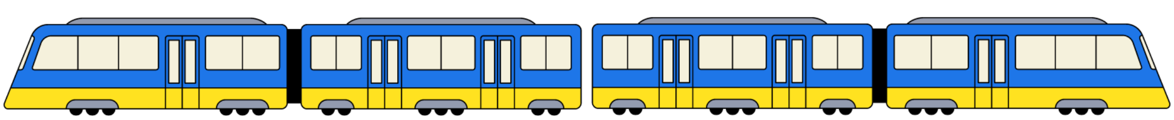
Digitalization: Everything starts with an A

EVALUATING THE IMPACT OF DIGITALIZATION ON THE MAINTENANCE STRATEGY OF DIGITIZED ASSETS

MSC THESIS



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ABSTRACT

KEYWORDS: Maintenance, Digitalization, Effect, Sensor, Asset

The number of digital systems that is used for business processes in many organizations is increasing. These digital systems can be used to support decision-making in the maintenance process. In this research the effects of digitalization on the maintenance process are evaluated. This is done by focusing on five aspects: actors, agreements, approach, applications and availability. By comparing the recent knowledge described in the literature with the experiences from practice, a maintenance aspect framework is designed. The experience from practice is obtained from conducting interviews at four organizations. These organizations are: NS (Nederlandse Spoorwegen), Port of Rotterdam, Rijkswaterstaat and ProRail. At each of the organization, one specific asset is selected for which the effects of digitalization are evaluated. The findings of the comparisons are reflected on the features of the asset and the organization to generalize the conclusions. Furthermore, an implementation plan and recommendations on how to use the framework to ensure that all the relevant aspects are included in future policies, are derived from the findings. The implementation plan is designed to be applicable in general, and the recommendations are made for NS specifically. In the recommendations, advice is provided on which aspects should be prioritized more and which aspects are already well formulated in the long-term plans. Lastly, a time line is presented in which the phases of the digitalization transition process are represented. The implementation plan can be used as a guideline to determine in which phase an organization is currently in, and what steps should be taken to proceed to the next phase.

PREFACE

Dear reader,

In front of you lies my master thesis, which documents my research about the effects of digitalization on the maintenance process of four public assets. This includes the Sprinter New Generation (NS), the RPA-12 inspection vessel (Port of Rotterdam), the Kreekraksluizen (Rijkswaterstaat) and the Kap van Barendrecht (ProRail). I enjoyed the research and writing process very much as it is a topic that is relevant in many organizations and processes.

During the research I had the opportunity to evaluate and learn more about the processes and operations of four organizations, which was very interesting. Furthermore, it offered the opportunity to investigate what the organizational structures and the modus operandi for each organization looks like. Furthermore, the context of the maintenance process allowed me to discover how many operational processes look like and I even visited Watergraafsmeer, one the of the maintenance facilities of NS. Therefore, I want to thank all the organizations that participated in the case studies. I also would like to thank NGInfra to give me the opportunity to present my proposed research to potential organizations for the case studies.

I want to thank my supervisors for their support and input that they provided during the research process. I want to thank Wijnand Veeneman for the time and effort he took to guide me when the research was shifting in a different direction. I want to thank Niels van Oort for the critical yet useful feedback he provided. Furthermore, I want to thank Milan Toet for making me feel comfortable at NS and giving me a enjoyable experience at the NS office. More importantly, I want to thank all my supervisors for amount of freedom they provided and with that the encouragement to let me discover what does and does not work for my research.

Lastly, I really want to thank my friends and family for their love and support.

In conclusion, I had a great experience and I am really thankful for the opportunity that I could have a look behind the scenes in such a large company. Furthermore, this experience helped me to develop new skills and helped me to determine where my interests lie for my next challenge: a new job!

I hope you enjoy reading this thesis as much as I had writing it.

Eleanor Thelen

EXECUTIVE SUMMARY

Introduction

In today's society, digitalization is making information and data more readily available. This trend is seen in the emergence of concepts such as "Smart Cities," in which data and information are used to create human-centred urban environments. These concepts rely on sensors, networks, and wireless connections, all part of the Internet of Things (IoT), to generate data. The data can be used for two purposes. It can ben used to enhance efficiency of everyday processes, and also to predict when maintenance is required. However, the maintenance of the data-providing sensors, networks, and connections themselves is often overlooked. The maintenance of sensors is important to guarantee a level of reliability, which makes it possible to base decisions on the acquired data. In order to determine why this aspect is often overlooked and what challenges arise during the maintenance process of digital systems, the effects of digitalization on the maintenance process of digitized assets are researched.

The study will use four examples of assets at different organizations: the sprinter new generation (SNG) at Nederlandse Spoorwegen (NS), the RPA-12 (Rotterdam Port Authority) at the Port of Rotterdam, the Kreekraksluizen at Rijkswaterstaat and the Kap van Barendrecht at ProRail. The effects that are experienced in practice will be compared to what is stated in current literature to determine why the maintenance process of digital systems is not included in research often and what challenges play a role.

The research approach is structured in the following way. First, representation of the problem context is sketched to investigate which challenges play a role and which aspects are known and unknown. Next, a literature review is done to create an overview of the available knowledge and to determine which aspects have an effect on digitalization of the maintenance process, according to the literature. This knowledge is translated into a framework which will be used as a base for the interviews for the case studies. The outcomes of the interviews will be reflected on the information that is stated in the literature. Based on the similarities and differences the framework is adapted and a implementation plan is created. Furthermore, a general description of the digitalization transition process will be made, in the form of a timeline, in which all the case studies will be plotted. The research is concluded with the conclusions that can be drawn from the findings.

Problem identification

Because of the developments in and surrounding everyday operations, the maintenance process of digital systems requires adaptations, compared to the convention maintenance strategy for analogue or mechanical components. This is due to 7 main reasons. A visualization of these reason is represented in figure A.

First, the process of maintenance is present in many parts of the business processes, because many components need maintenance in order to maintain smooth operations. As a result, many actors are involved and many processes will be affected by changes in the maintenance process. This also means that agreements and interactions between the actors will change. Furthermore, the development cycle of digital systems is shorter compared to analogue systems, which means that the interval of the maintenance process has to be aligned resulting in a higher maintenance frequency. The shorter development cycle also means that the specifications for digital systems have to be set closer to the release of the system. Otherwise, the system will be outdated once the system is operational.

Another aspect that required a change to the maintenance strategy are the performance indicators. Availability is important for every asset of an organization. Digital systems allow different measuring methods for performance indicators, but also require different indicators. Also, digital systems are often new which requires new knowledge from the users and people that have to schedule and execute the maintenance activities. Furthermore, a new system requires effort time to get used to the system, which could result in aversion towards the system. A new system also requires different tools and procedures to do the maintenance activities. These tools and procedures are specifically designed for a system.

Lastly, digital systems have a twofold role: they are used to support the maintenance strategy, but the system itself has to be maintained as well, in order to guarantee data quality. The latter can be challenging as it is complex to determine the failure curve of a digital system, because it often contains a random failure component. This makes preventive maintenance difficult to apply.

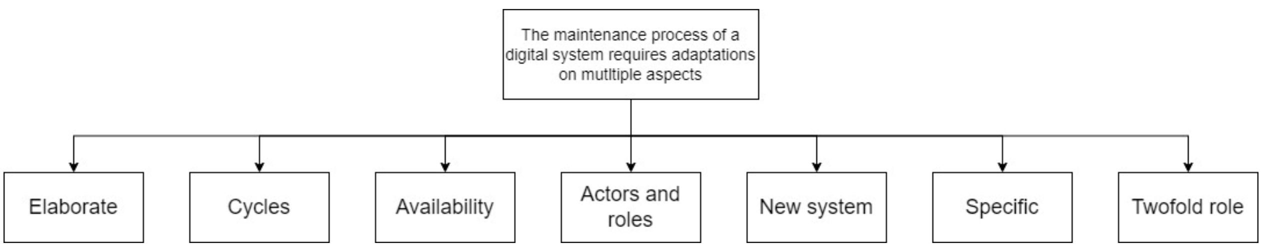

Figure A: Problem Context visualization (own work)

Based on the problem cluster, presented in figure A, the following research questions have been stated. The problem cluster mentions several aspects that play a role in the maintenance process of digitized assets. However, these research questions will be used to create an complete and valid overview of all the aspects that play a role according to the literature and the experiences from practice.

“What is the effect of digitalization on the maintenance strategy of large public assets?”

1. What are the standards and definitions of the maintenance process in the current literature?
2. What are the differences between the traditional maintenance approaches for mechanical and analogue systems and digitized systems according to the literature?
3. What is effect of digitalization of the asset on the maintenance strategy of a public asset in practice?
4. Which findings from the case studies can be translated into recommendations for the maintenance strategy of train operators, such as NS?

Framework

The current body of literature identifies five crucial aspects that must be taken into account when assessing the maintenance process. These aspects include the actors, agreements, approach and applications and the availability. Digitalization, as discussed in the literature, has a significant impact on these aspects. In this research, all of these aspects are integrated into a comprehensive maintenance aspect framework, presented in figure B. This framework serves as a tool for evaluating the practical implications of the effects discussed in the literature, while also evaluating the relationships between these aspects and the observable effects.

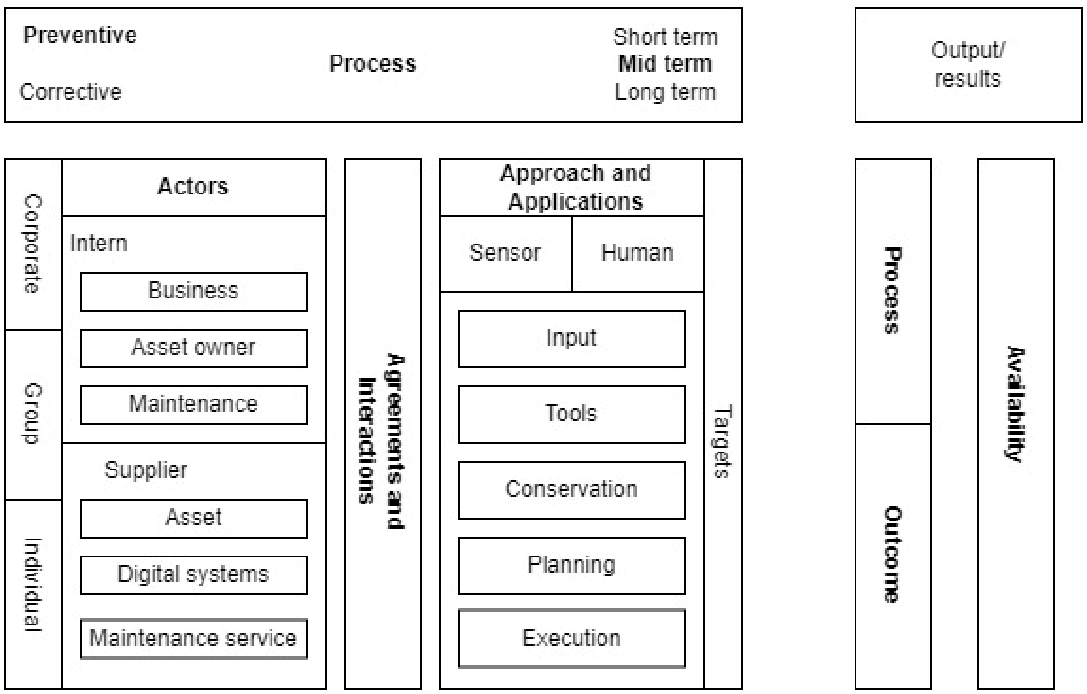

Figure B: Maintenance aspect framework (own work)

By interviewing actors that are involved in the maintenance process in four different organizations, the effects that are mentioned in literature are evaluated in practice. The goal is to find differences and similarities between the experiences in practice and the information that is stated in the literature. This way the information in the literature is either supported, or questioned, which contributes to the quality of available knowledge in the literature. In the interviews many interesting findings have been gathered. These findings consist of examples and experience with data use in practice, current challenges and future plans and the role of data in these future plans. The interviews were also used to validate and verify the framework by assessing whether the framework is useful and complete.

Case studies

Four cases were selected to be included in the research: the SNG (Sprinter New Generation) of NS, the RPA-12 (Rotterdam Port Authority) at the Port of Rotterdam, The Kreekraksluizen at Rijkswaterstaat and the Barendrechttunnel at ProRail. The interviews provided much information, and several insights can be derived from these interviews.

