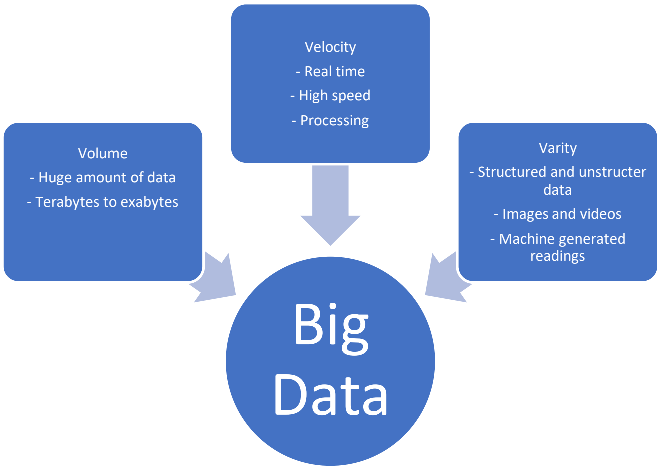


Figure 22: Big data 3 V's (adapted from [46])

- Volume: The size of the datasets and it can range from terabytes to petabytes to exabytes.
- Velocity: The speed of which a system can handle data in real time. By quickly handling the data input and proving real-time information as output.
- Variety: The capability to handle different data structures from various sources.

As a result of this vast amount of available data, new ways to conduct analysis become reality. By transferring data from components into cloud storage/processing, comparing the data to historic data, models can be created revealing information management operators can use in decisions.

In figure 23 a concept proposed by the European union agency for railways is presented. The model is adapted to closely resemble Bane NORs use of big data, where the data sources is data Bane NOR is collecting today[47].

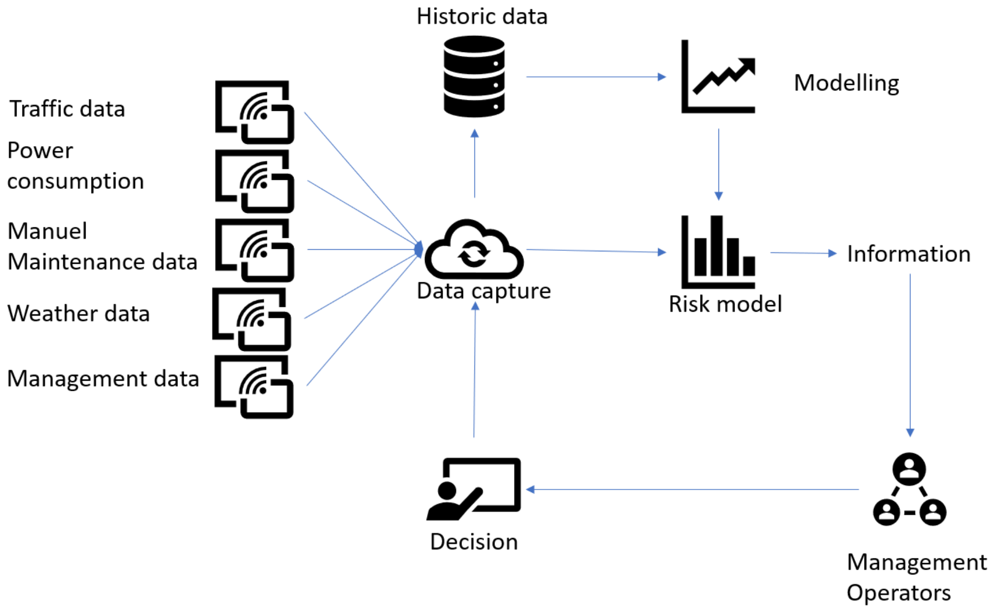


Figure 23: Big data risk mode (adapted from [44])

By using big data companies have the ability to monitor thing that haven't been measurable earlier. Through the use of Big data Bane NOR was able to identify where delay hours originated, something that wasn't possible before the use of Big data[48].

4.2.5 Machine learning

Machine learning is a central part of the evolution of smart maintenance and data processing. Machine learning can be defined as:

“Machine learning is a method of data analysis that automates analytical model building. It is a branch of artificial intelligence based on the idea that’s systems can learn from data, identify patterns and make decisions with minimal human intervention”[49].

Machine learning is what makes it possible to use big data in a reliable way. With such a big amount of information being provided, it opens the possibility for examination and extraction of patterns. These patterns will typically be too dense and complex to be detected manually, but by running machine learning on the process, the patterns can help users solve problems. Machine learning examines large amounts of data searching for patterns, then providing the user with a code which recognizes those patterns in future data. By having this code, a system could make better predictions when it comes to e.g. failures and help create smarter maintenance.

The process of machine learning is a continues enhancing process, in figure 24 an example of the process is described. Gives an overview of how the basic process of machine learning is modelled. The model starts with raw data and the more data available, the better the output will become[50].

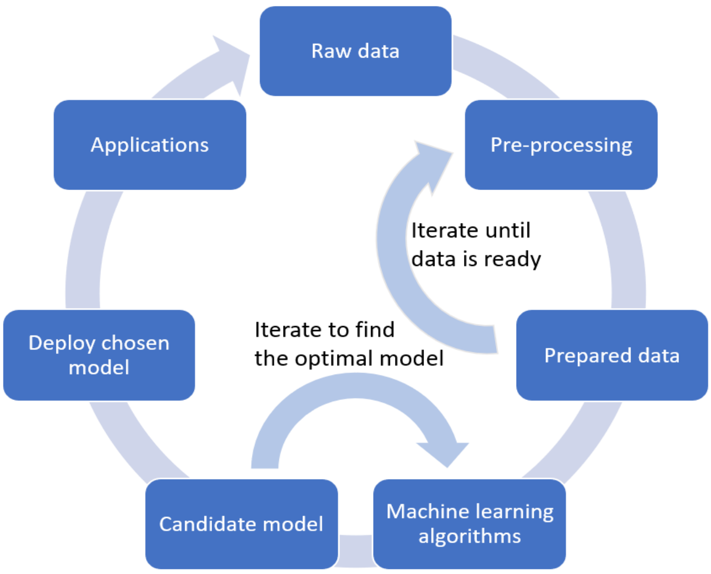


Figure 24: Machine learning process from raw data to model

This process can be divided into 3 parts: Data, learning and application, and will be explained under[50].

Data capture:

As seen in figure 24 machine learning needs raw data, and to receive this data there are different methods for capturing.

Raw data can be categorised into two main type, condition data and event data. Event data is data that registers failures, conducted preventive maintenance and corrective maintenance. Condition data is data which describes the technical condition of an asset, such as vibration data, temperature, pressure and weather data[21]. Condition data can also be categories into 3 subcategories; data that directly describes the condition of an asset such as crack sizes in a structure. Data that indirectly describes the condition of an asset such vibration measurements. Data with describes the factors that effects the degradation speed of an asset, such as the load spectrum or the corrosiveness of the environment[21].

For collection of event data a control tool that automatically logs a shutdown could be used. The control tool automatically logs a shutdown or conducted work and categorises with a time stamp.

For collection of condition data sensors can be used. Sensors can register data such as vibration, temperature and pressure. Condition data can also be collected from a database such as weather data.

This raw data will be fed into the machine learning process and the rest of this process is described under.

Data:

Since the process starts with obtaining raw data, selecting the correct data is critical to get the best result possible. Regardless of what raw data is obtained, it’s usually not in the required condition to be applied directly. This is where the Data Pre-processing Modules comes is used. After filtering data through different prepossessing modules prepared data is created. This is a long and repetitive process and will take the majority of time within the machine learning process[50].

Learning:

After the data is prepared, the machine learning process searches for the best way to solve the problem. Then machine algorithms begin work on the prepared data by applying statistical analysis tools like regression analysis to recognise the patterns within the prepared data. The process is repeated until the best model possible is created[50].

Application:

The final step is the implantation of the model. Applications use the model to recognize patterns and gives useful information to the operators using it. As an example, a model which recognizes the variations in temperature will notify operators if a pattern leading to a fault occurs and actions to prevent failure can be taken[50].

4.3 Industry 4.0 today

This chapter aims to present an overview of the development and implementation of industry 4.0 concepts within industry today. Germany has been the leading pioneer within industry 4.0 and hence the German Industry 4.0 index will give a good description of the use of Industry 4.0 today.

4.3.1 German industry 4.0 index

The German industry 4.0 index is a measure of the German progress with the implementation of industry 4.0. This survey was done to map how companies are tackling industry 4.0 problems and how important they see industry 4.0 for the future. The report shows how companies have experienced industry 4.0.

In one of the first chapter a very important statistic is shown about the general successful of industry 4.0. In figure 25 the results of the survey are shown.

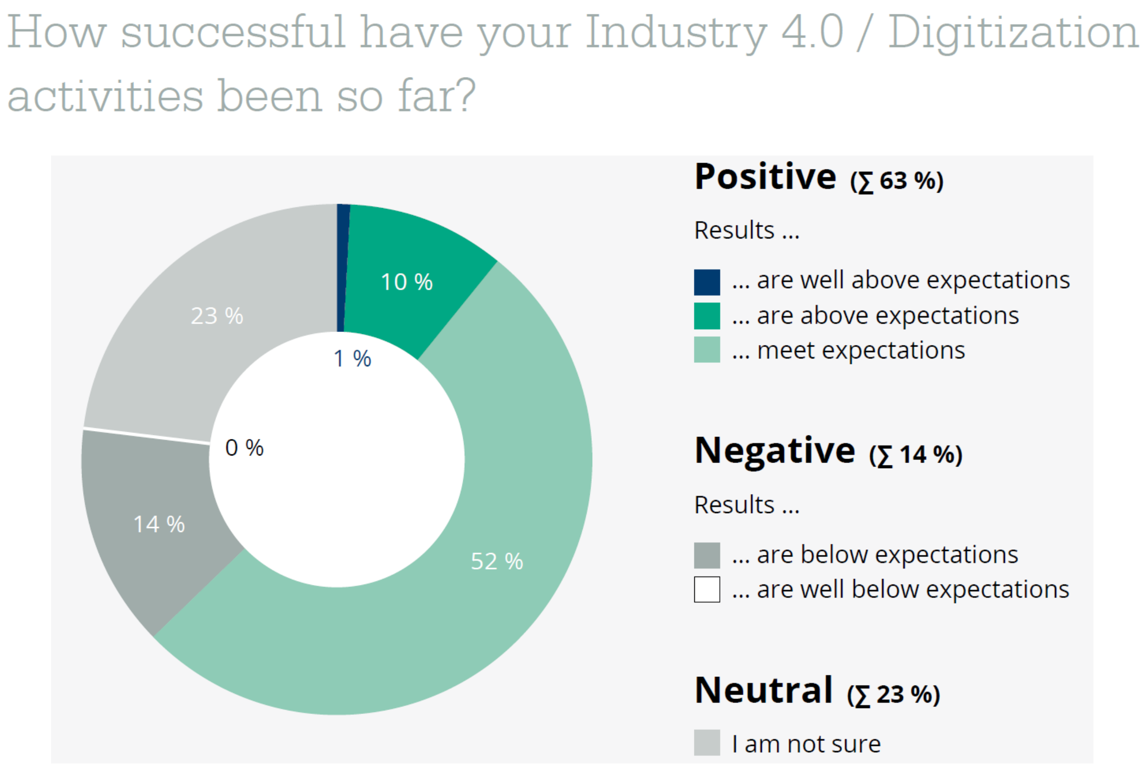


Figure 25: How successful industry 4.0 activities has been[17]

This specific statistic is very important to industry 4.0 since it's a proof of concept. It shows that the implementation of industry 4.0 works and it meets the expectations of the industry.

After achieving it is interesting to focus ahead and see what the next step is, and this might be Society 5.0.

4.4 Society 5.0

In this subchapter an introduction to society 5.0 will be given, the next step after industry 4.0.

Japan has today shifted focus from industry 4.0 to the next step in the evolution, Society 5.0 surpassing industry 4.0.

One definition of society 5.0 is[51]:

"A human-centered society that balances economic advancement with the resolution of social problems by a system that highly integrates cyberspace and physical space"

In figure 26 the evolution from society 1 to 5 is presented. Society 1.0 revolved around small groups of people hunting and gathering for survival. Society 2.0 started with the development of agriculture and allowed humans to settle bigger communities. Society 3.0 started with the industrialization of production allowing mass production. Society 4.0 is based on an interconnected information society connecting every human around globe. Society 5.0 aims to be a society which allows anyone to create value anytime, in security and harmony with nature and free from constraints existing today[52].

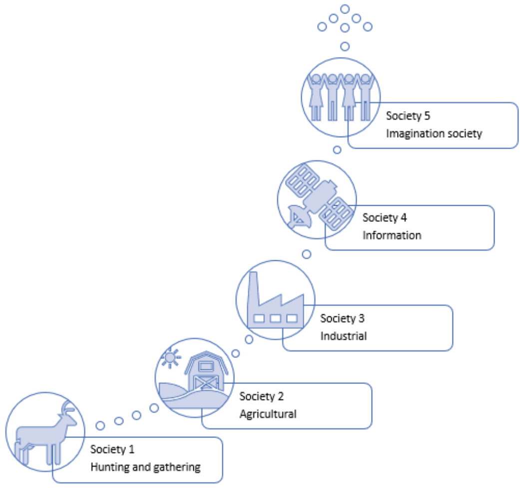


Figure 26: Society 5.0, From hunting to harmony (adapted from [52])

By combining digital transformation concepts such as IoT, AI, robotics and distributed ledger technology with the imagination and creativity of diverse people, an imagination society can be created. It is called imagination society since people can utilize these digital technologies to lead diverse lifestyles and pursue happiness in their own way.

4.4.1 The benefits of Society 5.0

How will this benefit the people and provide solutions for better human life? The realization of society 5.0 would bring with it some positive changes; Economics, Diversity, Decentralization, Resilience and lower the environmental impact[52].

Economics:

Society 5 will liberate people from the focus on efficiency by making a society where problem solving, and value creation is the main focus. By implanting blockchain technology money transfers will become easier and making burdensome actions such as overseas transfer an ease. Blockchain technology and cashless payments will reduce bank fees giving the people better access to banking[53].

Diversity:

By implementing the mentioned digital technologies people will be liberated form the suppression of individuality. This will create a more diverse society by giving anyone the ability to exercise their diverse abilities.

Decentralization:

In society 5.0 people will be liberated from disparity and make people more independent. This will create a society where anyone can get opportunities anytime, anywhere.

Resilience:

People in society 5 will be liberation from anxiety by providing better healthcare i.e. tailored made healthcare based on life-stage data. The liberation will also involve freedom of speech and actions, allowing people to live and pursue challenges in security.

Sustainability and environmental harmony:

Today's society 4.0 relies on a high environmental impact and a mass consumption of resources. In society 5.0 it is important to live in harmony with nature, providing a sustainable and environmentally friendly society. By providing clean, sustainable and reliable energy through decentralized micro grids will lower the environmental impact of people.

In figure 27, society 5.0 is presented in correlation to the Sustainable development goals put forth by the United Nations. It illustrates the imagination society, with the concepts and changes to achieve society 5.0[54].

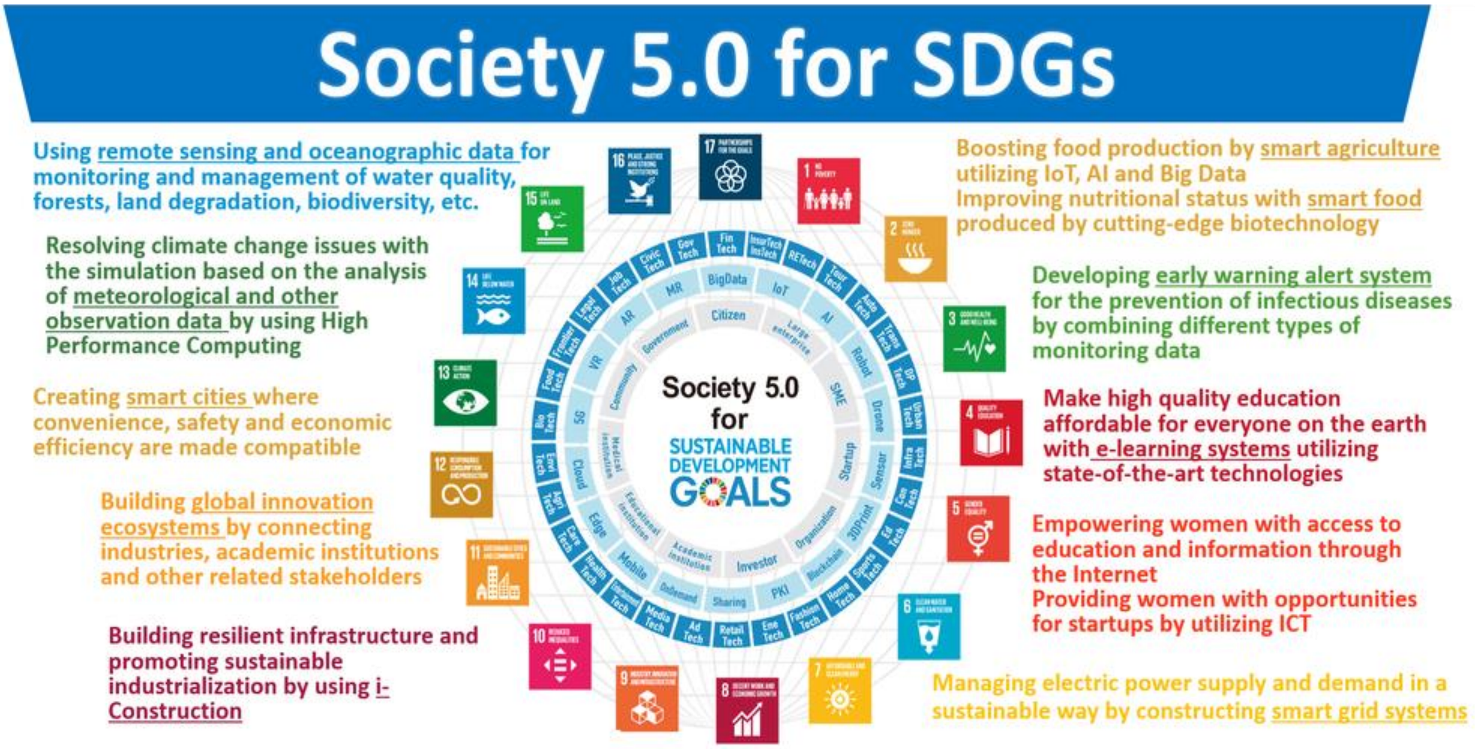


Figure 27: Society 5.0 for sustainable development goals [54]

"*Society 5.0 is not something to come, but something to co-create"[52].*

This is how Keidanren concludes society 5.0. Japan presents a vision of bringing the concept of society 5 to all players within the world. If society 5 is realized it will be a big step towards a sustainable future for the planet.