There were similarities between the findings from the interviews and the literature. Examples of these similarities are the importance of communication with external suppliers as a part of these different contracts was visible during the interviews and in the literature reviews (van den Boomen et al., 2012). Furthermore, the trade-off between reliability and costs was clearly noticeable. The literature describes this as the base for an optimal maintenance policy (Coetzee, 1999), which is relevant for the approach aspect, in which focus was on two points. First, the considerations about the maintenance activities and how these should be prioritized and executed. Secondly, the sensor selection and which data and information is currently relevant. Higher reliability often corresponds with higher costs, and so it depends on the requirements and goals of the organization what the required reliability level is, or how much they are willing to pay.

The four organizations were considered to be in similar position in the transition process in which the shift from a combination of corrective and scheduled preventive maintenance towards condition-based preventive maintenance plays a central role. The aim of all four organizations is to reduce the number unexpected failures and therefore to have no corrective maintenance activities. A general timeline was made, which includes the phases and activities that organizations go through during the digitalization transition. All four organizations were plotted in the timeline, which can be seen in figure C. The line in the figure follows a stairs-like pattern, which represents the challenges or processes an organization needs to overcome. When a phase has been completed, a higher level of digitalization is reached.

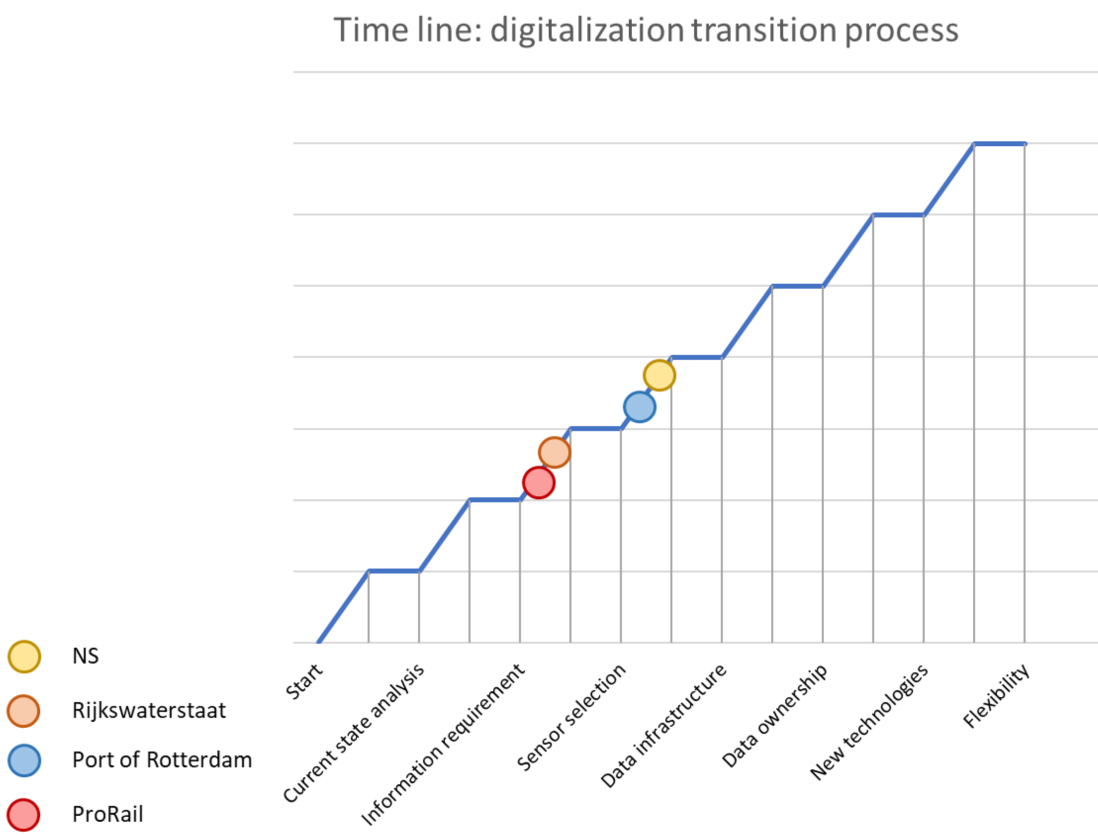

Figure C: Digitalization transition timeline (own work)

Despite the similarities between the literature and the effects in practice, some differences have been identified as well. The main difference is the focus on having a uniform strategy and vision, which is noticeable throughout the entire company and the decisions. To some extent, a general vision was mentioned during the interviews, but the focus on this vision was not as present as it should be according to the literature. Moreover, the process of how the vision is translated into decisions was often unclear. According to the literature, the objectives are one of the three instruments that is essential for successful asset management (van der Velde et al., 2013)

Data quality was not considered as a high priority during the interviews. The relevance of data quality was clear, but it was considered to be an issue that will be dealt with once the data infrastructure is ready. However, it is suggested in the literature that data quality has to be considered simultaneously as part of the data infrastructure, to guarantee that the data from the sensors is useful and reliable for basing maintenance-related decisions on.

Furthermore, based on the feedback from the interviews some adaptations to the framework have been made. The main change was done to increase the memorability of the framework, in order to recognize the aspects and to consider the effects. This was done by phrasing the aspects in the framework in such a way, that all the aspects start with the letter A.

Implementation plan

Based on timeline, an implementation plan is created to guide organizations towards the next phase in the time line. Along with the framework it can also be used to check whether all the relevant aspects of the maintenance process of digitized assets have been included in policies and long-term visions. The implementation plan follows the same structure as the framework and is therefore divided into the following sections: process, actors, agreements and interactions, approach and application and availability. In each sections, specific action and questions are stated to guide organizations through the process and let them make the right considerations.

Conclusion

To conclude the research, the main research question was answered and recommendations for NS have been provided. These recommendations are based on the reflections that have been on the maintenance vision document. These reflections are translated into recommendations for NS on where the vision might need more attention and which aspects are already well formulated based on the findings from the literature and the interviews.

The answer to the main research question “What is the effect of digitalization on the maintenance strategy of large public assets?” was explained by looking at five aspects: actors, agreements, approach and applications and availability.

Actors: Actors involved in maintenance processes need a deeper understanding of IT systems, and the challenge lies in connecting existing asset mechanisms with IT systems to ensure data reliability. Furthermore, actors need to have to trust the data base their decisions on the data with confidence. So, if the data states that maintenance actions have to be taken, this needs to be done, even though the experience of the actor would suggest to do it differently. Digitalization also results in additional and different tasks for these actors. Data analysis was considered the most important aspect. Data analysis is a crucial component of the maintenance process. It is often conducted by either the service provider or the organization itself. By combining the knowledge of the mechanical system and the knowledge on IT-systems, high quality and accurate data analysis can be done. This allows to increase the confidence that the actors need to have in the data to be able to base the decisions on the analyses based on the data.

Agreements: Agreements have become more long-term, with increased supplier involvement early in the process. This can be considered as an advantageous development, as the earlier involvement results in more considerations about the maintainability of the design of the assets. Furthermore, the long-term agreement also results in involvement of the supplier later in the process, which allows to use the knowledge of the supplier during the life cycle of the asset. Data ownership and sharing agreements are also key aspects, which have to be included in the contracts between the involved parties.

Approach and Applications: The approach has shifted from corrective to preventive and predictive maintenance, supported by sensors and data analysis. An important development of digitalization which was already observable was the possibility to digitally record maintenance actions, providing a real-time asset profile.

Availability: In the short term, data analysis may lead to increased maintenance needs, due to unexpected insights in the state of the asset. In the long run, using data optimizes maintenance planning and enhances asset availability. Digitalization was therefore considered as beneficial to the organization in the long term.

In addition on the conclusions, based on the maintenance aspect framework, some additional takeaways can be noted. First, organizations seem to have a positive attitude towards digitalization and the expected result on the availability of the asset. This shows that a potential aversion towards new systems might not play a large role.

Furthermore, the outcomes of the case studies were often in line with what was presented in the literature. Nevertheless, there was one example in which the expected effect was not in line with the actual effect of digitalization. The number of maintenance cycles is expected to increase, as digital systems have to be updated regularly. In the case of the Port of Rotterdam the number of cycles has decreased based on the data, which was unexpected. After a more detailed research, this difference could be explained. The reduced maintenance interval is a short term effect. Moreover, the reduction is not related to the maintenance of the digital system and the higher update frequency. It is therefore expected that once more digital systems have been implemented in the vessels, the maintenance frequency increases again. This examples showcases that the effects of digitalization are long-term effects and are often not noticeable yet.

Contributions

Given the novelty of the digitalization process, there exists limited literature that describes the exact process. Moreover, organizations fill in this process differently, tailoring the steps specifically on their own targets and goals. Nevertheless, a general similarity exists in the overall process, which is represented by a time line. Such a timeline, or description of the entire digitalization process has not been presented in current literature yet.

Furthermore, the maintenance aspect framework provides an overview of the relevant aspects of the digitalization of the maintenance process. Each of these aspects has been described in the existing literature, but a combined overview has not been presented yet. Furthermore, this overview can be used as a guideline by organizations for developing policies and long-term visions, which is a contribution to the practical use of this thesis.

The assets have been compared based on the features of the assets and the organizations and one finding in particular is interesting to mention, as it is an interesting starting point for further research. This research shows a potential connection between the following features: the tendered maintenance, the categorization of the assets and the number of types of assets, owned by these organizations. It is expected that maintenance is outsourced, because of the numerous types of assets, or the location of the asset, because it could require too much specific knowledge and resources to be able to manage the maintenance process from within the organization that owns the asset.

Lastly, the added value of the role of asset user is argued in this research, which is not covered in the current research yet. Currently, it is only described that the role exists, so research on the added value of this particular role could be interesting. Especially, since this role only exists at NS. Moreover, there is potential for further research into the effect of digitalization on the asset management roles in general, and whether these roles and responsibilities evolve with the digitalization transition.

LIST OF ABBREVIATIONS

AI	Artificial Intelligence
APM	Asset Performance Management
AR	Augmented Reality
CAF	Construcciones y Auxiliar de Ferrocarriles
CBM	Condition-Based Maintenance
COB	Centrum voor Ondergronds Bouwen, Centre for Underground Construction
CT&U	Civiele Techniek & Utility, Civil Engineering & Utility
D&IT	Data and IT
DDAM	Data Driven Asset Management
DHMR	Divisie Haven Meester Rotterdam, Harbor Master
DO	Dagelijks Onderhoud, Daily maintenance
ECM	Entity in Charge of Maintenance
ERTMS	European Rail Traffic Management System
FMECA	Failure mode, effects, and criticality analysis
HCC	Haven Coordinatie Centrum, Port Coordination Centre
IoT	Internet of Things
IT	Information Technology
KCO	Kort Cyclisch Onderhoud, Short-Cycle maintenance
LCO	Lang Cyclisch Onderhoud, Long-Cycle maintenance
MTTR	Mean Time to Repair
N&O	Netwerkontwikkeling & Ontwerp, Network Design & Development
NS	Nederlandse Spoorwegen
OEM	Original Equipment Manufacturer
ORA	Optimal Risk Analysis
OT	Operational technology
PGO	Prestatie Gestuurd Onderhoud, Performance-Based Maintenance
Pin	Performance Indicator
POSMAD	Plan, Obtain, Store and Share, Maintain, Apply and Dispose
PPO	Programmas, Projecten en Onderhoud, Programs, Projects, and Maintenance
RAMS(HE)	Reliability, Availability, Maintainability, Safety, Health
RBI	Risk-Based Inspection
RCM	Reliability Centred Maintenance
ROI	Return on Investment
RPA	Rotterdam Port Authority
RTM	Real Time Monitoring
SAMP	Strategic Asset Management Plan
SDLC	Systems Development Life Cycle
SLA	Service Level Agreement
TD	Technische Dienst, Technical Service
TVTA	Te Verklaren Trein Afwijkingen, Train deviations to be explained
VDM	Value Driven Maintenance
VR	Virtual Reality

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1 Introduction

1.1. Emerging digitalization

Information and data are becoming increasingly available in the current society, as a result of digitalization of society. Concepts like ‘Smart Cities’ are emerging, in which information and data are used to create a human-centred urban environment (Verhulsdonck et al., 2023). The entire system is built on sensors, networks, wireless connections and so on, which generate a lot of data. These are all part of the concept of Internet of Things (IoT) (Ghazal, et al., 2023). In addition to creating efficient environments, the concept of IoT is used to predict when maintenance is required (Soori et al., 2023). One issue that seems to be neglected when discussing these topics is how the data-providing sensors, networks and connections itself should be maintained. An important aspect of a digital sensor is that it is often hard to determine when the sensor is failing and consequently providing incorrect information. This is essential to make sure the data is reliable in order to be able to use the data for business operations, such as a maintenance planning for an asset. The solution is often to install multiple sensors, to ensure that at least one is working. This results in more data flow and leads to challenges involving the quality and the reliability of the data.