Society 5.0 is a very forward-thinking concept, based on an ideal world. The main challenge for society 5.0 is making a society that is green and nature friendly. It is difficult to propose a specific solution to this problem, but within the transport sector electrical railway will be a step in the right direction.

The freight industry is a good example of this. Railway uses around 90% less energy than trucks per unit of freight [55]. By transferring freight from trucks to railway will help society move towards an energy efficient and green future.

5 Industry 4.0 in the railway sector

As the production industry develops smart ways to produce, the railway sector develops smarter ways to transport people and equipment. A central part of transporting people and equipment efficiency is having a low amount of delay hours. The goal is to have every train leave on time and arrive on time, and to do this smart maintenance and a high availability is needed. To see why the railway sector could benefit for industry 4.0 chapter 5.1 presents the savings that could be found by implementing industry 4.0 concepts.

5.1 Benefits of implementing Industry 4.0 within railway

In a report produced by McKinesy for over 400 executives from the US, China, Japan and Germany provided findings for PdM within the railway sector. In figure 28 the global maintenance market for railway is presented in a combination between operators, Original Equipment manufacturers (OEM) and third party companies.

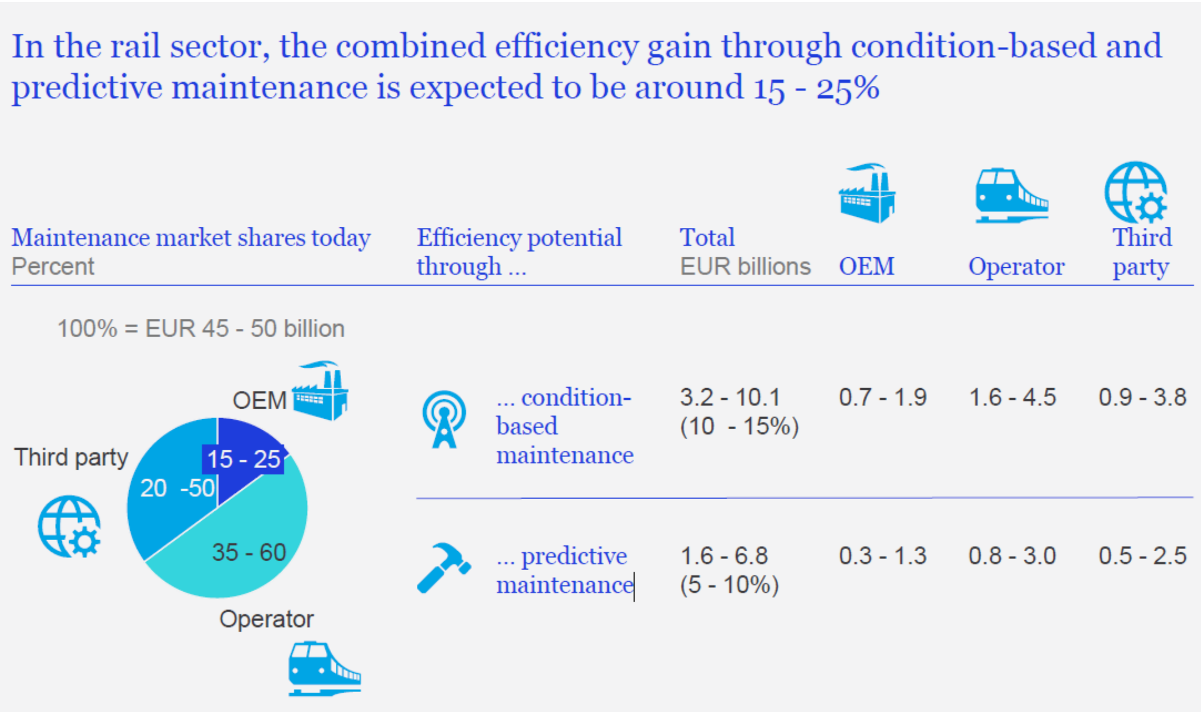


Figure 28: Benefits of PdM within railway[12]

As seen in figure 28 the potential for efficiency increase is around 10-15% for CBM and an additional 5-10% for PdM. The main benefactor from this development would be the train operators, such as Bane NOR.

To reach these savings all parts of the railway industry needs to focus on digitalization and realize the potential.

Realizing the potential:

To explain how one can realize the potential an overview of how maintenance is managed in today's railway sector has to be presented. The Entity in Charge of Maintenance (ECM) in figure 29 is the current method maintenance is done, where ECM 1 is the regulations entity, ECM 2 is the maintenance requirements entity, ECM 3 plans and orders the maintenance and ECM 4 performs the maintenance.

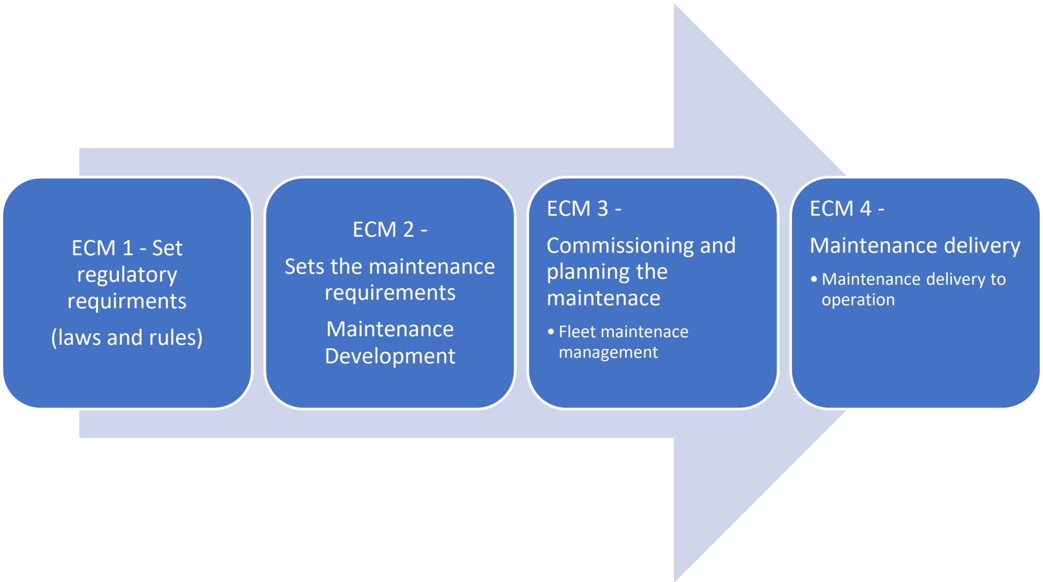


Figure 29: Today's maintenance method (adapted from[12])

Continuing from figure 29, figure 30 presents the what needs to be done by the different entities to realize the potential within smart maintenance. To realize the potential in smart maintenance it is important that the whole industry contributes. The actions descried in figure 30 is recommendations to reach the savings potential presented in figure 28. In figure 30 the different colours are coded to what entity are responsible for the digitalization, based on the same ECMs defined in figure 29.

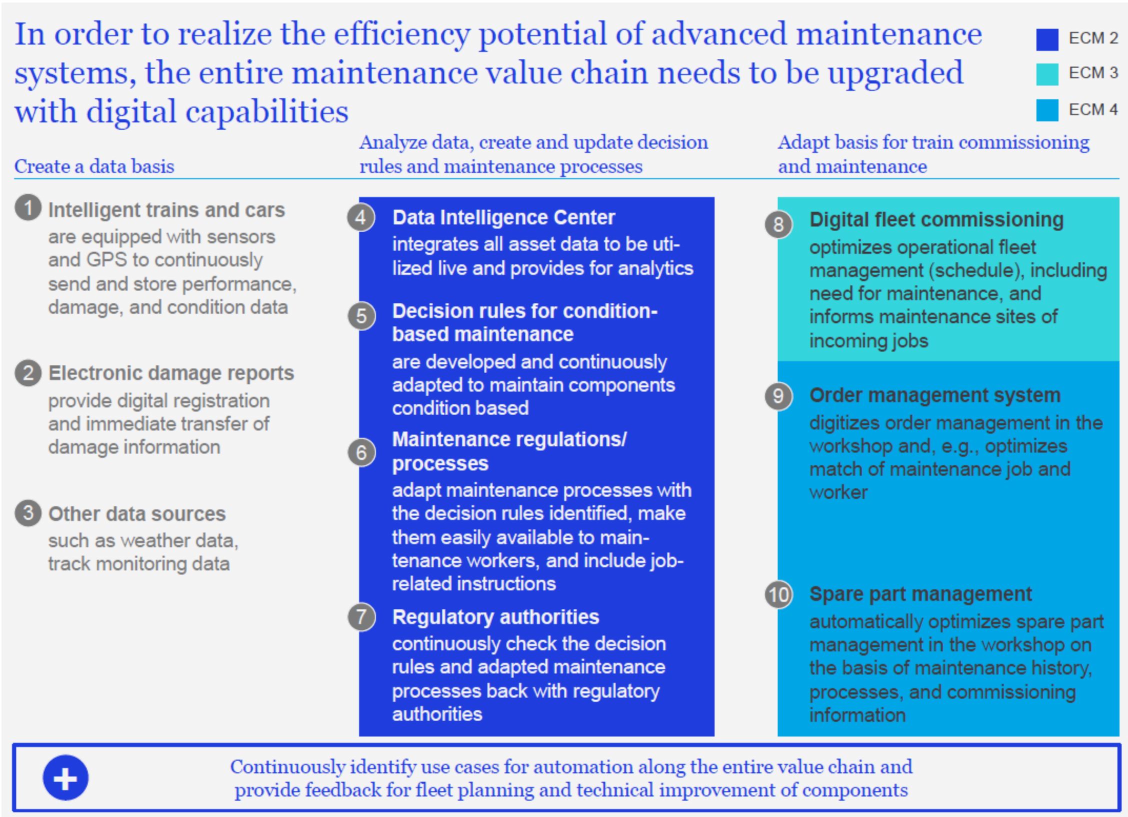


Figure 30: Realizing the potential of advanced maintenance systems in the railway industry[12]

As seen in figure 30 some of the recommendations is already being used in the railway industry today. This is the points 1,2,3 in figure 30, implementing sensor to start using data such as weather and condition to improve. This is a good start in realizing the potential in smart maintenance.

To continue the evolution of smart maintenance a system for analysing and updating maintenance processes must be created. In points 4 and 5 in figure 30 revolves around being able to use the data basis to predict failures. By having a data intelligence center it allows data to be processed and analysed in a central location, making it easier to monitor assets. After more experience in using smart maintenance older thresholds such as sensor thresholds needs to update to increase the control over surveillanced components[12].

With the evolution of prediction analysis maintenance legal and regulations needs to be updated, presented in points 6 and 7 in figure 30. This includes the decision rules implemented in the maintenance process and thresholds for surveyed components. By changing the legal and regulatory processes for maintenance it opens up for extended life of different assets by regulating the replacement interval based on condition and not time which will result in reduced costs.

After laws and regulations have opened up for smart maintenance the next step should be digitalizing the fleet and maintenance management. This requires optimizing the operational maintenance through scheduling and maintenance needs i.e. scheduling maintenance when traffic is low and matching the right worker to the right job.

As a final step within digitalization a smart spare part management system would further increase efficiency by always knowing which parts are need.

The potential of industry 4.0 within railway has now been presented. In the next subchapters different aspects of industry 4.0 such as machine learning, Big data and predicting failures will be presented in a correlation to railway. After this some introduction to different industry 4.0 cases will be presented.

5.2 Machine learning within railway

Machine learning is a central part for the evolution of effective scheduling and maintenance management within railway. Algorithms provided by machine learning can help operators with decision making as well as predicting failures. The concept has yet to be utilized to its fullest potential but high interest in the subject drives advances daily.

5.2.1 Planning and scheduling using machine learning

In the transportation industry effective scheduling and planning is key to optimizing availability. This is often hard to achieve effectively due to the randomness and constrains of the activity and is classified as a hard problem. In figure 31, the different aspects of scheduling and planning is presented. As more and more activities are involved, planning get increasingly difficult.

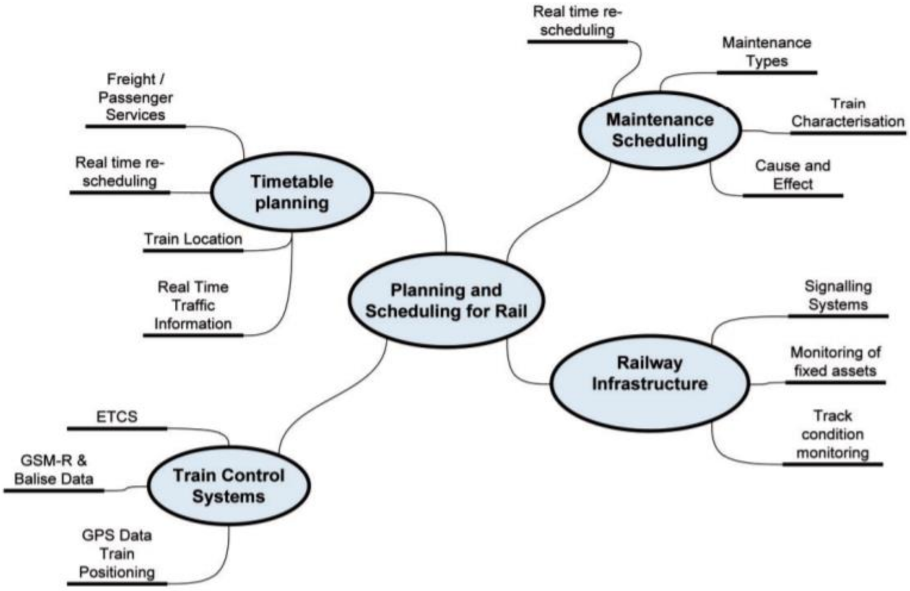


Figure 31: Planning and Scheduling for railway[56]

A concept that has gained increasing interest is an expert based system that helps with decision making when it comes to planning and scheduling. An expert based system is a machine learning system that relies on human expertise being translated into a model which then emulates the decision-making process of said expert. This system will provide solutions for a problem area and then a human expert either accepts the solutions or runs more simulations [56].

5.2.2 Predicting failures with machine learning

The versatility of machine learning opens the possibility to predict failure in e.g. train wheel failures. By predicting railcar defects ahead of time operators can inspect potential failures before they occur. In a report conducted by IBM and the state university of New York [57], machine learning was used to predict failures with high accuracy for train wheels. They used machine learning to analyse data from condition data, historic failure data, multi-detector observations and equipment configurations to find the hidden patterns within the data. By utilizing huge volumes of historical data, failure data, maintenance action data, inspection schedule data, train type data and weather data, combined with analytical approaches a system for alarm prediction and failure prediction was created. The report centered around class 1 railway in the USA which include around 32 000 km of railway. By implementing the predictive alarm and failure analysis system for the class 1 railway, the report calculated savings between 200 000 to 5 million USD per year, showing the potential of machine learning within railway.

5.3 Big Data within railway

Big data in combination with machine learning aims to increase availability and reduce delay. A valuable tool in the hunt for delay hours, a main goal set forth by Bane NOR.

In an interview Sverre Kjenne the CEO for Bane NORs digitalization and technology division talked about the importance of big data to reduce signalling errors [58].

In figure 32 the delay hours for personnel trains in 2016 are presented. As seen the biggest total contributor to delay is safety, signalling and remote-control systems.

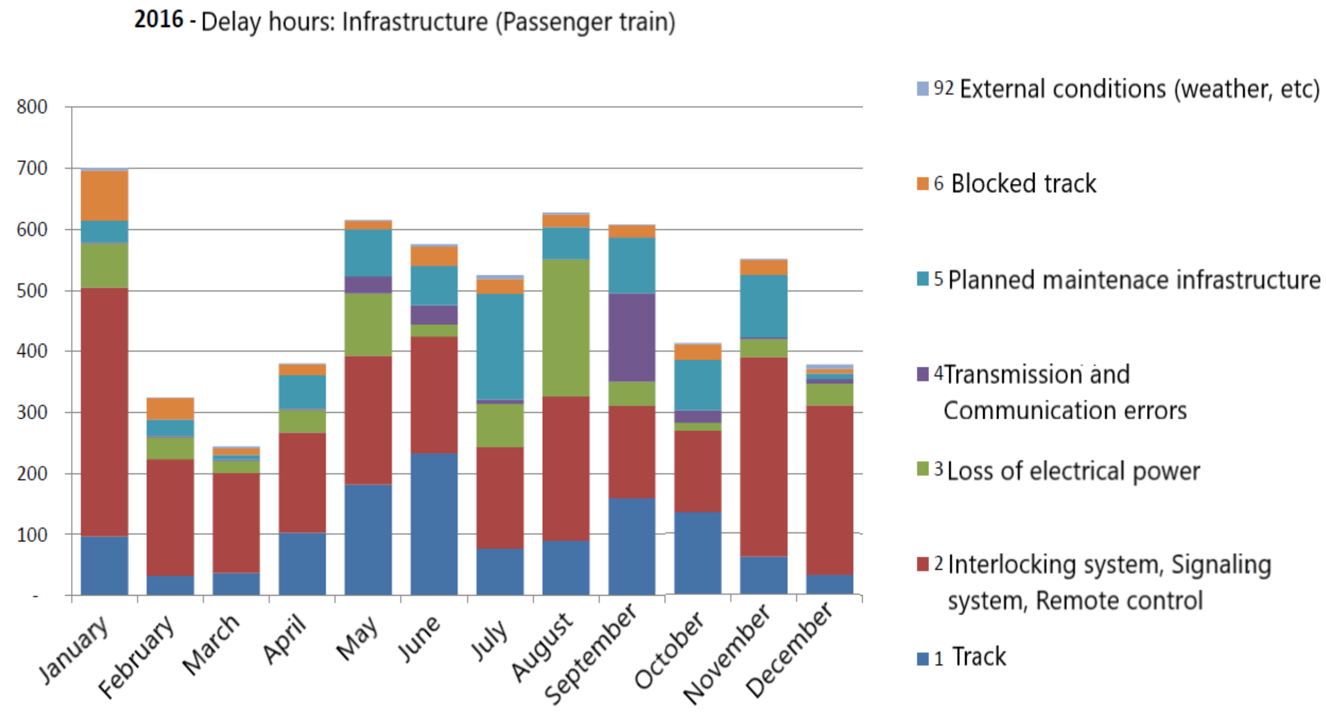


Figure 32: Delay hours 2016 Bane NOR for personnel train(adapted from[48])

By measuring power consumption and time, Bane NOR were able to map when failures may occur for railway switches. Further in the interview Sverre stated that the introduction of big data and predictive analytics reduced the number of delays by 50%

and 600 delay hours for the placed they introduced the system. This is supported by a presentation given on big data by Bane NOR[48].

In figure 32 one can see the effects predictive analytics have had on railway switches. Not only did the analytics find more errors it was able to correct them before they became failures and caused delays. These errors are represented by UKV (green) and AKV (blue) in figure 33.

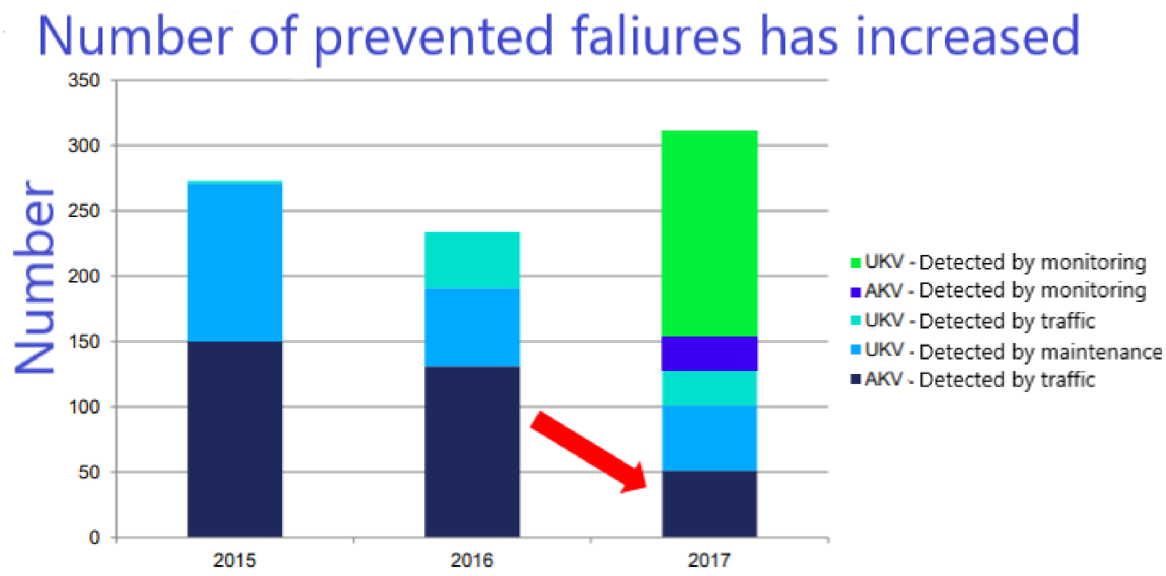


Figure 33: Numbers of failures detected by big data(adapted from[48])

This graph presents the failures prevented around Oslo S and "Askerbanen"[59]. This shows the possibilities for big data within the railway sector. When reducing these failures, one will see less delay hours and the efficiency of transport increases and the company become more trusted as a whole.

5.4 International use of smart maintenance within railway

With major changes to the global maintenance society with the use of communication technology, an introduction of smart maintenance to the railway sector was natural. Japan was early apart of this development.

Japan:

As a part of this modernization japan was the first to introduce trains capable of monitoring track. The smart maintenance initiative was in a research and development project tasked with proposing a new structure for maintenances, and the initiative identified 4 challenges connected to smart maintenance[60].

- Achieving condition-based maintenance
- Introduction of asset management
- Work supported by Artificial intelligence
- Database integration

The solution to these was the monitoring train E235, which utilized a track monitoring system placed on the train. By gathering data such as track irregularity, the train was able to identify deterioration in the tracks. In figure 34 a model of the E235 monitoring train is presented.

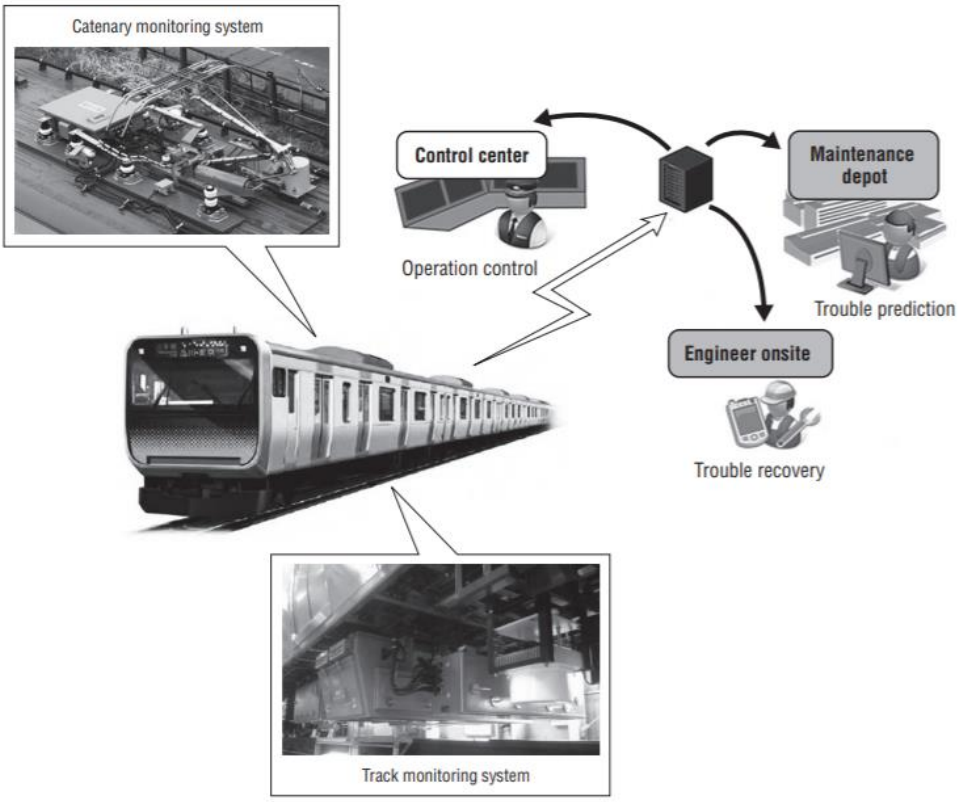


Figure 34: Monitoring train E235[60]

The train was able to identify both irregularities with millimetre precision as well as using machine learning to spot degradation of railway tracks. In figure 35 an example of how image recognition on board the E235 together with machine learning could spot deteriorating railway track.

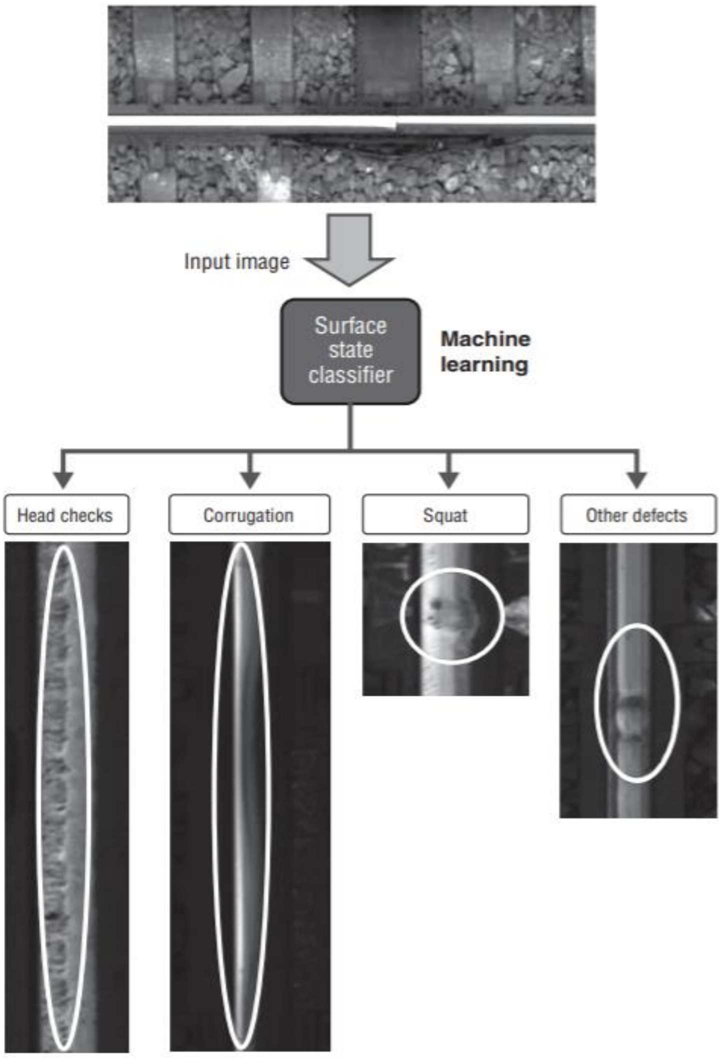


Figure 35: Deteriorating of track[60]

Presented in figure 35 are different examples of deteriorating, which is a combination between the pictures from the E235 and a machine learning program built on engineering experiences. This example of condition monitoring was able to discover rail defects with up to 98% success rate[60].

As a result of this monitoring the Japanese railway gain additional benefits e.g. monitoring the efficiency of the maintenance being performed on the tracks. Figure 36 shows the different efficiency of how maintenance is performed on the tracks. By comparing machine tamping and manual tamping, the monitoring done by E235 revealed that machine tamping was a lot more reliable when it came to deterioration. Providing information useful in future predictions.

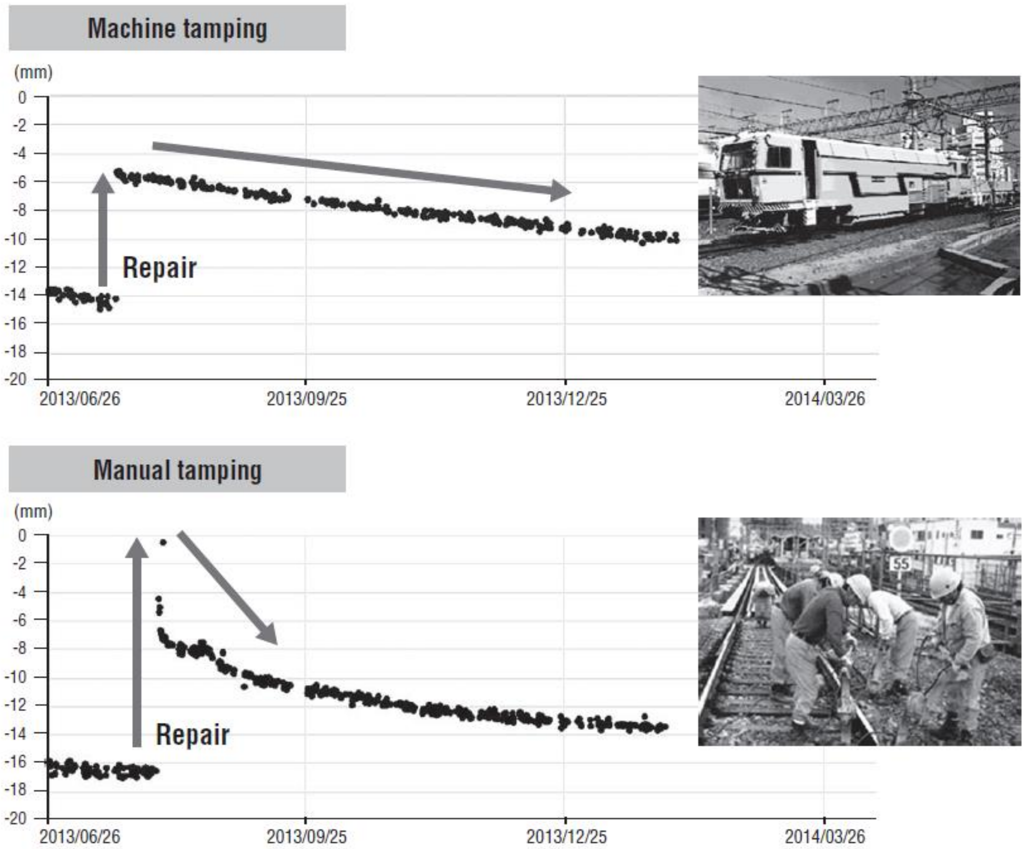


Figure 36: Difference in maintenance method[60]

Such a system is a machine learning system called an expert system. This system of machine learning shows correlations to the system proposed for the USA class 1 railway system, by using engineering experience to create a machine learning algorithm.

England:

In a study conducted by the university of Birmingham did a case study on condition monitoring and PdM for axelboxes on trains.

In this study there was 4 various sensing technologies:

1. Acoustic emissions / ultrasound
2. Vibration / acceleration
3. Microphone / sound measurement
4. Thermal

The first three technologies are used to detect early stage of damage. When bearing defects become severe, they generate heat that can be detected by thermal sensors. In table 4 the relevant sensing technologies are presented with advantages and disadvantages.

Table 4: Pros and cons of bearing condition monitoring technologies [61]

	Sensor technology		
	Vibration	**Thermal**	**Acoustic Emission**
Advantages:	1. Reliable and standardized method 2. Reacts immediately to change 3. Ability to perform fault diagnostics	1. Can detect abnormality in an interest area 2. Standardized method	1. Performs fault detection and diagnostics well 2. Sensitive to microscopic changes 3. High signal to noise ration
Disadvantages:	1. Expensive 2. Requires physical contact	1. Too late for PdM when rise in temperature occurs 2. Does not perform fault diagnostics	1. Expensive 2. Sampling frequency must be high 3. Requires physical contact

In this comparison acoustic (air-borne) sensor technology is not presented due to the fact that vibration sensors can detect faults sooner than acoustic sensors[62].

Figure 37 shows the given p-f curve related to the degradation of the axelboxes.