The research will evaluate which aspects of the maintenance process of assets are influenced by the digitalization transition, and how these aspects are influenced. Furthermore, the use of sensors in the maintenance process for these assets is evaluated and the issues that arise with the maintenance of these sensors itself will be discussed. This research will specifically focus on the influence of digitalization on the maintenance of large public assets, as the research is done for NS (Nederlandse Spoorwegen).

Figure 1 shows a visual representation of the research context in which the relationships and the corresponding questions are included. Digitalization is the main process that is being investigated. The effect of digitalization on maintenance is evaluated, by considering the aspects that play a role. Furthermore, the increasing number of sensors as a result of digitalization is evaluated. The effect of the increasing number of sensors and the method for maintenance of the sensor itself is researched.

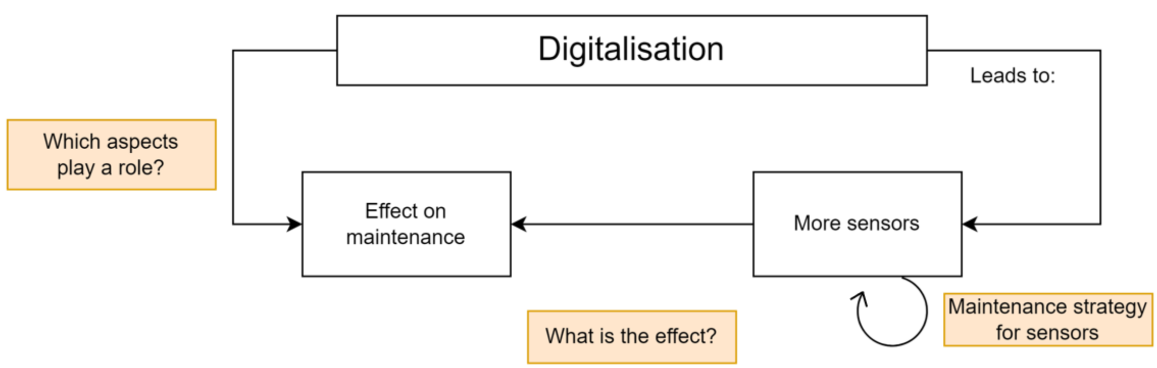

FIGURE 1: RESEARCH CONTEXT (OWN WORK)

1.2. Problem Identification

Digitalization plays a role in multiple perspectives of the maintenance cycle. This section addresses the issues that occur in each of these perspectives. Furthermore, a problem cluster is presented to determine how these problems are related to each other and how solving one problem can affect other problems as well.

First, digital systems can be used in many parts of the operations and business processes. This results in the fact that the maintenance process of these digital systems can affect different parts of the operations and business processes as well. This issue will become more apparent as the issues are listed in this section, or in the problem cluster in the next section.

Digital systems require a different maintenance frequency, compared to physical assets. Digital systems are developed and improved very quickly which results in the fact that systems can be outdated even before they are implemented. Large public assets often have a long tendering period, which means specifications have to be set early in the process. This can be conflicting with the high frequency in which the digital systems are developed, resulting in the risk of including a system that is already outdated. This risk is much higher for digital systems compared to the analogue systems. Furthermore, when the asset with the digital is in use, this effect is still relevant, as the maintenance cycle should be adapted to the shorter cycles in which the digital systems need to be updated.

Availability is important for all public assets. The process of digitalization also has an effect on the availability and how it is measured. Other performance indicators have to be used to measure the availability and considerations have to be made on how the measures are done, how required performance levels should be defined and what strategies will be used to reach the specified goals. For example, the information from sensors can be used to determine whether maintenance is required. This could lead to less maintenance moments, compared to the traditional cycles. Less maintenance moments means that the train be used for the operations, which could lead to a higher availability. Another example for this challenge is that availability is not only measured in the percentage of the time the trains are one time but can also include minimal number of unexpected failures or less maintenance moments in general.

As mentioned earlier, digital systems are present in many parts of the business processes and operations. This means that many different are involved in the usage of these digital systems and the maintenance process of these systems. Compared to the old situation, more people and different people are involved than before, which requires different agreements and relationships between the involved actors. This occurs internally within companies and with external actors as well. An example of this challenge is that companies might outsource the maintenance activities to other companies, or the supplier of the system, because they do not have the required knowledge. This results in different and more long-term agreements, or service level agreements.

Companies also have to consider new aspects in the way of working. This could relate to agreements and operations, and examples can be issues like data ownership of all the data that is generated by the sensors, or what are the required performance levels and how is the data used to determine the performance levels.

Furthermore, digital systems are often new for the people that have to work with the systems. People are often not used to digital systems yet, they could have an aversion for IT systems, or they are more comfortable with the current way of working. Nevertheless, the transition towards digital assets is already taking place, which means people have to get used to the digital systems. This requires time to get used to the new system, but also aspects like education and training are important.

Furthermore, certain systems are specifically produced for a purpose in the operation and could therefore require a specific maintenance strategy. In other words, it depends on what system and what specifications are used to design a proper maintenance strategy. For example, ERTMS (European Rail Traffic Management System) is a safety system (ERTMS, sd) (European Union Agency for Railways, 2023). Therefore it is crucial that all the components work properly at all times. If this is not the case, the train will come to a halt. Therefore, a precise maintenance strategy is required to ensure a well-functioning system without failures. Systems that are less prone to result in safety-related risks when a failure occurs, might require less intensive maintenance. For example, when the tv screens in the trains are not working, the train is still operational.

An important difference between digital systems and traditional analogue systems is that digital systems do not follow the same failure curve as mechanical systems. For digital systems, there is a random failure component, which makes it harder to predict when a failure will occur. This means that preventive maintenance strategies often do not work for maintaining the sensors itself. Therefore, if digital systems are included in safety-related systems, such as ERTMS, it is very challenging to guarantee that the system will never fail. Proper maintenance and other practices, such as redundant systems, are essential for continuous operations.

The presence of digital sensors in the maintenance process of digitized assets plays two roles in the context of this research. On the one hand, the digital sensors are used to monitor the performance and status of the asset, to apply data-driven maintenance. On the other hand, these sensors have to be maintained themselves in order to keep the ability to act on the data to perform (data-driven) maintenance, for which data quality is essential. Data quality can be measured by specific indicators, which have be set in advance by the organization. Determining these indicators can be a complex process, because the indicators to measure digital data are different compared to measuring analogue data.

1.2.1. Problem cluster

To clarify how the problems and challenges that are mentioned above are related to each other, a visual representation is made. This can be found in figure 2. A more detailed version can be found in appendix II. The visual representation allows to add a structure and hierarchy to the problems to establish causal relationships between the problems. For example: a digital system is often new and unknown, which results in the problems that people need to get used to the system, which can take time. Furthermore, new systems can lead to aversion, or people need to change their mindset towards the system and the related activities. Lastly, the new system requires new knowledge and materials, which might be difficult to acquire.

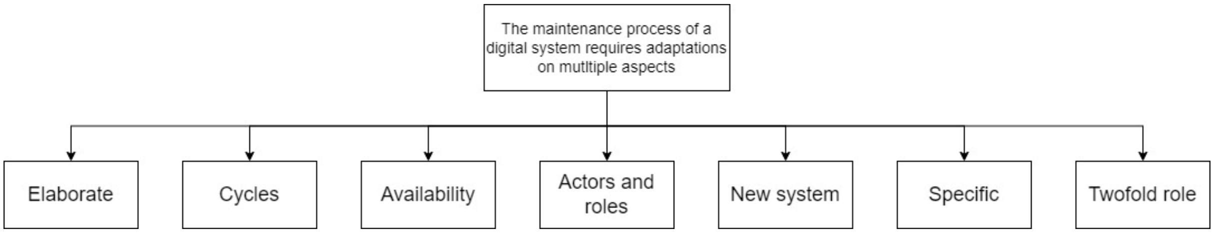

FIGURE 2: PROBLEM CLUSTER: VISUAL REPRESENTATION OF IDENTIFIED PROBLEMS AND CHALLENGES (OWN WORK)

1.3. Research design

The main perspective of the thesis is to determine what effects play a role in maintenance process for large public asset changes as a result of digitalization. These effects will be identified from literature and real-life examples, using case studies with other asset owners that have implemented a similar digital system in their existing operations. The research will be concluded by translating the relevant factors into recommendations for the maintenance strategy of NS.

A literature research is used to determine which aspects play a role in the design of a maintenance strategy and which aspects are affected by the digitalization transition. Furthermore, the standards and recommendations for these aspects are gathered and translated into a framework. This framework forms the basis for the interview questions that are used for the case studies. The case studies are used to determine the similarities and differences between what is written in the literature and what is experienced in practice. The case studies are done at companies inside and outside of the railway sector. This is done to determine if effects are related to the sector in which the asset operates. The main similarity for all case studies is that all assets are operational in the public domain. The outcomes of the interviews are systematically compared to determine potential best practices. On the one hand, the results will be included in a scientific paper as an addition to scientific literature. On the other hand, the results will be translated into potential recommendations for NS and other asset owners to deal with the digitalization process.

This section addresses the research questions that are derived from the problem context and the problem cluster, presented in section 1.2. It will be explained how the questions are derived and what methodology will be used to design a solution for the problem.

1.3.1. Main Research Question

The aim of the research is to determine how the maintenance of large public assets is affected by digitalization, considering the issues that have been identified in section 1.2. The main research question is therefore stated as:

“What is the effect of digitalization on the maintenance strategy of large public assets?”

By considering all the individual aspects (cycles, availability, actors, interactions, system, and the twofold role of digital system) and comparing the situation before and after digitizing the asset, the effect is demonstrated. The main research question is not focused on the rail sector specifically, because the use of case studies outside the rail sector allows for findings that might not apply for the rail sector, but also more generally.

1.3.2. Sub-Research Questions

To answer this question, several sub-research questions are formulated. These are used to answer the main research question in a step-by-step approach. The aim of the sub research question is to create a clear vision on what the maintenance strategy looks like, and should look like according to the literature, before and after the asset is digitized. This way both situations can be compared, and the effect of digitalization can be evaluated.

The research is started by investigating what is stated in the literature about the definition of maintenance and which standards are described. Furthermore, the role of data and sensors is evaluated for this question as well.

1. What are the standards and definitions of the maintenance process in the current literature?
    a. Which standard maintenance approaches are known?
    b. How has maintenance developed over the years?
    c. Which new concepts have emerged from these developments?

The second sub-research question is focused on the differences between the maintenance approach for traditional mechanical or analogue systems, and the newer digital systems. The questions specifically focus on the aspects that have been identified in the problem cluster, but also aims are determining whether these provide a complete perspective, or that aspects are missing.

2. What are the differences between the traditional maintenance approaches for mechanical and analogue systems and digitized systems according to the literature?
    a. What is stated in the literature about?
        i. Maintenance cycles, intervals, and frequency
        ii. Actors and the roles of the actors
        iii. Interactions and agreements
        iv. Developments of the maintenance activities
    b. What other aspects should be considered according to the literature?

The third sub-research question is answered by the interviews conducted for the case studies. The goal is to determine what the maintenance approach looked like in practice before and after the digitalization of a specific and what effects could be observed. The description of the process is determined by the factors that have been established in the second research question. This is done to make sure that the results can be systematically compared. This question also focuses on the effect of the digitalization on the availability of the asset. Generally, this is the main performance indicator for an asset, which makes it an interesting measure to determine whether digitalization has a positive or negative effect.

3. What is effect of digitalization of the asset on the maintenance strategy of a public asset in practice?
    a. What does the maintenance process look like before the asset was digitized?
    b. What does the maintenance process look like after the asset was digitized?

   c. What are the key differences between both processes?
   d. What is the effect of digitalization on the availability of the asset?
   e. What challenges arise as an effect of digitalization related to the maintenance strategy of public assets?

The research is concluded by answering the main research question and translating the findings into recommendations for NS. In this question, the general findings from the case studies are included. Furthermore, findings that might only apply for the rail sector are included in the recommendations for NS and in the solution to this question.

4. Which findings from the case studies can be translated into recommendations for the maintenance strategy of train operators, such as NS?
   a. To which extend would implementing the findings improve the maintenance operations of NS?

1.3.3. Methodology

This section addresses the proposed methods to find the answers to the main and sub research questions. For each question, the research design is explained, and the potential risks and limitations of the proposed method is discussed. A summary of the proposed methodology can be found in table 1.