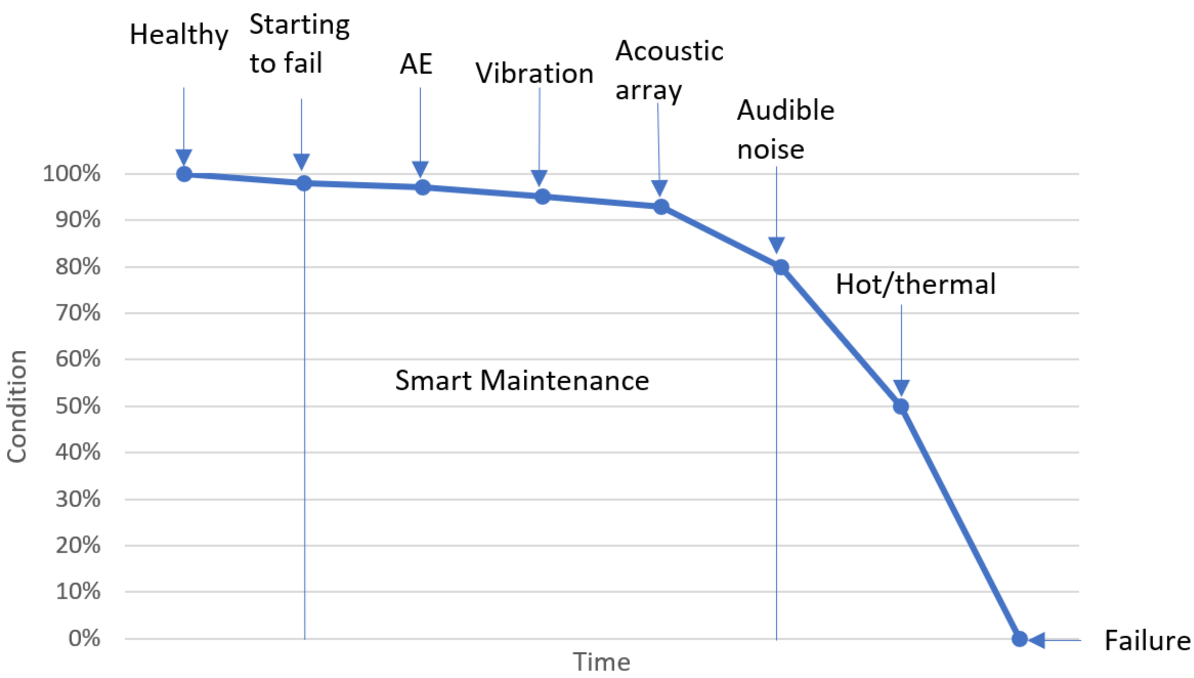


Figure 37: P-f curve for axelboxes[63]

In figure 37 shows acoustic emission (AE), vibration and acoustic array (air-borne) as the sensors that can detect failures within the prediction and prevention stage. Thermal sensors will not be a usable sensors technology due to the fact that the temperature will arise when the risk of failure is very high.

By comparing figure 37 to table 4 with the advantages and the disadvantages some conclusions can be drawn. AE and vibration sensors would be the best sensors types to use for condition monitoring of axelboxes. This is supported by a Ph.D. thesis done on the remote condition monitoring of axelboxes and wheels published by the university of Birmingham[64]. The test conducted in this Ph.D. shows that both AE and vibration data can be used to monitor the condition of the axelboxes as well as the wheels.

This technology developed for monitoring of axelboxes is applicable to the Norwegian railway, but this will mainly benefit “Norske Tog AS” and Mantena AS since they are the responsible organization for controlling and maintaining trains. If this technology is installed it would result in trains spending less time in the depot for repairs, hereby optimizing the use of the trains giving more mileage for less trains. This would in turn benefit Bane NOR since less train would result in less ware on tracks and railway switches. The implementation would lower the need for maintenance for both Mantena AS and Bane NOR, but the main benefactor would be Mantena AS.

6 Bane NOR

In this chapter a presentation of Bane NOR will be given together with a description of maintenance processes within the company that are central to the thesis.

6.1 Bane NOR

Bane NOR is a state-owned company responsible for the national railway infrastructure. With 4500 employees they are responsible for planning, development, administration, operation, maintenance, traffic management and administration for the national railway network. The main mission for Bane NOR is to ensure accessible railway infrastructure and efficient and user-friendly services, including the development of hubs and goods terminals[4].

The development of Bane NOR started with the railway reform and was founded the February 2016 as the successor to the Norwegian National Rail administration. The ambition of the reform is predictability and clearer distribution of responsibilities in the railway sector, as well as adapting for the competitive tending of passenger services[65]. In figure 38 all the different branches of the railway sector are presented along with their respective responsibilities.

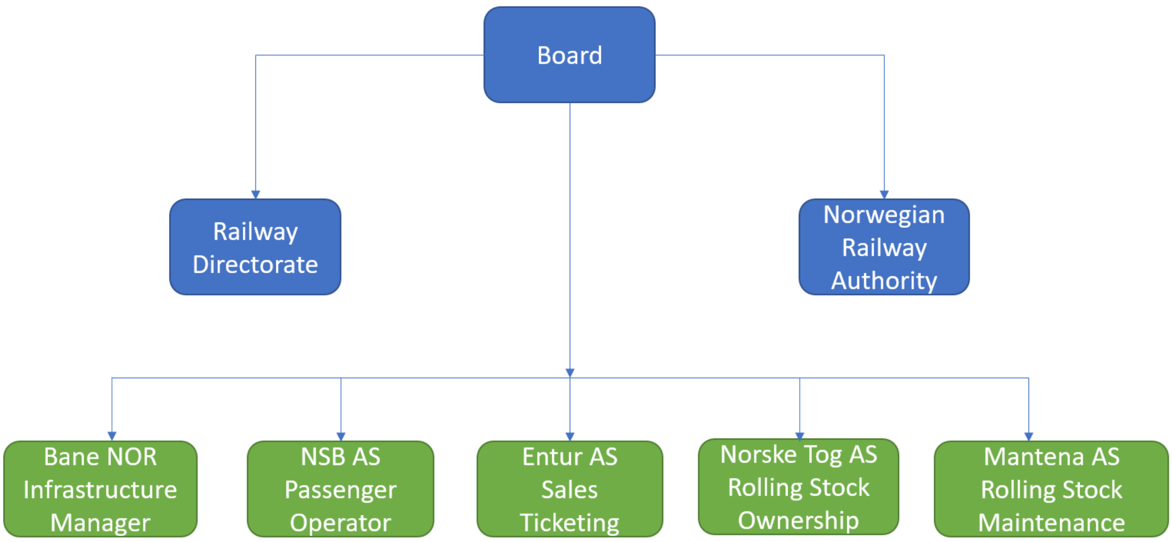


Figure 38: Railway organization map[65]

6.1.1 Operation and maintenance

As the railway reform was put in place so did serval renewal and maintenance project start. In 2017 Bane NOR spent 2.4 billion NOK on renewal projects and 6.3 billion NOK on maintenance. The reason for high spending on maintenance and renewal projects is to ensure the safety of the railway infrastructure. In a transportation sector where 74 million train journeys are completed every year, safety is of the utmost importance. With the introduction of new digital solutions for monitoring faults and defects can be detected early and remedied before causing any service stoppage, and hereby increasing the punctuality of the trains[65].

As a part of the spending on maintenance and operations the introduction of the European Rail Traffic Management system (ERTMS). The ERTMS is a signalling system and will have a price tag of 460 million NOK and will be completed around 2030. The system will provide passengers with even safer, more reliable railway and greater capacity. By updating the signalling system for track shifters, cables and road safety systems at train level crossings the possibilities for accidents due to signalling errors will decrease. ERTMS will also modernize the traffic management system by assisting the operators by having an automated database which can make automatic decisions and will decrease the probability of human errors[66].

6.1.2 Future of the Norwegian railway

The railways of the future will be characterised by modern computer technology. The introduction of a series of computerised systems will change the ways in which bane NOR operates, maintains and develops its railway lines. This major digital initiative will ensure that the railway infrastructure is always accessible and in good condition. For passengers and industry this will mean more trains with increased punctuality.

Bane NOR aims to continuously monitor the condition of its railways by suing sensors and monitoring the power consumption of track components. This is called smart maintenance and it allows Bane NOR to rectify technical faults before they affect the rail services and such a system has already been put in place between Drammen and

Oslo. The aim of the smart maintenance initiative is to implement it for all parts of the rail network in Norway[65].

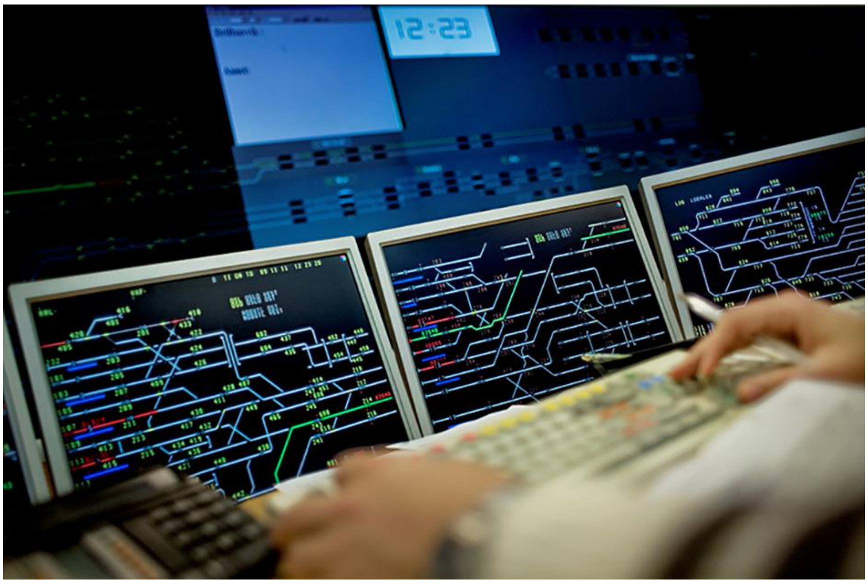


Figure 39:Digital control centre at Bane NOR[67]

6.2 Maintenance practises in Bane NOR today

Bane NOR is today one of the highest performing companies in Norway within maintenance, but to continue developing a digitalization project with a budget of 25 billion NOK has been initiated[46] . This is to help drive the digitalization of the Norwegian railway forward.

In a presentation held by Bane NOR in 2017, the future development of maintenance within Bane NOR was presented and the focus was smart maintenance. This is summarized in figure 40, which shows how Bane NOR wants to enhance maintenance.

From today's maintenance to modern maintenance.

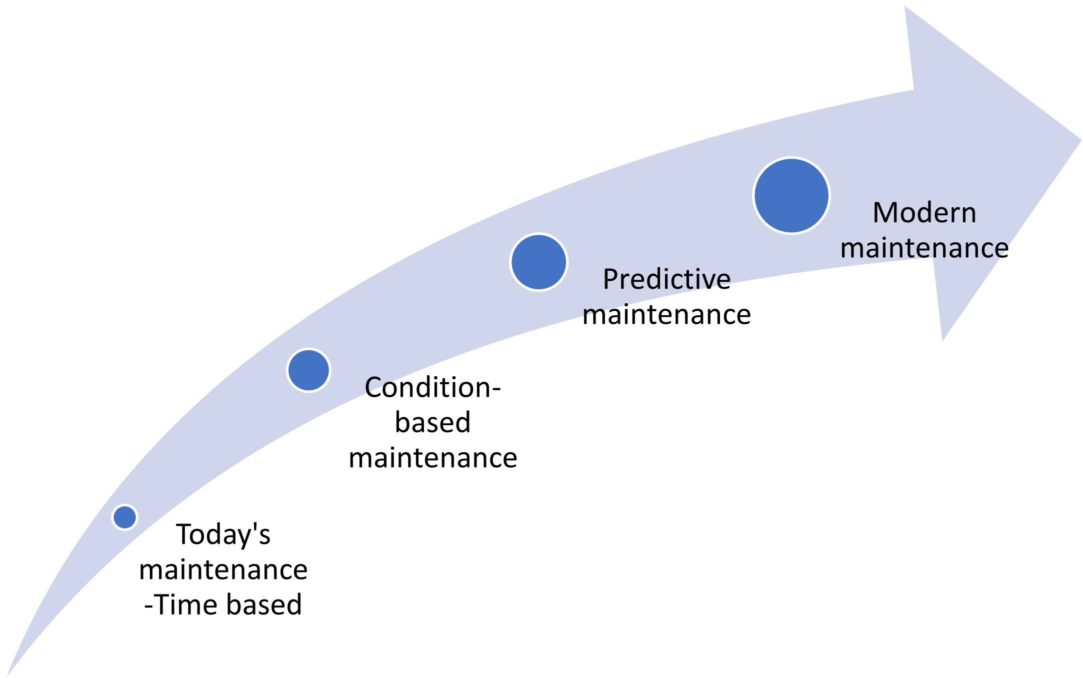


Figure 40: Evolution from today's maintenance to modern maintenance (adapted from [48])

Today the main maintenance method used is preventive time-based maintenance, called predetermined maintenance. Continuing from this an introduction to the history, operational and future of smart maintenance within Bane NOR will be given.

6.3 Smart maintenance within Bane NOR

In this chapter an introduction to Bane NORs smart maintenance will be given. This includes the start of smart maintenance within Bane NORs as well where they are today.

6.3.1 History of smart maintenance within Bane NOR

In this subchapter the goal and early history of smart maintenance in Bane NOR. The digitalization of maintenance started with a goal of lowering delay hours by increasing uptime and reliability[47]. With a vison of automated maintenance and the possibility of using modern maintenance methods to gain increased overview of assets within the Norwegian railway.

Since Bane NOR is a stated owned company there was a financial limitation to development of smart maintenance. Hence the Smart maintenance initiative needed to identify the biggest source of failures and the asset creating the most delay hours. After studies was conducted by Bane NOR, railway switches were identified as the main contributor to delay hours.

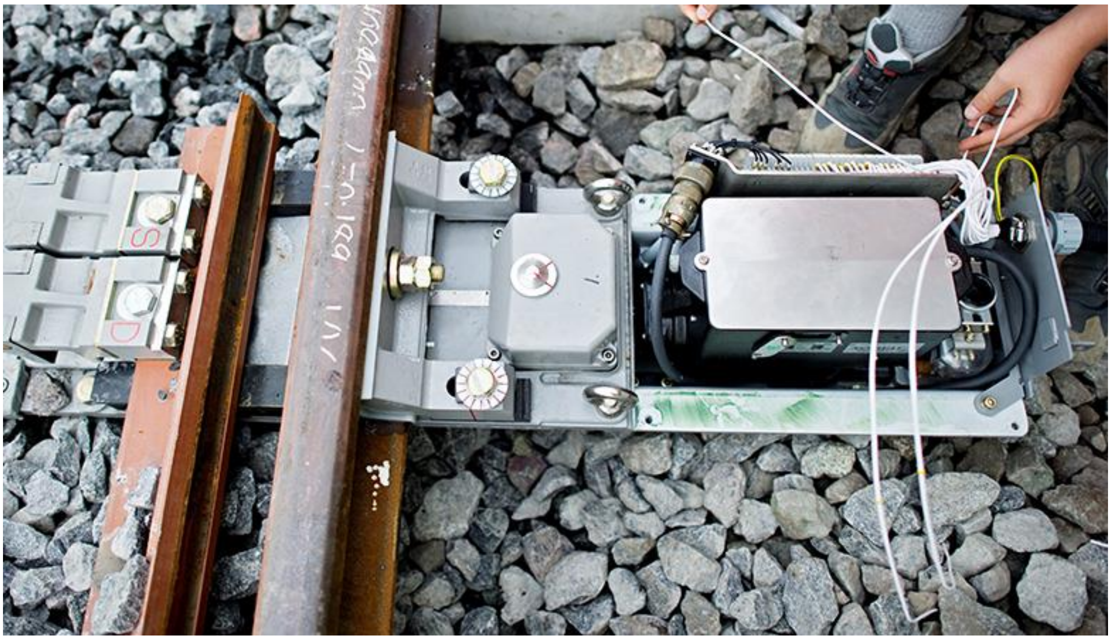


Figure 41: Smart railway switch[68]

In figure 41 one of the modern railway switches is depictured. This type of railway switch monitor power consumption, vibration and temperature, and by utilising these data points one can monitor the condition of the railway switches.

After installing these smart switches, the smart maintenance initiative started monitoring the captured data on august 2016[59]. In the beginning the actual value gain was questioned by other personnel, but after providing solid results and providing a proof of concept the interest for smart maintenance increased. In the first year of release of 2017 smart maintenance detected 150 signal errors and lowered delay hours by 600 hours[58]. This proved that smart maintenance was a working concept and as applicable to the railway industry in Norway.

6.3.2 Smart maintenance in Bane NOR today

Today smart maintenance is a tested concept mainly applied in Oslo and Akerhus district. For the implementation of smart maintenance, Bane NOR has chosen to use Microsoft azure, a machine learning program used to create machine learning models and predict failures.

In Bane NOR today, smart maintenance is one of the main focus areas and the concept is gaining more and more traction as an efficient and modern maintenance strategy. After developing a method for smart maintenance for railways switches, Bane NOR focused on develop the concept further. In Bane NOR today there are over 1200 railway switches, 500 track sections and 320 heating systems being monitored by a central database at the smart maintenance group[59].

6.3.2.1 Microsoft azure

Azure is the machine learning tool developed by Microsoft. The tool is based on the same model as figure 42, with using input data to create a model, then training the model and then testing and deploying the model. In figure 28 an illustration of how Microsoft azure works. The cloud solution helps with creation of the model and the Azure API (Application Programming Interface) helps applications access the chosen model when its deployed by Azure.

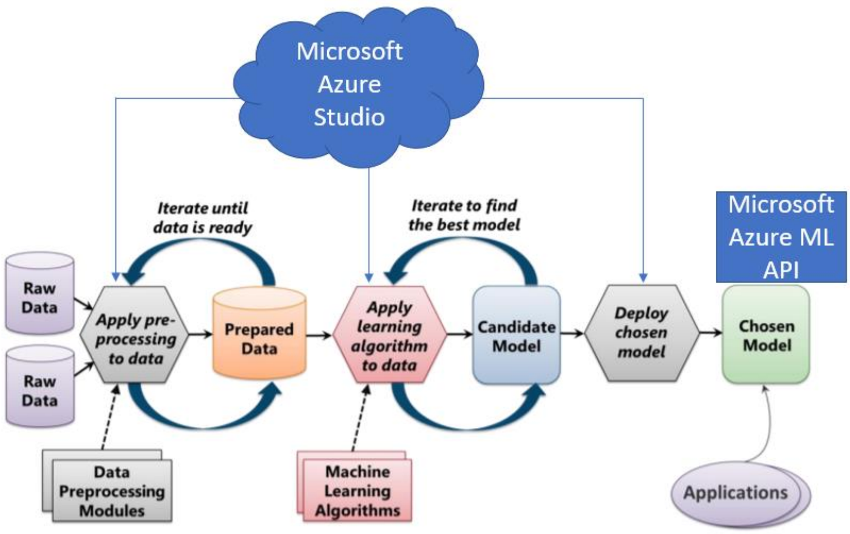


Figure 42: Microsoft Azure machine learning solutions (adapted from[50])

Microsoft Azure helps every individual and organization to gain the benefit of machine learning. Until very recently each of the steps in figure 42 could only done by a data scientist, but now everyone has the possibility to contribute. This gives technical personnel the opportunity to use their knowledge of asset failure modes to build a more effective machine learning model[69].

To have a gain greater benefits from the developed concept the plan is to combine smart maintenance to the CMMS system which controls the maintenance today.

6.4 The future of smart maintenance in Bane NOR

In this chapter an introduction to Bane NOR's plans to improve maintenance in the future.

The future of smart maintenance in Bane NOR is based on the same view that started the smart maintenance initiative, lowering delay hours and increasing availability. By improving the algorithm and training the model used to detect failures the system will be able to detect more failures and prevent more delay hours.

The goal set for 2019 has been set to prevent 800 hours of delay up from 600 hours the previous years[47]. This shows an eagerness to improve on the prediction system and increase the uptime of the railway as a whole.

To achieve the goal of a reduction of 800 delay hours Bane NOR has planned actions to gain even more efficiency by using smart maintenance. These actions are incorporating the smart maintenance system to the operational maintenance system. This will increase the ability to monitor condition as well as plan maintenance in a more effective way.

An example of increased efficiency with the fusion of these two systems would be the lubrication of the engine on a railway switch. Today the lubrication interval is time based, but by using the smart maintenance system it is able to predict when the most effective interval of lubrication would be. In operational terms this means that the railway switches would be lubricated when needed. This frees up technicians that can handle other tasks that are more pressing. Since the lubrication of railway switches differs between heavily used rail and rarely used rail, the smart maintenance will allow these switches to be lubricated in the optimal interval. Railway switches that are often activated will receive a lubrication interval that are shorter, while a railway switch that are rarely used will receive a longer lubrication interval. This will distribute maintenance resources in the most effective way which results in both savings and increased availability.

6.4.1 Future organization of Bane NOR

As of today, the controlling entity for maintenance is under the same company the controlling entity for infrastructure. This will change in the future. Bane NOR is working on separating the maintenance division to a separate company called “Spordrift Aksjeselskap/limited company (AS/Ltd)”[70]. By separating maintenance from the main organisation, it allows Spordrift to have more defined role within the Bane NOR organization. This will change the workflow by Bane NOR ordering a maintenance action from Spordrift and Spordrift performing said maintenance action. By creating this separate company, it facilitates the optimization process

In figure 43 a model for more modern maintenance method for railway is presented. By combining ECM 3 and ECM 4 on the same stage one can reduce the time need to perform and plan the maintenance.

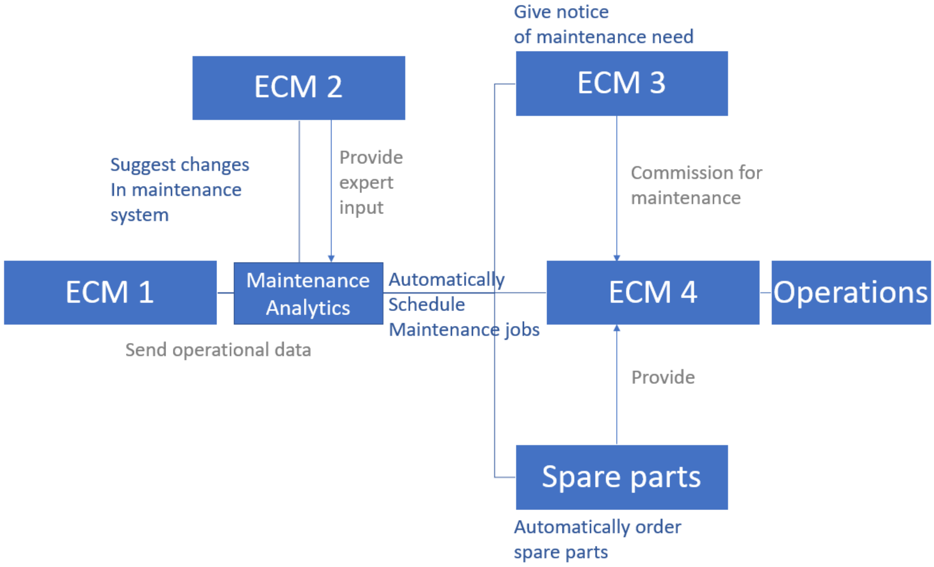


Figure 43: Smart maintenance management railway (adapted from [12])

To give a good comparison model figure 44 was created. By utilizing this modern setup for maintenance Bane NOR and Spordrift AS will be able to perform more maintenance actions in a shorter time. As shown in figure 44.

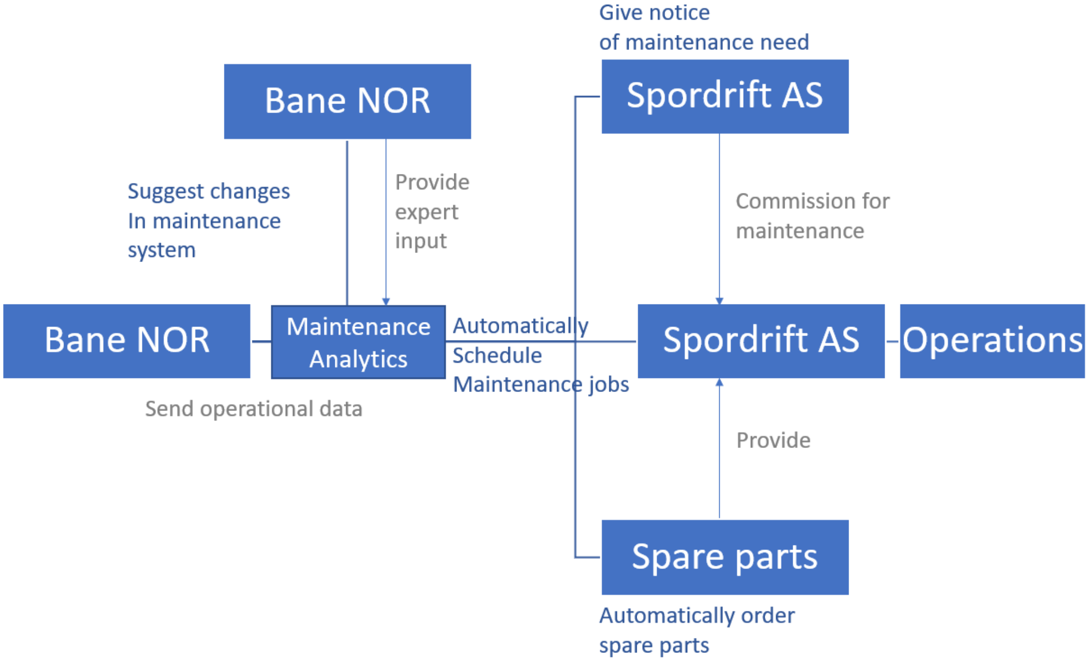


Figure 44: New setup for maintenance within Norwegian railway

6.5 World class maintenance in Bane NOR

This chapter aims to provide a WCM overview of Bane NOR and describe how efficient maintenance is in Bane NOR. The WCM overview will be based on indicators and information gathered from interviews.

6.5.1 WCM indicators Bane NOR

Bane NOR is currently establishing a set of KPIs to gain an overview of the performance of maintenance within the company. With Bane NORs aim of operating the infrastructure without having service disruptions an expansion of the use of KPIs is needed. This will give a better overview of where the delays originate from.

After the interview with Bane NOR there was identified some indicators that is already established by Bane NOR.

O22:

$$\text{(O22)} \quad \frac{Number\ of\ work\ orders\ performed\ as\ scheduled}{Total\ number\ of\ scheduled\ work\ orders} \quad \text{X100}$$

O22 is an organizational indicator and can be categorized as a measure of how many workorders are performed on time. By measuring the schedule compliance, it is possible to identify how well work orders are planned and schedule. By measuring this KPI one can also see indications for how big the backlog of uncompleted work orders is, another important factor for measuring maintenance organisational efficiency. A high schedule compliance and low backlog will be a good indicator for WCM.

Bane NOR has seen the importance of measuring the backlog, as was confirmed by Charles Nilsen[47].

T6:

$$\text{(T6)} \quad \frac{Total\ operating\ time}{Total\ operating\ time + Downtime\ related\ to\ failures} \quad \text{X100}$$

T6 is a technical indicator which is used to measure of the availability of a system. By measuring this KPI, a company can see when the system or asset can perform it's intended function. In this indicator failures means anything that stops the system from performing its intended function.

In Bane NOR this indicator is used but with some modification. Data from scheduling shows that Bane NOR runs the timetable with a 99,3 % punctuality. If one extrapolates this data one can say that if the train runs with a 99,3 % punctuality, the railway system also has to be available[71]. It is important to note that this 99,3% punctuality has some acceptance criteria; such has the fault has to originate from the infrastructure and within a 4-minute delay time window. These accept criteria excludes external events such as weather. The reason for these acceptance criteria is to see how the infrastructure prevents traffic services. This indicator measures how the infrastructure interferes with train traffic.

The goal is to have the infrastructure not interfere with train traffic and this indicator measures this.

In figure 45 the punctuality of personnel trains in Norway is presented. The red line is presented as the punctuality within a 10+ minutes delay and the blue is presented with a 4 minutes dealy.

Figure 45: Punctuality for personnel trains in Norway[2]

This figure does not use the same acceptance criteria as stated previously. The figure shows a total punctuality of 90,5 %, but with a very conservative approach to availability. In this figure every stop is measured giving a broad overview of total availability. This figure is presented to show that the infrastructure is not the main contributor to loss of punctuality.

By comparing this data to table 5 of WCM indicators one can see that within this indicator Bane NOR is on par with the Norwegian industry practise.

Table 5: WCM indicator

WCM indicators	Typical range	World class range	Norwegian industry practice	Recommended for Norwegian industry for WCM
Equipment Availability	65% - 99%	>97%	89,8 %	> 90%

T1:

(T1) $$\frac{Total\ Operating\ time}{Total\ Operating\ time + Downtime\ due\ to\ maintenance} X100$$

Bane NOR is currently working on developing the T1 indicator. By measuring the total availability of the infrastructure over one year (8760 hours) Bane NOR can measure if the maintenance being performed on the infrastructure interfere with train traffic. By giving an indication of how much maintenance is being conducted on the infrastructure and then comparing this with the punctuality indicators. Resulting in a better understanding of maintenance interference with train traffic.

6.5.2 Goals for WCM indicators in Bane NOR

The final goal for Bane NOR is to reach WCM level and to do this Bane NOR plans to increase the use of KPIs.

Today Bane NOR uses an asset management program called IBM Maximo but is currently not supplying enough data to establish accurate KPIs. A goal for Bane NOR is to gather data from IBM Maximo asset management and using this data to establish the needed KPIs[71]. When this project is completed Bane NOR will have a good base of KPIs to measure improvements.

Establishing the KPI basis should be of high importance to Bane NOR, since it will help Bane NOR identify the areas where maintenance has the most to gain.

As an example, if the indicator O5 shows that a big part of maintenance being performed is not planned or scheduled.

(O5) $$\frac{Planned\ and\ scheduled\ maintenance\ man-hours}{Total\ maintenance\ personnel\ man-hours} X100$$

By identifying which KPIs that is not up to a WCM standard, Bane NOR can implement actions to improve these KPIs. This is the reason why a good basis of KPIs is beneficial to implement before introducing maintenance improvements.

Bane NOR has realised the importance of using indicators and are hoping to establish more with the data gathered from Maximo.

6.5.3 WCM overview

WCM can be measured in different ways, and one is through the evaluation of the level of maintenance scale, focus, organization, digital tools, readiness, competence and methodology.

In table 6 the current status of bane NOR in a WCM perspective is presented. This table is based on the evaluation of the candidate after the interview and other information gathered about the current maintenance procedures in bane NOR today.

Table 6 shows the same as table 2 but with the current status of Bane NOR in a WCM comparison. Under table 6 the expiation for each evaluation is presented.

● : Current Level

Table 6: WCM progress in Bane NOR

	Scale	*Focus*	*Organization*	*Digital tools*	*Readiness*	*Competence*	*Methodology*
World Class	Competitive ness	Core maintenance	Optimal maintenance organization	Tools for optimization	Process improvement	Improvement expertise	Optimization of intervals and spare parts
Approaching the top	PLI	Condition based maintenance	Process oriented	Dashboard prediction	Ahead of the problem	Analysis competence	RCM
Well underway	Overall equipment efficiency	5 S Trained by operator	Separation of 1. line maintenance	Condition measuring/ analysis	Pit Stop	Process competence inter disciplinary	FMEA
Put in system	Stop time registration	Preventive program	Separating maintenance from core	EDB based maintenance system	Tools Spare parts Procedures	Machine competence	Trouble shooting
Basic	Maintenance budget	Repair	Traditional maintenance department	Maintenance board, manual workorder	Fire extinguishing	Subject competence	Own experience

In bane NOR today profit loss indicators (PLI) is a focus, where the profit is defined as a reduction in delay hours for the railway infrastructure. If smart maintenance prevents a failure and allows trains to run in according to the given schedule, it is seen as profit.

Bane NOR is working towards a smart maintenance traffic-based maintenance system and this will be at a WCM level. But today, Bane NOR is only using PdM for some assets and the main maintenance strategy is still time based. The evaluation is set to Condition based maintenance since the smart maintenance is used for some assets and e.g. the lubrication system for railway switches is based on usage, which is a reflection on condition.

As an organization Bane NOR is staring to separate the maintenance department as a separate organization. By separating the maintenance department into a separate company, it will increase the competitiveness and as a result of this, driving prices down and increase efficiency. The first contracts will be offered 1. of march 2022[72]. When this separation is completed Bane NOR will be closer to a WCM level since it will move towards an optimal maintenance organization, but as of today they have not reached a WCM level.

In Bane NOR the digital tools usage is categorized as well underway. Bane NOR is conducting condition measuring/analysis on both railway switches and tracks in the Oslo and Akerhus area. They are working to upgrade the use of digital tools with tools such as Microsoft Azure working on predictive analysis and Maximo working on asset management. In the future there is plans of incorporating Azure into the maintenance management system, and at this time Bane NOR will reach approaching the top by having dashboard predictions.

Readiness is also a high priority within Bane NOR and is the reason Bane NOR started the smart maintenance initiative. By using methods described in former chapters, Bane NOR is well underway to reach WCM. Today Bane NOR is on a pit stop and working towards staying ahead of the problem. With time the smart maintenance model will be more widely used and Bane NOR will move up from pit stop to ahead of the problem. This will give increased knowledge of the infrastructure, giving Bane NOR the ability to stay ahead of the failures and accurately predict them. By incorporating a more digital system the maintenance history can documented better, giving Bane NOR the ability to better tailor the maintenance to the specific asset. After moving up to approaching the top, the next step will be WCM with the introduction of smart maintenance into the maintenance management. Thereby creating a system that searches for improvements after each completion of the maintenance loop, resulting in a continues improvement of the maintenance process.