Research Question	**Proposed Methodology**
What are the standards and definitions of the maintenance process in the current literature?	Desk research: literature review • Identify which maintenance strategies can be distinguished. Use academic literature on specific categories or frameworks. • Determine the definition and role of data and sensors in maintenance. Use grey literature and academic literature. • Determine if (and how) different approaches are used in specific applications and if this can be generalized. For example: are certain industries always using the same approach? Use grey literature to look for examples.
What are the differences between the traditional maintenance approaches for mechanical and analogue systems and digitized systems according to the literature?	Desk research: literature review • Determine the role of the established list of factors. Use grey literature and academic literature. • Identify factors that can be added to the list. Use grey literature and academic literature. • Verify in academic literature if these factors have been identified already and check if the list of factors is complete.
What is effect of digitalization of the asset on the maintenance strategy of the specific asset?	Interview for Case Studies: use the framework as a guideline.

	• Visualize the maintenance process steps and sequence of process steps. • Identify the involved actors and their roles. • Determine the agreements between the parties and what interaction are made. • Determine which tools and sensors are used and how the input is used for the output. • Determine how availability is measured and how this is affected by digitalization. Desk research for Case studies: NS: NS SharePoint for documentation on processes and actors Other companies: Use documentation provided by the case study company, or available on the internet to support the findings from the interview.
Which findings from the case studies can be translated into recommendations for the maintenance strategy of train operators, such as NS?	Desk research on NS information and case study information. • Determine for each company the differences and similarities with NS, to determine to which extend the findings are directly applicable for NS. Use information from NS and the case study companies, gained from the literature and interviews with the employees. • Validate with NS employees if the recommendations would work in practice and determine the effect on the overall operations. Write down the specific tasks to create a roadmap for other companies to apply the lessons learned to their own company as well.

Each of the proposed methods comes with risks and limitations. This section will briefly address these risks and limitations and will describe how these will be mitigated.

The first research question is done using a literature review to determine the definition of maintenance and what standards are used. With this approach little risks are involved as this information is objective and can therefore not be misinterpreted.

The second research question also involves a literature review to determine the effect of the established aspects and to determine any missing aspects. A potential risk could be that relevant aspects are neglected, however because a systematic literature research is done this risk is assumed to be very small. This risk is mitigated even more because it is assumed that the relevant sources will provide similar information and the factors will be validated during the interviews with the case study companies. A potential missing aspect will be added in this phase of the research.

The third research question is answered with information acquired from interviews with employees from the companies that are selected for the case studies. A limitation of this approach could be that this can be time consuming because scheduling the interviews might not be very easy and fast. Furthermore, a potential risk could be that employees might not be able to share specific information, or that companies do not want to cooperate because of this limitation. This risk can be mitigated by having a clear communication and agreements with the companies, to make sure no unwanted information is shared. Furthermore, it can be assumed that the information for this research can be shared, which makes these risks very small.

The last research question aims at translating the findings from the interviews and the literature into specific recommendations for NS. Additional information on the similarities and differences on management, strategic and operational level between NS and the case study companies is required. This will be acquired by using information provided by the company via employees or shared databases.

1.3.4. Research goal and scope

The research goal is to fill the research gap, by identifying what the effect of digitalization is on the maintenance process of large public assets. This will be done by identifying the aspects that are derived from the problem context and potential additional aspects found in the literature. By building case studies in which the role of the aspects and the effect on the availability of the asset will be evaluated in practice. The aim of the research is to investigate and state which approaches are used and the reasonings behind these approaches. The aim is not to determine which approach works best and score the different approaches. Furthermore, new techniques are developed and are put into practice. Again, the aim is not to evaluate if the application of these techniques has positive results, or which technique works best, but the aim is to determine which techniques are used and what the effect in practice is.

These findings can be used to translate the 'lessons learned' from other companies into a general framework to fill the identified research gap and to set up recommendations for NS, which they can use to improve their transition process towards more digital systems in the rolling stock.

As an extension to the research goals and requirement, a research scope is defined to determine which aspects are included and excluded from the research. The research is scoped towards Dutch companies that own a large public asset, which is being digitized. Furthermore, the main focus is on the maintenance process of these assets. Within the selected companies, multiple business processes will change as a result of digitalization, but these are not considered.

1.3.5. Deliverables

As a result of this research, there will be three deliverables. First and foremost, the thesis is the main deliverable. This document will describe the research design, research execution, results, case study evaluations, implementation plan, conclusions and all the considerations that have been made in the research process. This will include the relevant aspects for the maintenance cycle and framework that is designed, based on these aspects. This framework and the conclusions from the case studies will be included an academic paper. This paper can be found in appendix I of this thesis. The paper will serve as an addition to academic literature as it focuses on the findings of the research that have not been addressed in the current research. Additionally, a list of recommendations will be created for NS, based on the findings of the case studies as this is the company that has provided the research context for this research. These recommendations will be this thesis' contribution to the practical field of asset management of digital systems at NS, and other companies with digitized assets.

1.4. Structure of the document

The document is structured in the following way. **Chapter 1** introduces the research context and describes the research questions and design. **Chapter 2** describes the theoretical framework and information that is obtained from the literature research, to answer the theoretical research questions. **In chapter 3,** the design process and the validation process of the maintenance aspects framework is described. **Chapter 4** provides a description of selection process for the case studies. Additionally, there is a description on the outcomes of the interviews for each of the aspects in the framework. The outcomes are translated into a comparison which is presented in **chapter 5.** This comparison is translated into a set of best practices in general, and for the rail sector specifically. **Chapter 6** describes the recommended steps on how to apply the best practices from chapter 5 in practice in an implementation plan. This is done for NS specifically, in the form of a list of recommendations and the related activities that need to be implemented. In **chapter 7**, the conclusion of the research is described, and all the research questions are answered. **Chapter 8** describes the discussion, including the limitations and the contributions of the research to the current literature and to practice.

2. Theoretical Background

This section describes the theoretical background for the research, and the theoretical research questions are answered. The chapter is structured in the following way: first a general explanation is given on the concept of maintenance. Standards, definitions, and categorization are explained. Secondly, information on the individual aspects from the problem context is evaluated and clustered into an overview. If additional aspects are considered to be relevant according to the literature, they are added in this section as well. Next, the concept of data management and data-driven maintenance will be explained in more detail. Furthermore, the definition of data, information and knowledge is established. The concept of sensors and data providers is scoped in the theoretical framework as well. The chapter is concluded with the definition of a digitalization process. These findings will form the basis of the framework that will be described in chapter 3.

2.1. The definition of maintenance

There are many descriptions of the definition of maintenance, but all the descriptions practically cover the same aspects. According to Karki et al. (2022), maintenance can be described as the "activities that are executed to keep a product in a reliable state and operable. This is done by repairing faults, regulating the environment in which the product operates, and anticipating potential risks and mitigating these risks".

The aim of the research is to determine which aspects play a role in the digitalization process of the maintenance strategy of a large public asset. First, it is relevant to analyse the general concept of maintenance and what it consists of. This section describes the maintenance standards and the development towards digital maintenance. Additionally, the maintenance aspects that have been identified in the problem context. Furthermore, the list of aspects is extended with aspects that are relevant according to the existing literature.

2.1.1. Maintenance standards and categorization

In the literature, a general categorization for maintenance strategies is described. Lind and Muyingo (2012) describe a model, which is based on the EU standard (EN13306). A visualization of the model can be found in figure 3.

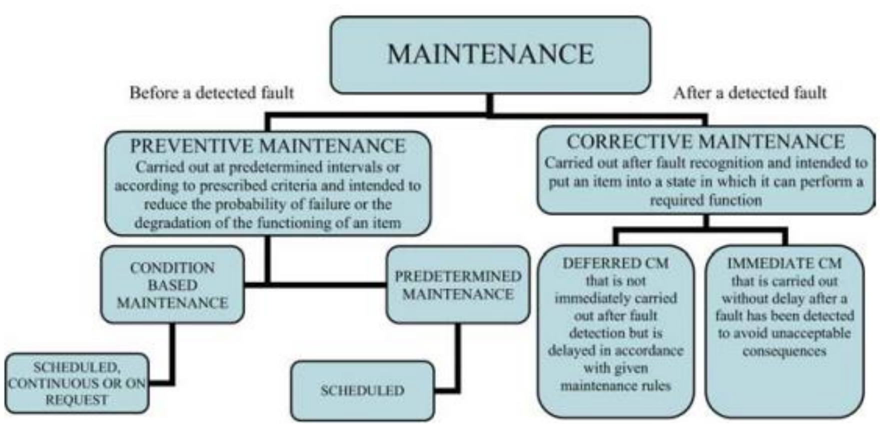

FIGURE 3: OVERVIEW OF MAINTENANCE IN EN 13306 (LIND & MUYINGO, 2012)

Traditionally, maintenance is divided into preventive and corrective maintenance. Preventive maintenance is based on doing repairs or replacements before a potential breakdown has occurred. Corrective maintenance on the other hand, is failure based, and focuses on repair or replacement activities as soon as a failure has occurred (Lind & Muyingo, 2012). As can be seen in figure 3, the main difference between the two types has to do with the fact whether the maintenance activities are done before, or after the failure has occurred. As mentioned in section 1.3.4., the scope of this research is set at focusing on preventive maintenance. Therefore, the rest of this section will focus on preventive maintenance.

Preventive maintenance can be divided into two categories as well: condition-based maintenance and predetermined maintenance. The maintenance is either based on the condition of a part, or the maintenance is done after a specific amount of time has passed, regardless of the condition of the part. The frequency of both types can be scheduled, continuous, or on request (Lind & Muyingo, 2012).

In the research context of maintenance various terminology is used to define the different elements of maintenance. Kobbacy & Prabhakar Murthy (2008) distinguish three terms: maintenance actions, which are the tasks that are executed; maintenance policies, which are the triggers for the maintenance actions; and maintenance concepts, which is the logic and the set of policies and procedures that are used to do the maintenance. Figure 4 shows how these terms are further divided.

Maintenance actions are either corrective or precautionary. This division is consistent with the distinction that is made in figure 3, in which it is described as preventive (before breakdown) or corrective (after breakdown) maintenance. Kobbacy & Prabhakar Murthy (2008) describe five generic maintenance policies. These are failure-based, time-based, condition-based, opportunity-based and design-out. Design-out maintenance refers to maintenance actions that are done to re-design or re-assemble the component, to prevent recurrent failures (Muganyi et al., 2018). This is again comparible with the division that is made in the diagram in figure 3, where it is divided into condition-based and predetermined maintenance. The last category are maintenance concepts which can be described as a combination of actions and policies to create the optimal maintenance prorgram (Kobbacy & Prabhakar Murthy, 2008).

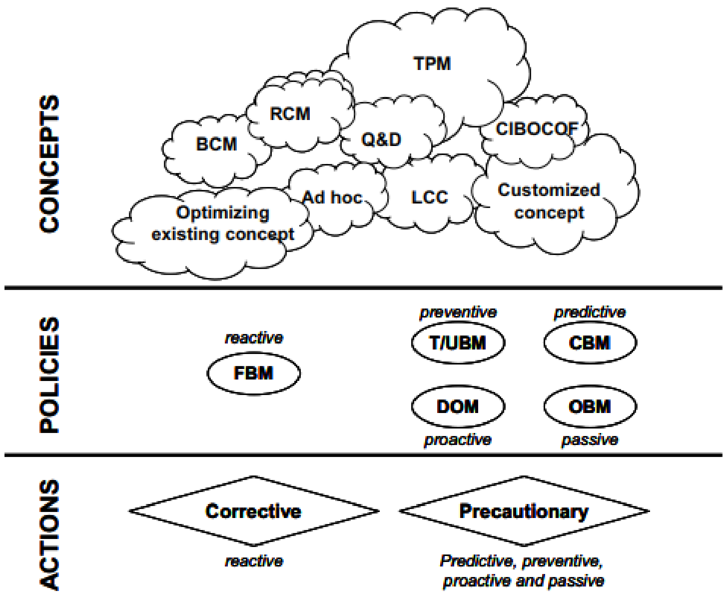

FIGURE 4: MAINTENANCE TERMINOLOGY (KOBBACY & PRABHAKAR MURTHY, 2008)

2.1.2. The development of maintenance

With the development of new technologies and improvements in current maintenance methods, more and more new terms are entering into the maintenance environment. In addition to the two main categories for maintenance types, corrective and preventive maintenance, a new category has been added: predictive maintenance. In this maintenance type, data from new technologies is analysed to predict when possible failures will occur (Karki et al., 2022). This requires continuous monitoring, data collection, data analysis and the use of diagnostic and prognostic tools.

The difference between the traditional maintenance approach and the digital maintenance approach has been visualized by Karki et al. (2022). This visualization is presented in figure 5. It shows multiple differences between the traditional approach and the digital approach. First, the digital approach consists of less activities and therefore takes less time from a human employee. The employee does not have to travel towards the site to investigate what is failing, and what causes the failure. Additionally, some feedback loops are required in the traditional approach, which can take some time as well. Furthermore, the point at which human intervention to repair, or visually inspect the component, is required much later in the process.