The competence within Bane NOR is on a high level. Within Bane NOR there has been a focus on analysing data and categorizing it. This is seen with Bane NORs work within WCM indicators and their goal of gaining a better overview of the maintenance performance. Bane NOR is working towards improvement expertise but needs to build a solid foundation of KPIs before starting to measure the improvement of these KPIs. When Bane NOR starts with comparison and improvement of these KPIs, they will have reached a WCM level.

Bane NOR has had a clear vision of focusing on reliability centered maintenance. Having a highly reliable railway infrastructure has been the aim for Bane NOR and is also the reason for continued improvement through smart maintenance. This methodology has resulted in a very high reliability as stated with 90,5 % of trains running on the set schedule. To achieve such a high availability the railway needs to be very reliable. The next step in reaching WCM methodology will be implemented in the future with the introduction of smart maintenance into the maintenance management system.

7 What should Bane NOR implement?

Bane NOR is one of the top companies using smart maintenance in Norway today with a high focus on improving the effectiveness of their maintenance. After proving that smart maintenance was a concept worth pursuing, Bane NOR increased the commitment to further optimize maintenance.

In table 7 Bane NORs implementations are shown, in prioritized order.

Table 7: Bane NORs use of modern maintenance concepts

Bane NORs implementations of modern maintenance concepts	
Theory: ➢ Smart maintenance ➢ WCM ➢ Proactive maintenance ➢ Smart maintenance management ➢ Cyber physical systems ➢ Internet of things ➢ Internet of service ➢ Big data ➢ Machine learning ➢ Train mounted monitoring	Bane NOR: 1. Smart maintenance 2. WCM 3. Machine learning 4. Big data 5. Smart maintenance management

As seen in table 1, there is different concepts that have not been implemented by Bane NOR.

As of 2019 the smart maintenance initiative is working towards implementing their PdM into the CMMS system. By working towards a traffic-oriented maintenance strategy the benefits will be increased since the planning and scheduling will be optimized.

The recommendations for implementations is presented under.

WCM:

As presented in the chapter 6.5.3 the WCM overview of Bane NOR was presented. it showed that Bane NOR have not reached WCM level in any of the presented categories. Only two indicators were confirmed that was under monitoring (O22 and T6). To gain additional insight into the maintenance performance a selection of KPIs are presented below. These KPIs should be monitored after the data gathering project for Maximo is completed.

Equations 3: WCM indicators of interest

(E5) $$\frac{Total\ Mainteance\ Cost + unavailability\ cost\ related\ to\ maintenance}{Total\ maintenance\ Cost} \quad X100$$

(E17) $$\frac{Condition\ based\ mainteance\ cost}{Total\ maintenance\ Cost} \quad X100$$

(T8) $$\frac{Preventive\ maintenance\ time\ causing\ downtime}{Total\ downtime\ related\ to\ maintenace} \quad X100$$

(O5) $$\frac{Planned\ and\ scheduled\ maintenance\ man - hours}{Total\ maintenance\ personnel\ man - hours} \quad X100$$

(O17) $$\frac{Immediate\ Corrective\ maintenance\ man - hours}{Total\ maintenance\ man - hours} \quad X100$$

(T7) $$\frac{Total\ operating\ time}{Total\ operating\ time + Downtime\ related\ to\ planned\ and\ scheduled\ maintenace} \quad X100$$

Smart maintenance of tracks:

As seen Bane NOR choose to focus on mainly railway switches with smart maintenance. After seeing positive results from this project, the smart maintenance initiative should also explore the possibilities of implementing a smart maintenance for the rails themselves. In figure 46, the second highest contributor to delay hours is tracks.

Today the track condition is monitored by measuring traffic [47]. By expanding the data pool to include new sensors the accuracy of the predictions would be increased. This will increase Bane NORs insight into the tracks condition and maintenance can be adjusted thereafter. One new data type could be the development of a system in correlation to the Japanese track monitoring system. This will give Bane NOR the ability to monitor thickness of the tracks and small faults/bends. This will give Bane

NOR a better understanding of the actual condition of the tracks and not an estimate based on traffic and weather data.

If such a system was to be developed there would be more benefits than the accuracy of condition monitoring. With a train mounted track monitoring system, the number of tracks available for monitoring would be increased. The track monitoring system would not be limited to Oslo and Akerhus area.

In figure 46 a concept sketch of a train mounted track monitoring process is shown.

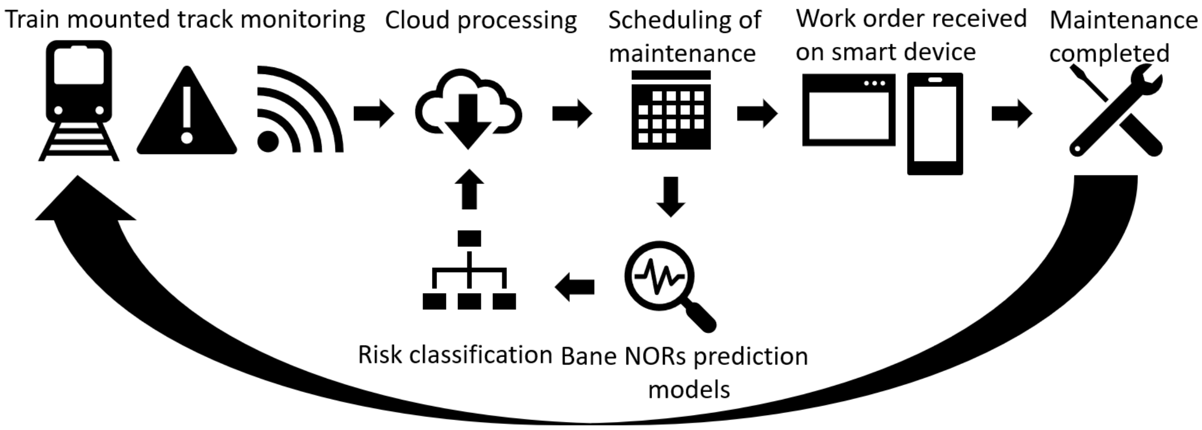


Figure 46: Train mounted track monitoring system

This will optimize the maintenance intervals and will make maintenance management easier.

Culture/knowledge:

The biggest challenge identified with the implementation of smart maintenance was culture/knowledge. One of the challenges the smart initiative in Bane NOR described was being doubted. This will be a non-technical recommendation but will benefit Bane NOR by giving technical personnel the ability to contribute to maintenance in a bigger way. By including technical maintenance personnel in courses in the use of smart maintenance concepts such as sensor technology and PdM it will increase their ability to improve smart maintenance.

This will in turn help with the identification of more preventable failures, where maintenance personnel will have the knowledge about the root cause but is lacking knowledge about how to predict it. If the technical personnel acquire a A.6 qualification defined by standard NS-EN 15628:2014 their ability to contribute to improvement of smart maintenance will increase. This may increase Bane NORs ability to prevent more root causes with the increased knowledge from the technical maintenance division.

8 Discussion

At the beginning of this master's thesis some objectives were defined. In this subchapter the results provided will be discussed and compared to these objectives.

Bane NOR is one of the most dedicated companies working on smart maintenance. The information obtained from interviews and case studies from different countries show that smart maintenance has great potential.

Several literature resources were reviewed and a basis for smart maintenance and WCM was developed. The relevant theory that was found was presented in the thesis. The literature identified that there are no generic model for smart maintenance and WCM. Therefore, the most relevant models were selected and used to develop the theoretical framework.

After the theorical framework was completed the thesis focused on the use of smart maintenance in industry and the railway sector. An introduction of Industry 4.0 was presented since there is a close correlation between industry 4.0 and smart maintenance. Then, two different cases related to the use of smart maintenance in the railway sector was presented, describing the use of smart maintenance in railway.

The German industry 4.0 index was researched to map how Germany's industry moves towards industry 4.0 with a focus on smart maintenance.

The next objective was to map smart maintenance within Bane NOR. After researching literature from Bane NOR and conducting an interview with maintenance personnel, a basis for evaluation was developed. The basis described the use and future plans for smart maintenance in Bane NOR and was verified by Bane NOR employees as an accurate representation.

Then the thesis mapped Bane NOR WCM status. By using information gathered from interviews of maintenance personnel a WCM overview was made. The overview was compared to the theoretical framework, and it was concluded that Bane NOR has not reached WCM, but is working towards this goal.

Bane NOR has planned some actions to improve maintenance, such as implementing smart maintenance into the maintenance management program. If these planned actions are implemented, Bane NOR will reach WCM in the future.

In the final part of the thesis, a set of recommendations was presented. These recommendations are developed by the candidate on the basis of the theoretical framework presented earlier in the thesis. The recommendations presented in this thesis are only potential future projects that might increase the effectiveness of maintenance. The thesis does not take into account how much upfront investment is needed or how much savings that each recommendation will yield.

9 Conclusion and further work

This chapter will be a finishing chapter that contain the conclusion and a recommendation for further work.

9.1 Conclusion

In the beginning of the thesis four problems was presented and this chapter aims to answer these.

The thesis main goal was to establish a firm theoretical basis for smart maintenance and WCM, as well as mapping the smart maintenance status in Bane NOR. By using knowledge about smart maintenance, WCM and industry 4.0 together with interviews conducted with maintenance personnel in Bane NOR, the problems described in chapter 1 was solved in an adequate way.

Firstly, the goal was to present theory about smart maintenance and WCM. After the relevant theory was presented the next goal was to present theory about the use of smart maintenance within railway, where two relevant cases was presented. When theory and international use of smart maintenance was established, the next problem was familiarization with Bane NORs use of smart maintenance. This was done to give a basis for comparison between international railway and Norwegian railway. The final problem was presenting recommendations for implementation in Bane NOR, based on the theory and cases presented.

These problems were solved by the thesis and generated these results:

- A theoretical understanding of smart maintenance and WCM was presented.
- Two different cases and other relevant theory about the use of smart maintenance was presented.
- A correct description of smart maintenance and WCM in Bane NOR was presented.
- Recommendations for implementations was provided as a result of research conducted in the master thesis.

After comparing Bane NOR's railway maintenance strategies to other international entities, Bane NOR is shown to not be far from the maintenance efficiency achieved in leading markets within railway efficiency worldwide, such as Japan. They share the same vision of how to implement smart maintenance to lower maintenance costs and infrastructure downtime. It is clear that a high focus on digitalization will provide a better basis for maintenance in the future.

Finally, Bane NOR's expertise within maintenance is at a very high level. By having several employees who are European certified experts in maintenance and working dedicatedly towards smart maintenance, it is clear that Bane NOR will reach WCM level in the future.

9.2 Further work

The findings in this thesis is a recommendation of measures to help Bane NOR reach WCM. With these recommendations there is additional work that could be implemented based on the findings in this thesis.

- Increased collection of relevant WCM indicator data to gain more overview of the effectiveness of the maintenance.
- Include the recommended indicators from the maser thesis to gain insight in economics, maintenance and personnel performance.
- Conducting a risk analysis and feasibility project for expanding smart maintenance to other parts of railway, both tracks and machines.
  - Establish the possibility to monitor tracks through photographic machine learning models, i.e. Japanese railway case.
- Facilitate the cooperation between NTNU and Bane NOR to continue the work towards WCM
  - Gather data from Maximo to measure an increased number of KPIs
  - Consult Per Schjølberg in guidance to WCM indicators

List of references:

1. Samferdselsdepartement, D.K., *Meld. St. 27 Melding til Stortinget. På rett spor. Reform av Jernbanesektoren*. 2015: Regjeringen.
2. Nilsen, C., *Email*, J. Flesjå, Editor. 2019.
3. NTNU. *Om NTNU*. 2019; Available from: https://www.ntnu.no/om.
4. NOR, B. *About Bane NOR*. 2017; Available from: https://www.banenor.no/en/startpage1/About-Us/.
5. Kans, M., Galar, D., *The Impact of Maintenance 4.0 And Big Data Analytics within Strategic Asset Managment.* 2017.
6. Zenisek, J., et al., *Smart maintenance lifecycle management: A design proposal*. 2017. 546-551.
7. Rafael Penna, M.A., Danubia Espindola, Silvia Botelho, Nelson Duarte Carlos E. Pereira, Marcos Zuccolotto, Enzo Morosini Frazzon, *Visualization tool for cyber-physical maintenance systems*. 2014: 2014 12th IEEE international Conferrence on Industrial Informatics.
8. Hai Qiu, D.J.L., *Near-Zero downtime: Overview and trends*. University of Cincinnati.
9. Hoftun, L.B., *Fremtidens vedlikeholdsstyring av trommelmotorer ved SalMar AS*, in *RAMS*. 2017, NTNU: Oria.no.
10. Delaware. *Smart maintenance: from fail and fix to prevent and predict*. [cited 2019; Available from: https://www.delaware.pro/en-SG/Solutions/Smart-Maintenance.
11. Henk Akkermans, L.B., Leo van Dongen and Richard Schouten, *Smart Moves for Smart maintenance*. 2016.
12. Sebastian Stern, A.B., Elke Eisenschmidt, Stefan Reimig, Lisa Schirmers, Isabel Schwerdt, *The rail sector's changing maintenance game*. 2017: McKinesy.
13. norge, S., *Maintenance Terminology*. 2017: Standard.no.
14. Mark Haarman, M.M., *Predictive Maintenance 4.0: Predict the unpredictable.* PricewaterhouseCoopers and Mainnovation, 2017.
15. Graney, B.P. and K. Starry, *Rolling element bearing analysis.* Materials Evaluation, 2012. **70**(1).
16. Sebastian Feldmann, O.H., Hartmut Rauen and Peter-Michael Synek, *Predictive maintenance, Servicing tomorrow - and where we are really today*. 2017: Roland Berger.
17. STAUFEN.AG, *German Industry 4.0 Index 2018*. 2018: Staufen AG.
18. *What is proactive maintenance?* 2018; Available from: https://www.accelix.com/community/proactive-maintenance/what-is-proactive-maintenance/.
19. Labib, A.W., *Next Generation Maintenance Systems: Towards the Design of a Self-maintenance Machine*. 2006, University of Portsmouth: IEEE.
20. S. F. Imam, J.R.a.R.M.C.R., *World Class Maintenance (WCM): Measurable indicators creating Opportunities for Norwegian Oil and Gas indsutry*. 2012, University of Stavanger and Apply sørco.
21. Ole Meland, P.S., Jørn Vatn, Harald Rødseth, *Forskning og utvikling innen vedlikehold med relevans for petroleumsvirksomheten*. 2009, SINTEF Teknologi og Samfunn.
22. Mobley, R.K., *An introduction to predictive maintenance, Second Edition*. 2002: Butterworth, Heinemann.
23. Norge, S., *NS-EN 15628: Qualification of maintenance personnel*. 2014, standard norge: standard.no.
24. Norge, S., *NS-EN 15341:2007 Maintenance Key Performance Indicators*. 2007.
25. Schjølberg, P., *Email*, J. Flesjå, Editor. 2019.
26. Standard, N., *Risk based maintenance and consequence classification Z-008:2017*, in *Maintenance Managment*. 2017.

27. Schjølberg, H.R.a.P., *Maintenance Backlog for improving integrated planning.* Journal of Quality in Maintenance Engineering, 2017.
28. Norge, S., *Maintenance Terminology*, in *Maintenance Plan*. 2017.
29. Karim, P.T.a.R., *Enhancing the usability of maintenance data management systems.* 2014.
30. Hadi Balouei Jamkhaneh, J.K.P., Seyed Mohammed Sadegh Khaksar, S. Mohammad Arabzad, Reza Verji Kazemi., *Impacts of computerized maintenance management system and relevant supportive organizational factors on total productive maintenance*, in *Emerald Publishing Limited*. 2018.
31. Bagadia, K., *Computerized maintenace managment systems made easy: how to evaluate, select, and manage CMMS*. 2006.
32. Peycheva, R. *Industry 4.0 CMMS: Future maintenance is happening now*. 2018 [cited 2019 28/05]; Available from: https://www.mobility-work.com/blog/industry-40-cmms-future-maintenance-happening-now.
33. Schjølberg, R.R.a.P., *Industry 4.0 and Maintenance*. 2016: Norsk Forening for Vedlikhold.
34. Biedermann, H. and A. Kinz, *Lean Smart Maintenance—Value Adding, Flexible, and Intelligent Asset Management*. 2019.
35. Fordal, J.M., H. Rødseth, and P. Schjølberg. *Initiating Industrie 4.0 by Implementing Sensor Management – Improving Operational Availability*. in *Advanced Manufacturing and Automation VIII*. 2019. Singapore: Springer Singapore.
36. Commission, E., *Germany: Industrie 4.0*. 2017, European Commission.
37. Jazdi, N. *Cyber physical systems in the context of Industry 4.0*. in *2014 IEEE International Conference on Automation, Quality and Testing, Robotics*. 2014.
38. Per Schjølberg, R.R., *Industry 4.0 and Maintenance*. 2016: Norges Vedlikholds Forening.
39. Bayoumi, A. and R. McCaslin, *Internet of Things – A Predictive Maintenance Tool for General Machinery, Petrochemicals and Water Treatment*, in *Advanced Technologies for Sustainable Systems: Selected Contributions from the International Conference on Sustainable Vital Technologies in Engineering and Informatics, BUE ACE1 2016, 7-9 November 2016, Cairo, Egypt*, Y. Bahei-El-Din and M. Hassan, Editors. 2017, Springer International Publishing: Cham. p. 137-146.
40. O'Brien, J. *Improve Maintenance with the Internet of Things*. Available from: https://www.reliableplant.com/Read/29962/internet-of-things.
41. Fraga-Lamas, P., T. Fernández-Caramés, and L. Castedo, *Towards the Internet of Smart Trains: A Review on Industrial IoT-Connected Railways*. Vol. 17. 2017.
42. Menmicro. *Connected Computing: Reliable Electronics for the Robust Regions of the IoT*. Available from: https://www.menmicro.com/competencies/connected-computing/.
43. Reis, J.Z. and R.F. Gonçalves. *The Role of Internet of Services (IoS) on Industry 4.0 Through the Service Oriented Architecture (SOA)*. in *Advances in Production Management Systems. Smart Manufacturing for Industry 4.0*. 2018. Cham: Springer International Publishing.
44. Carr, A.D.a.J.A.a.C., *Big Data in railways*. 2016, European Union agency for railways.
45. Laney, M.A.B.a.D., *"The Importance of 'Big Data': A defention"* Gartner, 2012.
46. Su, X., *Introduction to Big Data*. NTNU: NTNU.no.
47. Gjerstad, C.N.a.A., *Bane NOR skpye meeting*, J. Flesjå, Editor. 2019.
48. Kjenne, S., *"Big data" Bedrer punktligheten*. 2017.
49. SAS. *Machine Learning: What it is and why it matters*. 2018 [cited 2019 14.03]; Available from: https://www.sas.com/en_us/insights/analytics/machine-learning.html.
50. Chappell, D., *Intoducing azure machine learning: A guide for technical professionals*. 2015, Microsoft Corporation.
51. Office, J.C. *Society 5.0*. [cited 2019 27/05]; Available from: https://www8.cao.go.jp/cstp/english/society5_0/index.html.
52. Ogawa, N., *Society 5.0 - Co-creating the future*. 2018: Keidanren.
53. Goverment, J., *Realizing Society 5.0*.

54. Keidanren. *KeidanrenSDGs*. 2018 [cited 2019 27/05]; Available from: https://www.keidanrensdgs-world.com/blog/about-this-website.
55. Timperley, J., *Eight charts show how 'aggressiv' railway expansion could cut emissions*. 2019.
56. Turner, C., et al., *A review of key planning and scheduling in the rail industry in Europe and UK.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2015. **230**(3): p. 984-998.
57. Li, H., et al., *Improving rail network velocity: A machine learning approach to predictive maintenance.* Transportation Research Part C: Emerging Technologies, 2014. **45**: p. 17-26.
58. NOR, S.K.K.f.d.o.t.f.b., *Big Data, Slik kan Big Data predikere fremtiden*, in *Lørn tech*, S.R. Lørner, Editor.: Lørn.tech.
59. Gjerstad, A. *Punktlighetsseminar 13.11.2018*. Bane NOR.
60. Takikawa, D.M., *Innovation in Railway Maintenance utilizing Infoamtion and Communication Technology (Smart Maintenance Initiative)*. 2016.
61. S Jammu, N. and P. Kankar, *A Review on Prognosis of Rolling Element Bearings*. Vol. 3. 2011.
62. Tandon, N. and B.C. Nakra, *Comparison of vibration and acoustic measurement techniques for the condition monitoring of rolling element bearings*. Vol. 25. 1992. 205-212.
63. Entezami, M., et al., *Perspectives on railway axle bearing condition monitoring.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2019: p. 0954409719831822.
64. Huang, Z., *Integrated railway remote condition monitoring* in *University of Birmingham*. 2017.
65. NOR, B., *We create the railway of the future*. Bane NOR.
66. NOR, B. *Fakta om signalsystemet ERTMS*. 2016 [cited 2019 26.02.2019]; Available from: https://www.banenor.no/Prosjekter/prosjekter/ertms/kort-om-ertms/.
67. NOR, B. *The Digital Railway - Bane NOR signs contract with Thales*. 2018 [cited 2019 26/02]; Available from: https://www.banenor.no/Prosjekter/prosjekter/ertms/innhold/2018/the-digital-railway--bane-nor-signs-contract-with-thales/.
68. Bjerkaker, B. *Finner feilen før den feiler*. 2018 [cited 2019 03-05-2019]; Available from: https://www.banenor.no/Nyheter/Nyhetsarkiv/2018/finner-feilen-for-den-feiler/.
69. *What is Azure?* 2019 [cited 2019 14/05]; Available from: https://azure.microsoft.com/en-us/overview/what-is-azure/?OCID=AID719817_SEM_qfuoud6f&lnkd=Google_Azure_Brand&dclid=CjkKEQjwzunmBRCc_b7S2Z_1zs8BEiQAxaNdxEzAaiuqBeXufXN_n95-bFI15NwlEM8J8bm9E4XtVjPw_wcB.
70. NOR, B. *Bane NOR skiller ut drift og vedlikehold av jernbane i eget selskap*. 2018 [cited 2019 09/05]; Available from: https://www.banenor.no/Nyheter/Nyhetsarkiv/2018/bane-nor-skiller-ut-drift-og-vedlikehold-av-jernbanen-i-eget-selskap/.
71. Nilsen, C., *Mail from Bane NOR*, J. Flesjå, Editor. 2019.
72. Sandberg, T., *Hvem skal få togene fram i Norge?*, in *Dagsavisen*. 2019.

Appendix A - Abbreviations

NTNU: Norwegian University of Science and Technology

AR: Augmented reality

ERTEMS: European Rail Traffic Management system

CM: Corrective maintenance

PM Preventive maintenance

PdM: Predictive maintenance

I40: industry 4.0

CPS: Cyber Physical system

HTTP: Hypertext Transfer Protocol

IoT: Internet of things

IoS: Internet of service

IT: Information technology

HSE: Health Safety and environment

NORSOK: The Norwegian shelfs competitive position

CMMS: Computerized maintenance management system

WCM: World Class maintenance

KPI: Key performance indicator

PLI: Profit loss indicator

RCM: reliability centered maintenance

FMEA: Failure mode and effective analysis

EKG: Electrocardiogram

CEO: Chief executive officer

OEM: Original equipment manufacturer

AS/Ltd: Limited company

Ph.D.: Doctor of philosophy

Appendix B: Pre-study

Pre-study report

TPK 4590 – Safety, reliability and maintenance, master thesis

Smart Maintenance

Department of mechanical and industrial engineering
NTNU

Joachim Flesjå

Spring 2019

Supervisor 1: Per Schjølberg, NTNU

Supervisor 2: Fahad Rehman, Bane NOR

Preface

As a part of the subject safety, reliability and maintenance – Master's thesis, TPK4590, this pre-study report aims to present a brief thesis overview and progress plan. The pre-study report will serve as a management tool for time controlling, resource effectiveness and thesis progress.

I want to extend a thanks to my supervisor, NTNU Associate Professor Per Schjølberg for his help and guidance while writing this pre-study.

This document is prepared by Joachim Flesjå of the Department of Mechanical ad Industrial Engineering at NTNU.

Table of contents

1 Introduction

The railway sector has always been a high performing maintenance sector where maintenance and safety has had the highest importance. As a part of the never-ending chase for improvement in maintenance and reliability new concepts arise, and as a part of this innovation smart maintenance emerged. Through new technology such as machine learning and sensors, Bane NOR seeks to find the failures before they happen.

As a part of this digitalization process the candidate and supervisor approached Bane NOR about their interest in a collaboration. By giving an overview of smart maintenance and world class maintenance (WCM) the aim was to find recommendations to implement in Bane NOR. A successful implementation of these recommendation would result in less delays in railway traffic.

2 Thesis description

The master thesis is conducted as part of the 2-year master program Subsea Technology at the University of Science and Technology (NTNU). The specialization for the candidate carrying out the thesis is operation and maintenance. The thesis is valued at 30 study points and is conducted in the fourth and final semester.

The master thesis is the finalizing part of the master program and will be carried out by the candidate Joachim Flesjå in collaboration with Bane NOR and NTNU, for the department of Production and Quality Engineering.

Bane NOR will contribute as industry partner, to provide data that will be utilized during the master thesis.

As a part of this thesis a description of which steps needs to be taken to reach world class maintenance will be presented, with a focus on smart maintenance. The candidate will also address areas of today's maintenance system at Bane NOR.

3 Thesis Goal

The objective of this master thesis is to research and present theory about smart maintenance and using this theory to recommend improvements for smart maintenance within Bane NOR. In according to the smart maintenance, a WCM overview for Bane NOR will be presented, with the objective of categorizing Bane NOR progress towards WCM.

4 Scope

The scope of this master thesis is to gain increased understanding of smart maintenance and document how it is used in the railway industry. By gaining increased understanding of smart maintenance the candidate aims to present a selection of recommendation to improve smart maintenance in Bane NOR. The department at Bane NOR relevant for this thesis is the smart maintenance division and therefore other divisions in Bane NOR will not be studied in this thesis. The thesis is structed on the basis that the reader has a general engineering background with an understanding of modern concepts related to maintenance.

5 Problem description

The problem presented in the master thesis is articulated in collaboration between supervisor Per Schjølberg from NTNU and candidate.

1. Research and present theory on smart maintenance and world class maintenance.
2. Research and present the use of smart maintenance in the railway industry.
3. Familiarization and presentation of smart maintenance within Bane NOR
4. Recommend improvements for smart maintenance in Bane NOR.

6 Thesis Contributors

In this master thesis there is one internal contributor and one external industrial contributor. The internal contributor is NTNU with supervisor Per Schjølberg and the external industrial contributor is Bane NOR with Fahad Reman as the main contact person. The thesis has also been guided by two Bane NOR employees; Charles Nilsen and Anna Gjerstad.

a. NTNU

The Norwegian university of Science and Technology is the largest university in Norway after combining with the colleges of Ålesund, Gjøvik and Sør-Trøndelag. There are around 40,000 students in total at NTNU. Within NTNU there is 8 different faculties with different focus areas, and this master thesis is written for the department of production and quality engineering which is a part of the faculty of engineering science[3].

b. Bane NOR

Bane NOR is a state-owned company responsible for the national railway infrastructure. With 4500 employees they are responsible for planning, development, administration, operation, maintenance, traffic management and administration for the national railway network. The main mission for Bane NOR is to ensure accessible railway infrastructure and efficient and user-friendly services, including the development of hubs and goods terminals[4].

7 Thesis management

This chapter will be used to describe how the candidate will monitor progress and keep control of the master thesis.

There will be used 3 different tools to monitor the master thesis, a Thesis Overview Statement, a Cost, Time and resource (CTR) schedule and a Gantt chart.

The Thesis overview statement aims to give a short-summarized problem description. The master's goals, objectives, obstacles and success criteria will be presented.

Documents of CTR for different parts of the master thesis will be presented and aims to help the candidate manage time and resources.

A Gantt chart show the anticipated workload and deadlines associated with each of the tasks in the master thesis. The proposed workload and deadlines are set by but the candidate and is believed to be reasonable. As the master thesis propagates the candidate takes reservations for changes in the schedule.

a. Thesis Plan

Through planning the different CTR packets where identified, with an assumed workload and goals for each packet. These CTR packets describe the tasks, goals, resources, work method, challenges and focus areas for each individual packet. These CTR packets will be displayed as a part of the GANTT diagram to give supervisor and the candidate of progress. The GANTT diagram posted in appendix C and the CTR packets in appendix B is to be considered as an overview for the whole master thesis.

After revising the thesis plan from the specialization course TPK 4550 the candidate wanted to include the supervisors more. Therefor the strategy will be based on regular meetings with Per Schjølberg to guide the candidate and provide valuable insight. This will ensure progress in the report and result in a better master thesis.

These meetings with the supervisor will be arranged during the progress of the Thesis. The main objective of these meeting is to give the supervisor an overview of the progress in the master thesis, and then plan progress for the next meeting. These meeting will be planned sporadically and the time between each meeting may vary.

The following CTR packets have been identified:

- CTR 1: Develop problem description
- ■ Defining a problem description
- ■ Identify Thesis Goals and restrictions
- ■ Delivering the pre-study report

- CTR 2: Literature review, data collection and planning
  - Plan research and data analysis methods
  - Collecting relevant literature
- CTR 3: Familiarize with the status of maintenance and governing documents for maintenance in Bane NOR.
  - Map maintenance methods being used today
  - Familiarize oneself with the terminology in the industry.
- CTR 4: World class maintenance and smart maintenance
  - Describe world class maintenance
  - Describe smart maintenance
- CTR 5: Maintenance methods
  - Present a description of today's maintenance system.
  - Identify today's procedures for surveillance, inspection and repair.
- CTR 6: Identifying potential areas of improvement in maintenance
  - Analyse differences between todays maintenance operations and world class maintenance.
  - Identify improvement potential.
- CTR 7: Present WCM overview and recommendations
  - Present guide for world class maintenance
  - Present recommendations
- CTR 8: Concluding the report
  - Concluding the findings
  - Describe research approach
- CTR 9: Commissioning
  - Proof reading
  - Refine layout

8 Limitations

In association with the master thesis there is some limitations that must be considered. In this chapter the candidate will briefly present the limitations.

a. Time

The official start of the master thesis is 15.01.2019 and the submission date is 11.06.2019 and after the unsuccessful cooperation between a former industrial partner will shorten the time available. The master thesis has a time limitation of 21 work weeks, which include 40 hours for each week totalling in 840 hours. The master thesis credits 30 study points and is the only course taken in the final semester.

b. Litterateur

As an NTNU student, the candidate has access to a wide range of licenses, scientific articles and books. Available literature for the master thesis will be limited to the litterateur available through the NTNU library and licences. The NTNU library and data from the industrial partners is extensive, but there might be some limitations regarding literature about certain subjects. This may limit the master thesis.

c. Industrial partners

Bane NOR will have limitations on how much time and resources they can contribute with. As a big company in the middle of a restructuring, there is not an abundance of time available for guidance. This will limit the master thesis in some way.

9 Risk analysis

The different factors that may affect the time consumption and quality of the end result is important to identify. The candidate has identified some of these risk factors and presented below. These risk factors have been assessed qualitatively, and a description, cause, consequence and risk reducing actions have been recommended.