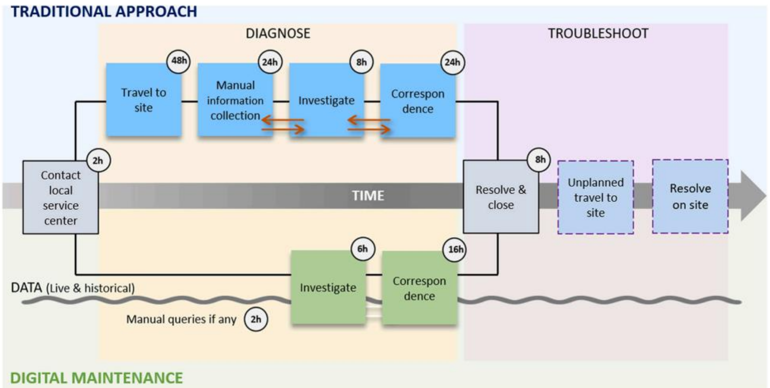

FIGURE 5: TRADITIONAL VERSUS DIGITAL MAINTENANCE APPROACH (KARKI ET AL., 2022)

The use of data and digital technologies is a development that returns in multiple aspects of maintenance. As mentioned earlier, maintenance is becoming more and more embedded in the operational chain, which means that maintenance is part of new strategies, or management method, in which the maintenance tasks and the increasing amount of available data are managed electronically (Muller et al., 2008). Maintenance plans are emerging, which is defined as a set of tasks. This includes the monitoring activities, the diagnosis and prognosis process, the decision-making process and control processes throughout the entire process. This is related to the new type preventive maintenance, in which the maintenance scheduled based on the available data. Maintenance support is also influenced by digital technologies by the fact that different parties in the process are able to communicate and share information in a smarter way (Muller et al.,2008). Examples are of these new plans and support are digital maintenance (Karki et al., 2022), e-maintenance (Muller et al., 2008) and Smartenance (FESTO, 2023).

According to Karki et al. (2022) the driving forces behind the development of digital maintenance are limitations and sustainability challenges. Examples of these limitations are the need to provide maintenance services in remote locations, the limited availability of information, economic loss linked to the unavailability of the product, or the halt in the operations. Because maintenance is embedded in the entire operational chain, it does not only consist of simple repairs anymore, which results in large effects when the maintenance is not done properly. Because of this embeddedness, digitalization of maintenance does not only result in modernized maintenance activities, but also in benefits for customers and positive sustainable impacts (Karki et al., 2022).

In addition to using data, collected through connected sensors creating an internet of things (IoT), and applying predictive maintenance, new technologies can be implemented. Marquez (2022) lists these new technologies such as the use of big data, predictive analytics, digital twins simulations, augmented reality and Business Intelligence and Data Visualization Tools. These innovations could support and upgrade the maintenance strategy in several ways, such as remote repairs, or creating optimization algorithms at high speeds. Also, developments are made in the maintenance activities. One example is the possibility of 3D printing new parts, which reduces down time and improves the productivity (ATS, 2023). It can be concluded that digitalization will be a long-term process, with a lot of possible developments.

2.2. Aspects that play a role in the maintenance process

This section will address the aspects that have been derived from the problem context. These aspects are a combination of maintenance actions, policies, and concepts. Furthermore, the literature is used to determine if this list of aspects can provide a complete view on what the maintenance strategy looks like and how it is affected by digitalization.

2.2.1. Maintenance cycles

Coetzee (1999) describes how a maintenance cycle is created. It consists of two parts: the strategic process, represented in the outer cycle, and the operational process represented in the inner cycle. These cycles are visualized in figure 6. The strategic process consists of the management planning and the management measurement. The management planning process consists of sub-processes such as determining the maintenance policy, the maintenance procedure and objectives (Coetzee, 1999). The maintenance procedures can be seen as an extension of the maintenance policy, to make sure that tasks are aligned and standardized. The management measurements are aimed at evaluating the performance of the processes in the inner cycle of the process.

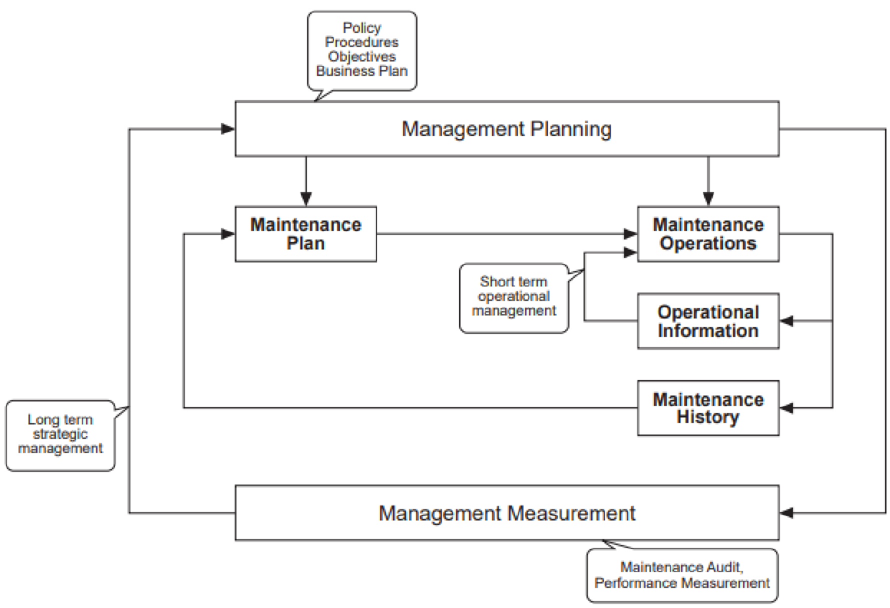

FIGURE 6: ESTABLISHMENT OF A MAINTENANCE CYCLE (COETZEE, 1999)

Faccio et al. (2014) propose an framework to determine the optimal maintenance policy. In their research, they describe the general phases of the establishment of a maintenance policy, which includes the optimal number of cycles. Furthermore, they propose the framework steps and which tools and methodolies to use in each step. These phases can be found in figure 7. It can be concluded that the optimal number of cycles can be determined based on the tradeoff between the reliability estimation and the estimated maintenance costs for the entire life-time of the specified parts and components of the system. It depends on the decision-maker and the parts or components of the system which number of cycles is selected.

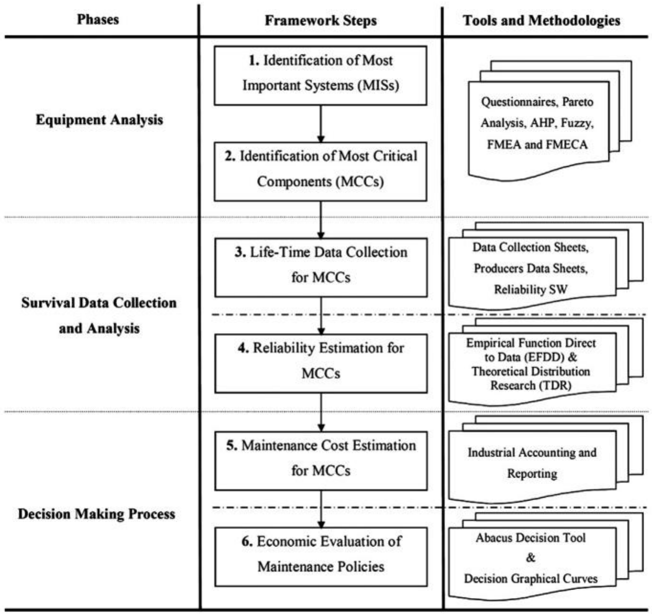

FIGURE 7: MAINTENANCE POLICY FRAMEWORK (FACCIO ET AL., 2014)

According to Singh et al. (2019), the initial maintenance strategy is designed based on Reliability Centred Maintenance (RCM) and Failure Mode Effect and Criticality Analysis (FMECA). Reliability Centred Maintenance is a systematic method to determine which preventive maintenance tasks are required (Rausand & Vatn, 2008). The method consists of 12 steps, which are executed sequentially to determine the critical parts and the required maintenance, based on the failure risks, which are identified by a FMECA analysis (Rausand & Vatn, 2008).

RCM and Risk Based Inspection (RBI) are used to guarantee operational reliability, availability, maintainability, and safety (RAMS). Recently, two factors are added to these RAMS requirements: Health and Environment, which results in RAMSHE requirements (van Dongen, 2015). In RBI, the three main goals are to define and measure risk (i), provide an overview of the potential risk for the organization (ii), use the probability of failure to optimize the inspection schedule (Bhatia et al., 2019). A combination of RCM, RBI and FMECA results in an inspection and maintenance schedule that is based on the potential failure risks of the critical parts.

The initial concept consists of a short-term and a long-term maintenance cycle. Furthermore, the maintenance is divided into preventive and corrective maintenance, in which preventive maintenance is divided into usage-dependent and condition-dependent maintenance. Usage-dependent maintenance is done after a number of kilometres, or a specific time has passed. Condition-dependent maintenance is done when the condition does not meet the pre-specified standards anymore. The inspection to determine the condition is done with a fixed frequency. Corrective maintenance is done once a failure occurs. This can be fixed during the next scheduled maintenance moment, or during an immediate maintenance moment (van Dongen, 2015).

An important feature of digital systems is the short development cycle, and thus the possibility to update the system often. Software is often developed using Software Development Life Cycle (SDLC) methodologies, such as rapid application development, joint application development, or agile development (Gillis, 2019). One common factor of these methods is using a short development cycle in which the feedback of the customer is constantly used as input to improve the product (Outsystems.com, 2023). Due to the short cycle, the product development process is very quick.

This, in combination with the idea of predictive maintenance, has an effect on the maintenance cycle. Instead of applying maintenance to the system at a predetermined frequency, maintenance is applied when it is required according to the data. Furthermore, the maintenance frequency can therefore be different throughout the life cycle of the system, depending on the required maintenance on a specific moment.

2.2.2. Actors and roles in the maintenance process

In the maintenance process, many actors are involved and similar to the standards for maintenance as a concept, there are standards for which roles should be included in the maintenance process in general. In the railway sector, when a vehicle is registered an ECM is assigned. ECM is short for Entities in Charge of Maintenance. In this approach, an entity is assigned to all railway vehicles to ensure that they maintain a safe state and are operational. The ECM provides a description of the maintenance strategy, which activities are included and how these activities are inspected. The maintenance activities can be outsourced, but the ECM will stay responsible at all times (ILENT, sd)

More general, van der Velde et al. (2013) mention three asset management roles. Firstly, the Asset Owner, who is responsible for making strategic decisions and the trade-off between long-term and short-term investments. Secondly, the Service Provider does the operational maintenance actions and is responsible for reliability, availability, maintainability and safety. Lastly, the Asset Manager is the link between the asset owner and the service provider. Van den Boomen et al. (2012) use the same three roles as the base for the roles in an asset management game. In the game, there are five roles: Engineering Manager, Operation & Maintenance Manager, Asset System Manager, Organization Manager (CEO) and a Customer Service Manager. In the game, the role of the Asset Owner is represented by the Organization Manager and the Customer Service Manager. The Asset Manager is represented by the Asset System Manager. The Service Provider is played by the Operation & Maintenance Manager and the Engineering Manager.

Singh et al. (2019) include a fourth role in the asset manager structure: the asset user. This structure is based on the ISO 55000 standards, which prescribes norms to divide tasks and responsibilities among the involved actors. The asset user determines the long-term plans, regarding network design, timetables and asset demands and employment.

FIGURE 8: ASSET MANAGER STRUCTURE (SINGH, MARTINETTU, MAJUMBAR, & VAN DONGEN, 2019)

2.2.3. Interactions and agreements between the actors

Between the roles that have been identified in the previous section, communication, agreements, and interaction is required to establish and maintain a successful maintenance strategy. This was also one of the conclusions from the game of van den Boomen et al. (2012). The literature does not specify which interactions and agreements are required specifically, as this depends on the asset. However, van der Velde et al. (2013) concluded that reliable asset data is one of the main requirements for successful asset management. According to van der Velde et al. (2013), adequate data quality can be reached by using the proposed three instruments: objectives and standards, plans and contracts. These instruments are specified in more detail in figure 9. The detailed specifications cover the agreements and contracts that have to be made between the parties. Because data quality is essential for digital maintenance, these interactions can be considered to be required for digital maintenance.

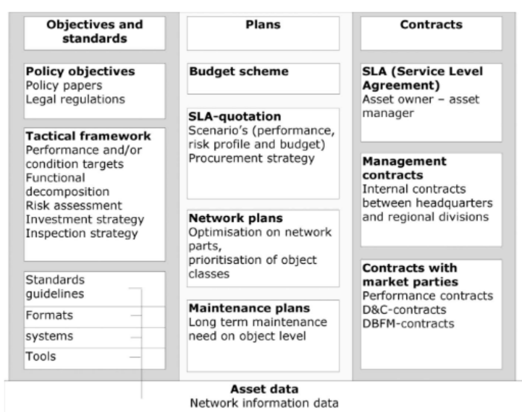

FIGURE 9: ASSET INFORMATION INSTRUMENTS (VAN DER VELDE, KLATTER, & BAKKER, 2013)

2.2.4. Maintenance activities

There are differences in the maintenance activities between the traditional approach and the digital maintenance approach. A clear visualization of these differences has already been presented in figure 5, in section 2.1.2. The main differences are the intervention moment and the time the overall process takes (Karki et al., 2022). Additionally, maintaining the digitalized systems requires different maintenance activities, which depend on the system. However, generally digital systems require more software, which requires maintenance in which a computer is involved, rather than mechanical tools.

2.2.5. Additional aspects from literature

After literature research, no additional aspects, compared to cycles, actors, interactions, and activities have been found that provide a relevant perspective on the maintenance of an asset. However, one important focus point has been identified, which need to be addressed specifically.

An important development in the interactions between the parties in asset management is the discussion about data sharing and ownership. The asset manager should have insight into the data, to determine when maintenance is required. But the asset owner needs to know the status of the asset as well. Furthermore, the challenges related cybersecurity can be linked to this aspect as well. Data and information for monitoring parts and components can be acquired from the operating system. However, this can lead to potential security risks, which is why attention is required to mitigate potential risks and create independence and resilience (Zhu & Liyanage, 2021). Jägare et al. (2019) provide some guidelines to deal with these issues. For example, consider the data and information as a cyber asset, which is similar to a physical asset. The ownership of the data belongs to the owner of the physical asset where the data is related to. Lastly, include all the considerations into the contract, and focus on purpose, period, dissemination, sorting and deletion, commercial conditions and security throughout the entire project period.

2.3. The role of data, information, and knowledge

As is stated in the introduction of this research, data plays an important role in many business processes. In order to make sure that these processes run as efficiently as possible, the data should be managed properly. This section will first address the definitions and differences between the relevant concepts, such as data and information. Furthermore, an explanation of knowledge management will be provided, and the section is concluded with a discussion on data quality and the relevance of data quality for data management.

2.3.1. Transition from data to knowledge

Prior to discussing how data management can and should be done, the definition of data has to be explained. The literature describes definitions of data, information and knowledge to distinguish the concepts, as they are different. Furthermore, the literature focuses on how these concepts are related. The latter is considered to be out of scope for this research, as this is specific for a company, sector or industry. This section therefore only focuses on the definitions of the concepts, and will build upon the definitions to distinguish the concepts.

Data consists of symbols (Chen, et al., 2009), or can be described as raw material for information and knowledge (Zins, 2007). Information is processed data in such a way that that it is considered to be useful. It can be used for answering “who, what, where, when and how”-questions (Chen, et al., 2009). Knowledge is related to the skills, abilities and habits of mind of people (Seely Brown & Duguid, 2000). Until the information is received by the people with the proper skill set, or the required pre-knowledge, the information is useless.

Therefore, the idea that more data directly results in improved operations is incorrect. Even more, it can be said that there is an data paradox, which is related to the concept that data does not necessarily results in more information and more knowledge. The transition can only take place if the requirements, such as the required skill set, are met.

FIGURE 10: TRANSITION: DATA TO INFORMATION (OWN WORK)

2.3.2. Digitalization and Information Technology (IT)

In this research the concept of digitalization and IT-systems play a central role. This section will provide a definition of these concepts and will explain their role in the research context.

The term digitalization resembles the term digitization, which is not the same. Digitization means that analogue systems and processes are replaced with digital systems and processes. Digitalization builds upon this concept but is more elaborate as it does not only involve the technical aspects. Digitalization means that "data from throughout the organization and its assets is processed through advanced digital technologies, which leads to fundamental changes in business processes that can result in new business models and social change" (Prause, 2023). Compared to digitization, the addition to changes in the business models and the social changes result in a significant difference between the two concepts. Within these concepts of digitization and digitalization, IT-systems play an important role. IT-systems are, among other things, used to handle electronic data and can therefore be the replacement of the analogue systems, thus resulting in digitization, and can be used to process the data in the entire organization, thus transforming the business processes and social relationships, resulting in digitalization. As a conclusion, it can be said that digitization and digitalization are processes which are supported by the use and implementation of IT-systems.

2.3.3. Sensors as data providers

Digital maintenance requires data, so the system needs to include data providers. Commonly, these data providers are called sensors. There are many types of sensors and many types of data that is provided by these sensors. This section will address the definition of a sensor that is used throughout this research. This way, there are no misconceptions and the sensors that are used in the case studies can be compared.

According to Oxford Languages (2023), the definition of a sensor is: "a device which detects or measures a physical property and records, indicates, or otherwise responds to it". All the devices that provide data from the asset to a distant computer is considered a sensor in this research. Van Dongen (2015) adds another function, specifically maintenance-related. Sensors can be used to read out data from a system to determine the 'health'of the system. Furthermore, sensors can be used to monitor specific parts where necessary, and therefore provide the possibility to identify a mailfunction before it actually occurs.

2.3.4. The importance of data quality

Based on the previous sections, it can be stated that data, information, and knowledge play a vital role in an efficient and effective business environment. In order to use the data, information, and knowledge, it needs to be of such a quality that it can be considered to be reliable and usable. To ensure that this is the case, there are several checklists and frameworks available which can be used to assess the data quality can be measured.

Cichy & Rass (2019) evaluate different frameworks and present an overview of the most frequently used frameworks. For a sufficient data quality level, data should be handled correctly. This involves planning, obtaining, storing and sharing, maintaining applying and disposing of data (POSMAD), which is also known as the data life cycle (McGilvray, 2021). Cichy & Rass (2019) present an overview of 12 frameworks, their components and the purpose of the framework. Data quality is often assessed using dimensions, or attributes. The dimensions that occur most often are completeness, accuracy, timeliness, consistency and accessibility (Cichy & Rass, 2019). The framework and attributes that are used to measure often depend on the organization and the sector in which the organization operates. The specific attributes that are used at the companies of the case studies in this research will be discussed in chapter 4.

2.3.5. Knowledge Management

With the increasing number of digital systems, more information is available, which can be used to optimize operations like maintenance schedules. However, there is a big pitfall that arises as the amount of available information increases. The pitfall of the increasing amount of available information is that 'information overload' can occur. This phenomenon occurs when the information availability is larger than the information processing capacity. In practice, this means that the decision-making performance decreases as the information load increases (Roetzel, 2019).

In the book of Seely Brown and Duguid (2000), the concept of knowledge management is explained. Knowledge management is defined as "the capacity to manage information, including gathering knowledge from internal and external sources, transforming it into new strategies or ideas, and implementing and preserving it" (Idrees et al., 2023). The same increasement in digital systems that has resulted in more available data and information, has resulted in a development of knowledge management. The objective of knowledge management is to distribute the data, information and knowledge throughout the entire organization, to make sure it can be used effectively (Sarka et al., 2019).

Herder et al. (2004) have vizualized the concept of knowledge management as the 'knowledge management rainbow', which is presented in figure 11. Each of the segments of the rainbow represents a part of the method to distribute the information and to support the transition from information to knowledge. As mentioned in section 2.3.1, information can be turned into knowledge once it has arrived at the proper person, with the proper pre-knowledge and skill set.

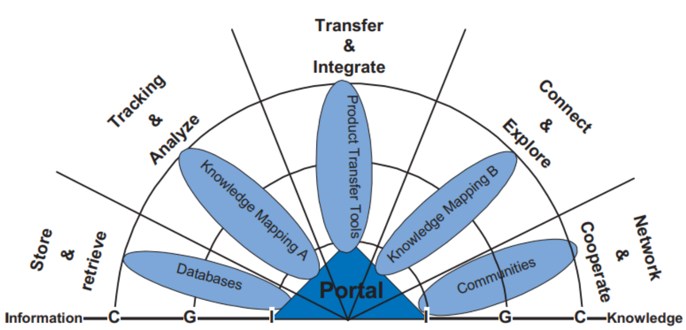

FIGURE 11: KNOWLEDGE MANAGEMENT RAINBOW (HERDER ET AL., 2004)

The horizontal axis of the rainbow represents the transition from information to knowledge. The five segments represent knowledge management strategies. On the horizontal axis, three levels are indicated: Corporate (C), Group (G) and Individual (I) (Herder et al., 2004).

The five strategies and the different levels will be described briefly. First, *Store and retrieve* is located at the most left side of the rainbow. This relates to information management and is focused on storing and retrieving information in a proper way, such that it can be used in the transition process towards knowledge. The storing and retrieving process occurs on all the C, G, I levels. Databases can be used as a tool in this process to facilitate storage location (Herder et al., 2004).

The second strategy is *Tracking and Analyze*, which aims at finding the right information from the databases from the first strategy. The three levels play a key role, as information exchange and best practices to find the right information are passed on between individuals, within groups, or announced throughout an entire company. Knowledge about these best practices can be depicted by using knowledge mapping (Herder et al., 2004).

The third strategy is called *Transfer and Integrate*, which focuses on transferring information and knowledge between facilities. Often this consists of information and a knowledge flow. The knowledge flow consists of information which is only meaningful for the actors that have the required knowledge to understand the information (Herder et al., 2004).

The fourth strategy *Connect and Explore* aims at connecting the actors throughout the entire company. This network can create a collective process of information sharing and can improve performance (Herder et al., 2004).

The last strategy is called *Network and Cooperate,* which focuses on creating a network in which specialized actors are in the right location in the network, to utilize the knowledge of the actors effectively (Herder et al., 2004).

To conclude, a proper approach for knowledge management within an organization could be a solution for issues such as information overload. By applying knowledge management properly, relevant data is selected to be transitioned into information. This information is thereafter moved to the right location where it can be used effectively.

2.4. Conclusion

Maintenance can be seen as an extensive and elaborate process that has an effect on the entire operational chain. Furthermore, the literature states a categorization that is defined by the approach and time in the process where maintenance is planned and executed. It can be seen that the focus shifts towards more predictive activities to determine the optimal time or condition of the part to apply maintenance. This shift requires different decisions which are all relates to different aspects of the maintenance process. Examples of these differences are cycle frequencies and how these fits into the current operations, required knowledge from employees and a description of the information that is needed from the asset to make the decisions.

An important note that has be made is about the transition from data to knowledge. Only if specific requirements, such as the presence of the required skill set, are met, data can be turned into information and further into knowledge. In addition to the transition, another important note has to be made, which can be described as an information paradox. This describes the idea that more data will not necessarily lead to more information and knowledge, if the requirements are not met. For example, the proper required skill set has to be available to translate data into information.

The current literature describes five relevant aspects that have be considered when evaluating the maintenance process. These aspects are the cycles, the actors, the interactions between the actors, maintenance activities and the tools that are used to create and monitor the maintenance process. These aspects are affected by digitalization, which is described in the literature. All of these aspects will be included in a maintenance aspect framework, which is described in chapter 3. The framework will be used to evaluate the effects, mentioned in the literature in practice and will evaluate the connections between the aspects plays a role and what effects can be noticed. Furthermore, chapter 4 will describe the effects of these aspects in practice, by explaining how these aspects are experienced in the organizations that are included in the case studies. In chapter 5, a comparison of the cases will be presented, based on these aspects. This will allow to reflect on these aspects play a role in the progress of each organization the in the digitalization transition.

3. Framework: Maintenance aspects

This chapter describes the design process of a maintenance aspect framework. The framework describes the aspects that are relevant in the maintenance process of digitized assets. These aspects have been identified by combining information from the problem context, described in chapter 1, and the theoretical background, described in chapter 2. Furthermore, the method of verification and validation will be explained. This is done to make sure that the framework is correct and complete. The goal of this section is to describe the design process and the logic behind design decisions. More details and instructions on how the framework can be used will be given in chapter 6.

3.1. Design process of the framework

The design process of the framework consists of three stages. In the first stage, the problem context is used to establish a base for the framework. This is further built upon in the second stage in which the aspects are checked and validated by a literature review. In the third stage the framework is evaluated once again, by using the interviews in the case studies.

The problem context showed that there are multiple perspectives that play a role in the digitalization transition and the resulting problem that digital systems require adaptations in the maintenance strategy. The perspectives that are derived from the problem context are: maintenance is an elaborate process, digital systems require different maintenance cycles, availability is measured in a different way, compared to mechanical systems, different actors are involved and actors have different roles, digital systems are often new and require specific maintenance. Lastly, sensors have twofold role, namely that they provide supporting data for the maintenance process and the sensors itself have to be maintained to guarantee data quality.