Index	Description	Cause	Consequence	Initial risk	Recommended actions	New risk
A	Literature not available	Low competence within literature search Lack of access to data	Quality	Medium	Acquire knowledge about literature searching Request access to relevant documents through other universities libraries	Low
B	Lack of time to complete master thesis	Not following the given schedule Failed cooperation	Quality	High	Start working with master thesis early Anticipate a high workload	Medium
C	Lack of involvement from industrial partners	Priorities from the industrial partners	Quality	Medium	Evenly contact between candidate and industrial partners	Low
D	Lack of feedback on master thesis	Master thesis is written alone	Quality	Medium	Supervisor at NTNU needs to be informed often and evenly to receive valuable feedback	Low
E	Job searching	Applying for jobs and interviews	Time	High	Be effective when working with job applications	Medium

Appendix A – Thesis Overview Statement

Thesis Overview Statement	
Master thesis:	
Smart maintenance	
Candidate:	Revision date:
Joachim Flesjå	14.02.19
Problems:	
- Familiarize with the present maintenance status and documents at Bane NOR. - Present a theory of world class maintenance and smart maintenance. - Analyse the effect of smart maintenance on the railway system. - Present a WCM overview and recommendations.	
Goal:	
- The Thesis goal is to provide theory on smart maintenance and WCM together with recommendations for implementation in Bane NOR	
Objectives:	
- Deliver the master thesis within the given deadline of 11.06.2019. - Deliver a master thesis of satisfying quality to the supervisors at NTNU and Bane NOR.	
Success criteria's:	
- Communication between supervisors and candidate. - Following the given thesis plan - Risk management	
Assumptions, risk and obstacles	
- Needed literature and data is available - Communication and collaboration between the three parties is adequate - Workload of job searching doesn't exceed expectations - Thesis plan is enough to fulfil objectives	

Appendix B – Cost, time and resources (CTR)

1 Develop problem description

Cost, Time and Resources (CTR)			
Thesis tittle:			Revision date:
Smart Maintenance			14.02.19
Work package:	Work package title:		Responsible person:
1	Develop problem description		Joachim Flesjå
Work tasks:			
- Develop draft of problem description - Discuss draft of problem description with supervisors - Develop final problem description			
Goal:			
- Develop a problem description that enables the thesis to create value for Bane NOR and NTNU.			
Focus areas:			
- Relevance for all internal and external partners.			
Literature and resources:			
- Talks with supervisor			
Work method:			
- Discussion between the internal and external partners.			
Challenges:			
- Communication - Common understanding of problem			
Outputs:			
- Problem description - Thesis goal - Thesis objectives			
Estimated time and resources			
Scheduled start:	Scheduled end:	Workload:	Duration:
14.02.19	15.02.19	8 hours	1 days

2 Literature review, data collection and planning

<table>
<tr><th colspan="4">Cost, Time and Resources (CTR)</th></tr>
<tr><td colspan="3">Thesis tittle:</td><td>Revision date:</td></tr>
<tr><td colspan="3">Smart Maintenance</td><td>14.02.19</td></tr>
<tr><td>Work package:</td><td colspan="2">Work package title:</td><td>Responsible person:</td></tr>
<tr><td>2</td><td colspan="2">Literature review, data collection and planning</td><td>Joachim Flesjå</td></tr>
<tr><td colspan="4">Work tasks:</td></tr>
<tr><td colspan="4">- Initial literature review and data collection
- Plan research and data analysis methods
- Continuously collect data and literature</td></tr>
<tr><td colspan="4">Goal:</td></tr>
<tr><td colspan="4">- Develop a theoretical frame for the thesis
- Develop a plan for the research approach, based on available literature and data</td></tr>
<tr><td colspan="4">Focus areas:</td></tr>
<tr><td colspan="4">- Technical documentation from Bane NOR
- Industry standards
- Academic papers</td></tr>
<tr><td colspan="4">Literature and resources:</td></tr>
<tr><td colspan="4">- Bane NOR operational data
- Standard.no
- SCOPUS
- NTNU Professors</td></tr>
<tr><td colspan="4">Work method:</td></tr>
<tr><td colspan="4">- Literature search and study
- Interviews
- Meetings</td></tr>
<tr><td colspan="4">Challenges:</td></tr>
<tr><td colspan="4">- Time and resources spent finding literature
- Unavailability of relevant literature
- Limited access to data and resources from Bane NOR</td></tr>
<tr><td colspan="4">Outputs:</td></tr>
<tr><td colspan="4">- List of references</td></tr>
<tr><td colspan="4">Estimated time and resources</td></tr>
<tr><td>Scheduled start:</td><td>Scheduled end:</td><td>Workload:</td><td>Duration:</td></tr>
<tr><td>15.02.19</td><td>01.06.19</td><td>220 hours</td><td>60 days</td></tr>
</table>

3 Familiarize with the status of maintenance and governing documents for maintenance in Bane NOR

<table>
<tr><th colspan="4">Cost, Time and Resources (CTR)</th></tr>
<tr><td colspan="3">Thesis tittle:</td><td>Revision date:</td></tr>
<tr><td colspan="3">Smart Maintenance</td><td>14.02.19</td></tr>
<tr><td>Work package:</td><td colspan="2">Work package title:</td><td>Responsible person:</td></tr>
<tr><td>3</td><td colspan="2">Familiarize oneself with the status of maintenance and governing documents at Bane NOR</td><td>Joachim Flesjå</td></tr>
<tr><td colspan="4">Work tasks:</td></tr>
<tr><td colspan="4">- Technical data from work package 2
- Map how smart maintenance is done today at Bane NOR
- Familiarize oneself with the terminology in the industry</td></tr>
<tr><td colspan="4">Goal:</td></tr>
<tr><td colspan="4">- Develop an understanding of how maintenance is done at Bane NOR
- Research ways to improve todays strategies and methods.</td></tr>
<tr><td colspan="4">Focus areas:</td></tr>
<tr><td colspan="4">- Understanding of how maintenance is implemented at Bane NOR
- Improvement</td></tr>
<tr><td colspan="4">Literature and resources:</td></tr>
<tr><td colspan="4">- Technical and governing documents from Bane NOR
- Bane NOR personnel
- NTNU professors</td></tr>
<tr><td colspan="4">Work method:</td></tr>
<tr><td colspan="4">- Meetings
- Studying documentation from Bane NOR</td></tr>
<tr><td colspan="4">Challenges:</td></tr>
<tr><td colspan="4">- Unavailability of relevant literature
- Limited access to data and resources from Bane NOR</td></tr>
<tr><td colspan="4">Outputs:</td></tr>
<tr><td colspan="4">- Document describing the status of maintenance at Bane NOR</td></tr>
<tr><td colspan="4">Estimated time and resources</td></tr>
<tr><td>Scheduled start:</td><td>Scheduled end:</td><td>Workload:</td><td>Duration:</td></tr>
<tr><td>18.02.19</td><td>25.02.19</td><td>40 hours</td><td>7 days</td></tr>
</table>

4 World class maintenance and smart maintenance

<table>
<tr><th colspan="4">Cost, Time and Resources (CTR)</th></tr>
<tr><td colspan="3">Thesis tittle:</td><td>Revision date:</td></tr>
<tr><td colspan="3">Smart Maintenance</td><td>14.02.19</td></tr>
<tr><td>Work package:</td><td colspan="2">Work package title:</td><td>Responsible person:</td></tr>
<tr><td>4</td><td colspan="2">World class maintenance and smart maintenance</td><td>Joachim Flesjå</td></tr>
<tr><td colspan="4">Work tasks:</td></tr>
<tr><td colspan="4">- Present a description world class maintenance
- Present a description smart maintenance</td></tr>
<tr><td colspan="4">Goal:</td></tr>
<tr><td colspan="4">- Provide the reader with an in-depth understanding of innovative maintenance methods
- Provide an overview of the future concepts</td></tr>
<tr><td colspan="4">Focus areas:</td></tr>
<tr><td colspan="4">- Precise explanations
- Figures</td></tr>
<tr><td colspan="4">Literature and resources:</td></tr>
<tr><td colspan="4">- Technical and governing documents from Bane NOR
- Equipment documents
- NTNU professors</td></tr>
<tr><td colspan="4">Work method:</td></tr>
<tr><td colspan="4">- Literature search and study
- Interviews</td></tr>
<tr><td colspan="4">Challenges:</td></tr>
<tr><td colspan="4">- Unavailability of relevant literature
- Limited access to data and resources from Bane NOR</td></tr>
<tr><td colspan="4">Outputs:</td></tr>
<tr><td colspan="4">- Case chapter in thesis</td></tr>
<tr><td colspan="4">Estimated time and resources</td></tr>
<tr><td>Scheduled start:</td><td>Scheduled end:</td><td>Workload:</td><td>Duration:</td></tr>
<tr><td>25.02.19</td><td>25.03.19</td><td>150 hours</td><td>28 days</td></tr>
</table>

5 Maintenance methods

Cost, Time and Resources (CTR)			
Thesis tittle:			Revision date:
Smart Maintenance			14.02.19
Work package:	Work package title:		Responsible person:
5	Maintenance methods		Joachim Flesjå
Work tasks:			
- Study relevant theoretical documents - Present a description of today's smart maintenance in Bane NOR - Identify today's procedures for surveillance, inspection and repair.			
Goal:			
- Present relevant maintenance strategies - Present smart maintenance methods			
Focus areas:			
- Technology - New digital tools			
Literature and resources:			
- Technical and governing documents from Bane NOR - Theoretical documenters - NTNU professors			
Work method:			
- Literature search and study - Interviews			
Challenges:			
- Unavailability of relevant literature - Lack of detailed system description for new technology			
Outputs:			
- Theoretical chapter in thesis			
Estimated time and resources			
Scheduled start:	Scheduled end:	Workload:	Duration:
25.03.19	01.04.19	40 hours	7 days

6 Identifying potential areas of improvement in operation and maintenance

<table>
<tr><th colspan="4">Cost, Time and Resources (CTR)</th></tr>
<tr><td colspan="3">Thesis tittle:</td><td>Revision date:</td></tr>
<tr><td colspan="3">Smart Maintenance</td><td>14.02.19</td></tr>
<tr><td>Work package:</td><td colspan="2">Work package title:</td><td>Responsible person:</td></tr>
<tr><td>6</td><td colspan="2">Identifying potential areas of improvement in operation and maintenance</td><td>Joachim Flesjå</td></tr>
<tr><td colspan="4">Work tasks:</td></tr>
<tr><td colspan="4">- Asses todays maintenance actions.
- Asses the investigation process leading to diagnostics of the error.
- Analyse differences between todays maintenance operations and world class maintenance
- Present a document on areas of improvement.</td></tr>
<tr><td colspan="4">Goal:</td></tr>
<tr><td colspan="4">- Identify potential areas of improvement in operation and maintenance for the equipment at Bane NOR</td></tr>
<tr><td colspan="4">Focus areas:</td></tr>
<tr><td colspan="4">- Gap between state-of-the-art and current operations</td></tr>
<tr><td colspan="4">Literature and resources:</td></tr>
<tr><td colspan="4">- Technical and governing documents from Bane NOR
- Theoretical documenters
- NTNU professors
- Interviews with Bane NOR personnel</td></tr>
<tr><td colspan="4">Work method:</td></tr>
<tr><td colspan="4">- Data collection and study
- Interviews</td></tr>
<tr><td colspan="4">Challenges:</td></tr>
<tr><td colspan="4">- Unavailability of relevant literature
- Limited access to data and resources from industrial partners</td></tr>
<tr><td colspan="4">Outputs:</td></tr>
<tr><td colspan="4">- Chapter in thesis</td></tr>
<tr><th colspan="4">Estimated time and resources</th></tr>
<tr><td>Scheduled start:</td><td>Scheduled end:</td><td>Workload:</td><td>Duration:</td></tr>
<tr><td>01.04.19</td><td>01.05.19</td><td>160 hours</td><td>30 days</td></tr>
</table>

7 Develop WCM overview and recommendations

Cost, Time and Resources (CTR)			
Thesis tittle:			Revision date:
Smart Maintenance			14.02.19
Work package:	Work package title:		Responsible person:
7	Develop step-by-step guide to world class maintenance		Joachim Flesjå
Work tasks: - Present a guide to world class maintenance. - Present a document with recommended implementations to Bane NOR.			
Goal: - Establish a theoretical frame with relevant content for the thesis			
Focus areas: - Relevance to content of thesis - Concise descriptions			
Literature and resources: - Academic papers and articles - NTNU professors - Books			
Work method: - Data collection and study			
Challenges: - Unavailability of relevant literature - Deciding the appropriate amount and selection of theories			
Outputs: - Chapter in thesis			
Estimated time and resources			
Scheduled start:	Scheduled end:	Workload:	Duration:
01.05.19	08.05.19	80 hours	8 days

8 Concluding the report

Cost, Time and Resources (CTR)			
Thesis tittle:			Revision date:
Smart Maintenance			14.02.19
Work package:	Work package title:		Responsible person:
8	Concluding the report		Joachim Flesjå
Work tasks: - Conclude the findings - Describe research approach			
Goal: - Provide a description of the approach and methodology for executing the thesis - Develop the thesis's conclusion, discussion and introduction			
Focus areas: - Describe the activities that have been performed and possible deviations from planned activities.			
Literature and resources: - Academic papers and articles - NTNU professors - Books - Internal documents describing research approach - Meeting summary from supervisors			
Work method: - Data collection and study			
Challenges: - Concluding the thesis in a proper manner			
Outputs: - Conclusion, discussion and introduction in thesis			
Estimated time and resources			
Scheduled start:	Scheduled end:	Workload:	Duration:
08.05.19	15.05.19	40 hours	7 days

10 Commissioning

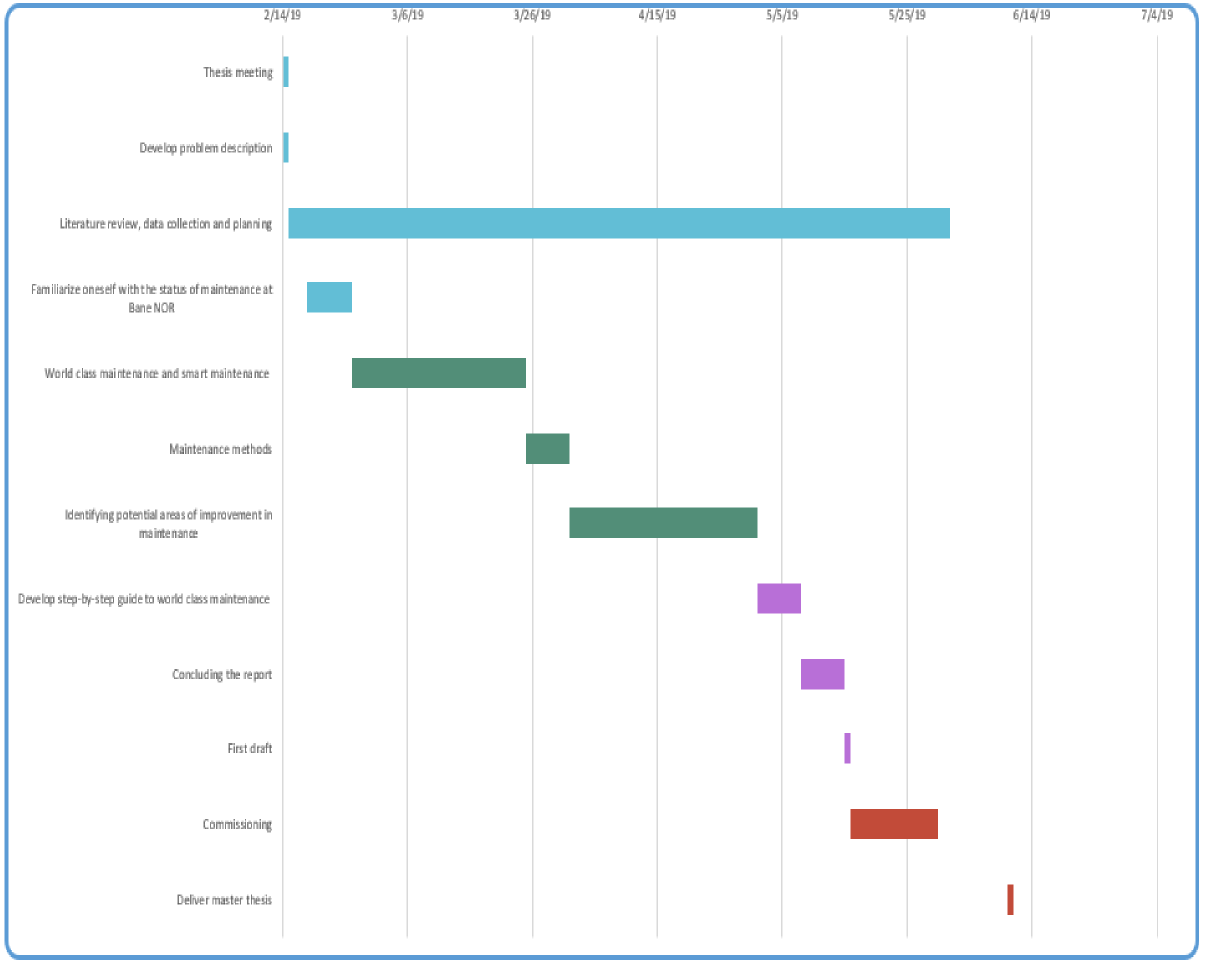
Cost, Time and Resources (CTR)			
Thesis tittle:			Revision date:
Smart Maintenance			14.02.19
Work package:	Work package title:		Responsible person:
9	Commissioning		Joachim Flesjå
Work tasks:			
- Proof reading - Develop summary - Refine layout			
Goal:			
- Prepare final version of the master thesis			
Focus areas:			
- Checking references - Layout			
Literature and resources:			
- Academic papers and articles - NTNU professors - Meeting summary from supervisors			
Work method:			
- Data collection and study - Interviews - Document reviews			
Challenges:			
- Obtaining and implementing constructive comments to the report			
Outputs:			
- Finalized thesis			
Estimated time and resources			
Scheduled start:	Scheduled end:	Workload:	Duration:
16.05.19	30.05.19	80 hours	14 days

Appendix C – GANTT diagram

Name	Start	End	Duration
Thesis meeting	14/02/2019	15/02/2019	1
Develop problem description	14/02/2019	15/02/2019	1
Literature review, data collection and planning	15/02/2019	01/06/2019	106
Familiarize oneself with the status of maintenance at Bane NOR	18/02/2019	25/02/2019	7
World class maintenance and smart maintenance	25/02/2019	25/03/2019	28
Maintenance methods	25/03/2019	01/04/2019	7
Identifying potential areas of improvement in maintenance	01/04/2019	01/05/2019	30
Develop step-by-step guide to world class maintenance	01/05/2019	08/05/2019	7
Concluding the report	08/05/2019	15/05/2019	7
First draft	15/05/2019	16/05/2019	1
Commissioning	16/05/2019	30/05/2019	14
Deliver master thesis	10/06/2019	11/06/2019	1

Start i nummerform	43510.00

Use this number for the Minimum Bound of the Horizontal Axis to set the beginning of the chart.



List of references:

1. NTNU. *Om NTNU*. 2019; Available from: https://www.ntnu.no/om.
2. NOR, B. *About Bane NOR*. 2017; Available from: https://www.banenor.no/en/startpage1/About-Us/.

Joachim Flesjå

Smart Maintenance in Bane NOR

NTNU
Norwegian University of
Science and Technology