After evaluating the role of these perspectives in a literature review, which is described in chapter 2, five aspects are selected to include in a framework. These aspects are the cycles, the actors, the interactions between the actors, maintenance activities and the tools that are used to create and monitor the maintenance process. The goal of the framework is to create a checklist for companies and organizations to ensure that all the relevant aspects are considered when creating new policies and visions for digitalization. In order to maintain a clear overview and the possibility to determine whether all aspects have been evaluated, a framework with blocks is designed. Furthermore, the blocks allow to distinguish between the different aspects and to maintain a separation between the aspects. This is important, because even though the multiple aspects might be relevant simultaneously, each aspect can be evaluated independently.

Each aspect is represented in a block, and more detailed concepts are included within these blocks. A description of each of these blocks will be provided in the next section.

3.2. Building blocks of the framework

The framework, which is presented in figure 12, consists of multiple building blocks, which will be explained in this section. Because of the separate blocks, each aspect of the framework can be evaluated individually. However, there is a suggestion for the sequence in which this evaluation has to be done, because information from a previous block can be used in subsequent blocks. For example, after evaluating which actors are involved and what their role in the maintenance process, the interaction between the actors can be evaluated. The blocks will be explained following the suggested sequence.

The framework is designed such that the evaluation process starts at the top, where the **process** is represented. In this block, the process steps of the maintenance cycle and frequency of the maintenance cycle are represented. Furthermore, how this maintenance cycle is established will be evaluated. In the block, there is a distinction between preventive and corrective maintenance. The goal of the research is to mainly focus preventive maintenance as this is closely related to the concept of data-driven maintenance and using information to determine and execute maintenance before the failure occurs. Additionally, a focus is set on mid-term perspective. This is done because the digitalization transition is a relatively new development for many companies. This means that the long-term is still unsure, so no actual data is available for this period. The short-term is also not as relevant as digitalization is intertwined in the entire operational chain, which means the transition towards noticeable results takes time.

The next block represents the **actors** that are involved in the maintenance process. On the left side, the levels Corporate, Group and Individual (Herder et al., 2004) are included to evaluate how information is handled within the different levels in the organization. The actor roles are also divided into internal and external roles. The aim is to determine which roles are involved and what the function-specific tasks of those roles are. Furthermore, the decision-making process of each level (C, G, I) is evaluated. The Corporate, Group and Individual level is included in the framework for internal and external parties, to include all the internal and external interactions.

Next to the roles, the **agreements and interactions** are represented. Because of the interest in the relationships internally, externally and between these parties, this block spreads across all of the actors. This is closely related to the roles and the actors as this aims at investigating what the relationship between the actors is and how this is affected by digitalization. Furthermore, the effect of digitalization on agreements and communication is evaluated.

The next block is the **approach**, which is related to the process in the first block. This section further investigates the activities and the role of sensor and human data-input in the process. The process of how data is gathered and translated into maintenance activities is researched. On the left-side of the block, the targets are represented. This is done to compare how the established maintenance plan connects to the targets that have been set to determine the strategy towards reaching the targets.

At the bottom of the framework, the two-fold role of sensors in **digitalization** is represented. On the one hand, sensors are used to support the maintenance strategy. On the other hand, sensors have to be maintained themselves as well. In each company, both perspectives are evaluated.

Lastly, the outputs and results are on the right-hand side. For each asset, **availability** is the indicator of how well the asset is performing. However, availability is measured by different indicators for each asset. These performance indicators are divided into process indicators and outcome indicators. The aim of this block is to determine how the previous blocks are combined to reach the required availability levels.

Figure 12 shows the framework. All the aspects that have been described are underlined in the framework.

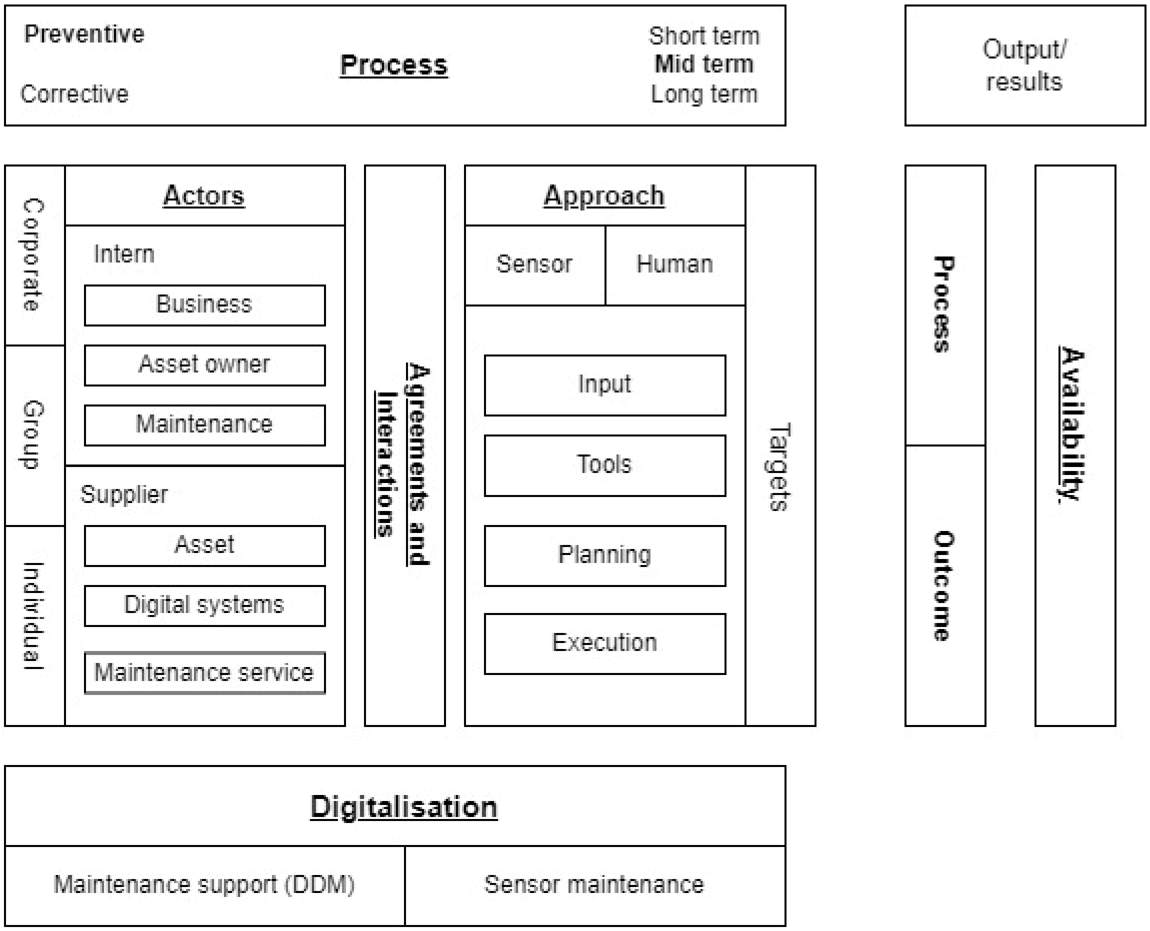

FIGURE 12: FRAMEWORK MAINTENANCE ASPECTS (OWN WORK)

3.3. Validation and Verification

The goal of the framework is to provide an overview of the relevant aspects that have to be considered when designing new policies and visions about the maintenance of digitized assets. The framework can be used as a checklist, to make sure all aspects are considered properly. In order to ensure that the evaluation is complete when the evaluation is done with the use of the framework, and that the framework is designed in such a way that it can be used by organizations.

The framework is validated to confirm that the framework has a use in practice and that organizations can actually use it for its intended purpose. The framework is verified to confirm that all relevant aspects are included and to guarantee that the framework is complete. This section will describe the process of how the framework is validated and verified.

In the verification process, it is evaluated if all the relevant aspects of the maintenance process are included and thus if the framework is complete. The literature review is used to determine which aspects of the problem context are relevant according to the literature. The fact that the literature underlines the importance of a specific aspect motivates the decision to include the aspect in the framework. However, a literature research does not guarantee that the framework is complete. Despite the systematic approach used in the literature review, some aspects or perspectives might be neglected. More importantly, some aspects that might be relevant in practice are not included in the current literature yet. Therefore, the interviews to build the case studies are also used for the verification process. Actors with practical experience have the opportunity to point out missing aspects, or to indicate less relevant aspects that might be included in the framework, based on the literature. In each interview, the set up of the framework is explained. At the end of the interview, it is asked whether all aspects that are included are, or if relevant aspects are missing according to the person being interviewed. The interview questions are included in appendix III.

If aspects are considered to be less relevant, the aspect is not removed from the frame immediately. Based on the role of the actor in the process, some aspects are less relevant than others. It is important to determine the reason behind the reduced relevancy to conclude if this applies in general, or for this actor specifically. Therefore other actors are asked the same question. Once it can be concluded that the aspect is not relevant according to multiple actors, it will be adapted or removed from the framework. This discrepancy between practice and the current literature will be noted and presented alongside the final version of the framework. The final version of the framework will be presented in section 4.4.

The validation process, it is evaluated if the framework has a use in practice. For this process, the base of the literature review is less valuable, compared to the verification process. This is the case, because aspects that might be relevant in practice could not be covered in the literature yet, which leads to these aspects being neglected. Therefore, similar to the verification process, the interviews will be used to determine if the proposed framework is useful. An explanation of the purpose of the framework, along with a proposed method for using the framework is provided. The purpose of the framework is to give an overview of all the relevant aspects of the maintenance process and show which aspects could be affected by digitalization. As a result, this could raise awareness that digitalization plays a role in multiple parts of the operational chain. Furthermore, it can be used as a checklist to consider all relevant aspects of the maintenance process of digitized assets, when creating new policies or visions about this topic. The usefulness is evaluated by asking if the framework is considered to be useful according to the person being interviewed and how this person would use the framework.

If a interviewee considers the framework as not useful, the reason behind this answer is very important. It is evaluated whether this is related to specific parts of the framework, or related to the purpose of the framework. Depending on the answers of the actors that are being interviewed, adaptations to the framework are made to increase the usefulness of the framework. The changes to the framework, as a result of the input from the interviews, and the final version of the framework will be presented in section 4.4.

3.4. Conclusion

A framework is developed which visualizes the relevant aspects of the maintenance process. The framework includes five aspects, which are represented in blocks. The purpose of the framework is to create awareness of which aspects of the maintenance process are relevant and to create a checklist for organizations to check if all the aspects are considered when creating new policies or long-term visions.

The design of the block is selected to support the idea of the checklist, because the aspects can evaluated individually. However, during the design process, a suggested sequence of the aspects for the evaluation process is determined, because the information from previous blocks can be incorporated into the evaluation of the upcoming blocks.

The aspects that are included in the framework, in the suggested sequence are **process**, which focuses on the preventive maintenance approach and a mid-term perspective. Next, the **actors** are evaluated. This is split in internal and external parties for which their role in the organization and process is evaluated. Next, the interactions and agreements between all the parties are discussed. Furthermore, the **approach** towards using more digital systems is included. Here is focus is on the digital tools as well as the human input towards the maintenance process. The digitalization aspect is included in the form of support tools, in which sensors are used to monitor the condition of an asset and provide information for condition-based maintenance. The other aspect is the maintenance process for the **sensors** itself. Finally, the framework is concluded with the **availability**. For each asset this is a common goal, even though it is measured and expressed differently. The framework will form the basis for the interviews that are done.

The framework is verified based on the literature research and the interviews that are done in the case studies to confirm that the framework is complete and all relevant aspects are included. The combination of literature and interviews is essential, because this ensures the input from research and practice. The framework is validated based on the interviews that are done in the case studies. This is important in order to ensure that the framework is useful in practice. Changes that are made to the framework based on input gathered from the interviews, will be discussed in section 4.4.

This chapter focuses on the design process and decisions that are made for the framework. This version will be used as the basis for the interviews for the case studies and can be changed based on input from those interviews. Once the final framework is established, an implementation plan for the framework can be developed, which describes a suggested method to use the framework in practice. This implementation will be included in chapter 6.

4. Case studies: descriptions and cases

In the previous chapter, the maintenance aspects framework has been presented. Based on that framework the effects of digitalization on the maintenance process of specific assets will be investigated. This chapter describes the companies and cases that are included in the research to determine these effects in practice. The goal of this chapter is to create a clear overview of effects of the predetermined aspects in practice and to determine if other aspects play a role as well.

The chapter is introduced with a description of the selection procedure for the cases and the considerations that have been made during the selection process. Furthermore, the interview procedure of the cases is described as well, along with the selection procedure on what actors will be interviewed. Additionally, the effects of the interviews on the framework are described and the final version of the framework is presented. The focus of this chapter is on each individual case and the outcomes of the interviews. This will form the base for the general comparisons that will be presented in chapter 5.

4.1. Selection procedure

As can be seen in the maintenance aspects framework, which is presented in Chapter 3, the maintenance process is elaborate and touches upon many aspects of operations. It is good to keep in mind that some considerations have to be made when selecting cases that are compared to each other. This research is executed for NS, so one of the cases is from NS to determine how all the aspects of the framework play a role at NS. This also allows for a smoother translation of the findings from the comparison of the case studies towards a list of recommendations for NS. This is the case because in the comparison process, all the findings have been compared to the approach of NS, which makes finding best practice that could actually work for NS more straightforward.

The aim is to use four cases to allow to investigate many examples and perspectives, but to also to keep the number of required interviews manageable within the available time. The remaining three companies have to comply with a predetermined set of requirements. The company has to be the owner of a large public asset. Furthermore, the asset itself has to have an example some transition towards using digital system for the maintenance of the asset. The organization and the asset have to operate in the public domain, because this ensures that the organizational structure and size of the asset and operations is comparable. There is no requirement for the sector in which the organization or the asset is active. This could exclude interesting findings that may be applicable regardless of the sector, or the type of asset.

Since the requirements are still elaborate, many companies are applicable to be used as a case study. This is why NGinfra is used to contact many companies with public assets. NGinfra, or Next Generation Infrastructure is an overarching organization, consisting of Alliander, Port of Rotterdam, ProRail, Rijkswaterstaat, Schiphol Airport and Vitens. Together, they share knowledge and collaborate on creating smart solutions for infrastructure-related challenges. One of the themes they work on is availability of assets. In this theme centre, the participating companies have been contacted with the request to use one of their digitized assets for the case studies. As a result, NS, the Port of Rotterdam, Rijkswaterstaat and ProRail are included in the research.

4.2. Interview set-up

The interviews will be used as a source of information for two purposes. First, information on the effect of digitalization on the maintenance process of a specific asset in practice will collected. Secondly, the interviews will be conducted to confirm if the framework that has been designed is complete and useful for the organizations. The interview questions are based on the proposed framework which is presented in chapter 3. All the blocks from the framework are included in the interviews and the effects related to each aspect of the framework will be evaluated. The interviews are also used to validate the framework, which is why a question about possible additional aspects is included in the interview questions as well. If none of the companies have additional aspects to expand the framework, the framework is considered to be complete. Furthermore, the interviews are used to verify if the framework is considered to be useful for the companies.

The approach for each interview is to start with the initial set of interview questions, based on the framework. The interview questions can be found in Appendix III. During the interview additional questions can be asked, which can be included in the next interview with another company, if it is considered to be a relevant question. All the interviews will be recorded with the consent of the interviewee to make sure all of the relevant information can be translated into a summary and can be included in the research. Furthermore, the recordings can be used to evaluate interview process and to possibly improve the process for the next interviews.

For each company, the aim is to interview multiple people that are related to the maintenance process, with different roles. Ideally, the asset manager, asset owner, asset user and the service provider are included. This way the full process and effects can be mapped from multiple perspectives. Similar roles are interviewed for all participating companies, to be able to compare the effects more systematically. In the pursuit for potential interviewees, the main focus is to include people that are involved in the execution of the maintenance strategy, instead of people that are improving the maintenance strategy. The actual effects are being investigated, rather than ambitions and plans. Table 1 shows an overview of the roles that have been included in the interviews for each specific company. It can be seen that for all the included organizations, the majority of the interviewed actors has the role of asset manager. Furthermore, no service providers have been included. More details on these decisions and the effects on the research, are discussed in chapter 8.

Company	Roles
NS	Maintenance Engineer, Reliability Engineer Rolling Stock Manager, Manager Maintenance Engineering, Lead architect, Manager Maintenance Development, Aspectmanager IT/OT
Port of Rotterdam	Asset Owner, Asset Manager, Reliability Engineer
Rijkswaterstaat	Asset Manager, Smart Maintenance Manager, Consultant Industrial Automation
ProRail	Asset Manager Civil Engineering and Utilities, Asset manager Infrastructure Innovations

TABLE 1: OVERVIEW OF INTERVIEWED ROLES

4.3. Companies and case descriptions

In this chapter, all the cases are described using the aspects from the maintenance aspect framework, described in chapter 3. For each case, the asset, actors, agreements, approach, and availability indicators are described. The effects of digitalization and examples of these effects will be described per aspect as well.

4.3.1. NS: Sprinter New Generation

Asset:

NS (Nederlandse Spoorwegen), or Dutch Railways is the main passenger railway operator in the Netherlands. For the case of NS, the maintenance process of the SNG, or Sprinter New Generation, is evaluated. Currently, the fleet of the SNG consists of 205 train sets. The first SNG trains were operational in 2020. Figure 13 shows the entire fleet of the NS and where the SNG is located in this overview.

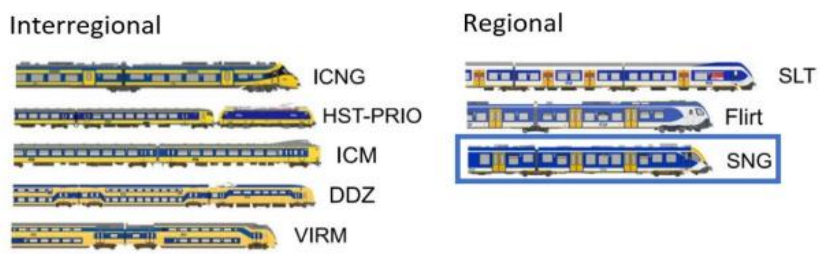

FIGURE 13: OVERVIEW ROLLING STOCK (NS, 2023)

Actors:

For each specific type of train set, a rolling stock team is formed, consisting of employees of NS. This team has a combination of skills, knowledge, experience, and responsibilities. For the maintenance process, the most relevant actors for the maintenance process in the rolling stock team are the Reliability Engineer, Maintenance Engineer, and a Maintenance Developer. Apart from the rolling stock team, there is a Systems Engineer who is often involved in the process as well.

The Reliability Engineer is focused on the continual improvement of the safety and security of the assets. This is done by monitoring the performance of the assets and by implementing so-called improvement loops, concentrated on safety, security, and costs (NS, 2023). The function of the Maintenance Engineer is to translate the requirements for specific rolling stock or systems into actual maintenance tasks. This way a maintenance approach is determined, improved, and monitored (NS, 2023). The Maintenance Developer is part of a team of data analysts that support the Maintenance Engineer in finding data to support new maintenance concepts. The main focus of the Maintenance Developer is to analyse and optimize the maintenance activities. The rolling stock team is led by a Rolling Stock Manager. The Rolling Stock Manager focuses on the performance of current and future rolling stock and maintaining the current fleet.

Train digitalization is a department which is established because of the increasing number of digital systems in and around the rolling stock. This department is responsible for the safe operation and maintenance of the of the digital services and systems. The department forms the bridge between the Information technology (IT) and Operational technology (OT) perspectives of the operations (NS, 2023). Figure 14 shows the relevant parties in the organogram of NS.

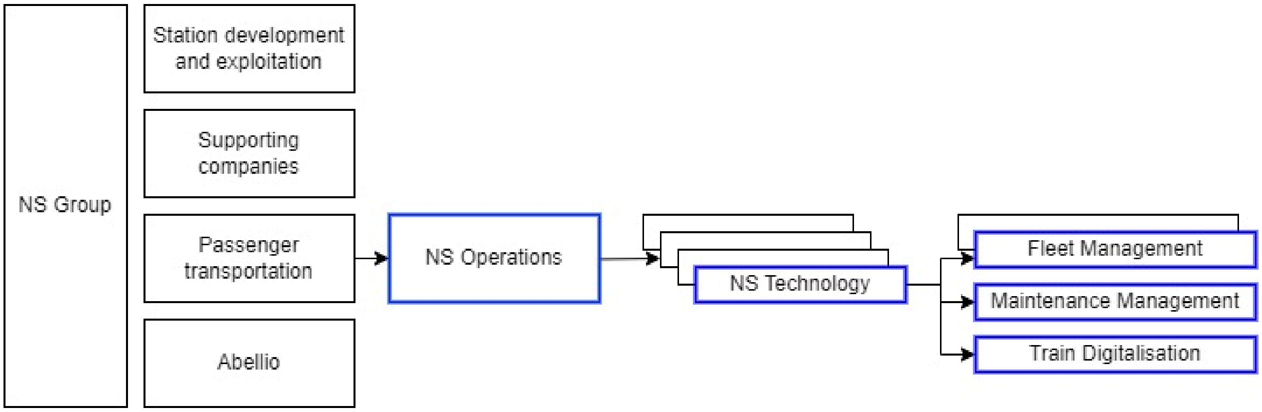

FIGURE 14: ORGANOGRAM NS (NS, 2023)

The SNG is produced and supplied by Construcciones y Auxiliar de Ferrocarriles (CAF), a Spanish train set producer. The train sets are supplied as a complete product, so all the systems and components are installed.

<u>Agreements:</u>
In the railway sector, maintenance roles are described by the ECM structure. ECM is short for Entity in Charge of Maintenance. In the case of NS, NS technology is the ECM and is therefore responsible for the safe and secure availability of the rolling stock (NS, 2023). The ECM tasks are divided into four categories, as is prescribed by the European union (European Union, 2023): ECM I-IV, which are represented in Figure 15. NS Techniek is responsible for ECM tasks I and II, which are mostly related to developing, implementing, and monitoring the maintenance functions.

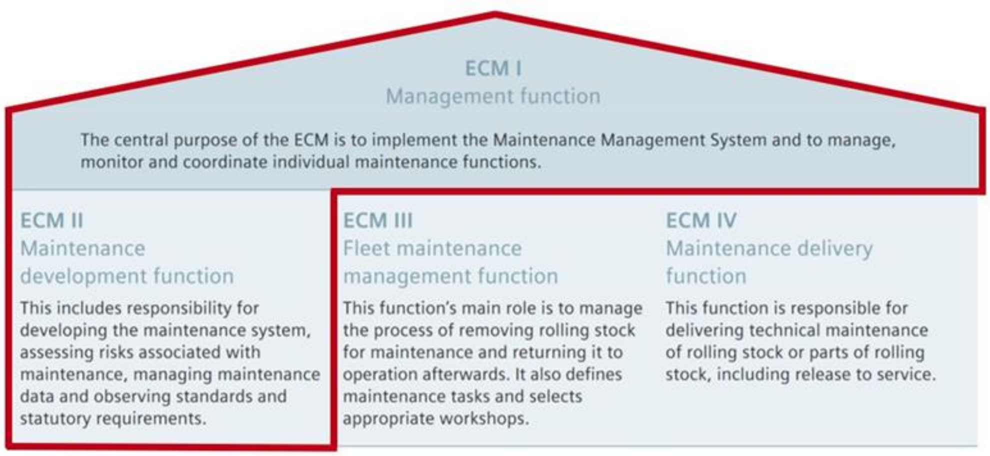

FIGURE 15: ECM TASKS IN NS (NS, 2023)

The ECM-1 task is done by a manager from the Fleet Management department for each specific rolling stock type (NS, 2023). The ECM-2 task is done Maintenance Management department for each specific rolling stock type (NS, 2023).

There are also agreements with external parties. The main agreement with the supplier of the train set is about the admission requirements to be able to use the Dutch railway network. The responsibility is primarily for the supplier to ensure and to show that the rolling stock complies with all the rules and regulations. Adaptations to the maintenance concept have to be communicated with the supplier very clearly to ensure the rolling stock maintains admissible to the Dutch railway network.

Another important agreement with the supplier of the train set, in this case CAF. The first two years, these agreements are mainly about the warranty of the systems and components of the train set. After these two years have passed, additional support agreements can be made to continue the collaboration between the supplier and NS.

Approach:

For the SNG specifically, the maintenance cycle is divided in three levels: DO, KCO and LCO. The first level is the daily maintenance (DO). This mainly consists of inspecting the train for safety-related irregularities. Furthermore, small defects can be fixed. In addition to the daily checks, there are inspections, which are done every 15 days for the SNG (NS, 2023).

The second level is the so-called Short-Cycle maintenance (KCO). The aim of these maintenance activities is to make sure that there will be no failures until the next maintenance moment. The duration of the activities within this interval is at most 3 years. KCO consists of preventive and corrective maintenance. The preventive predetermined maintenance consists of replacing parts and taking care of periodical activities like refilling, greasing, and cleaning the moving parts. The preventive condition-based maintenance focuses on measuring, checking, and inspecting the systems. Corrective maintenance consists of repairing or replacing failing parts and systems (NS, 2023).

The last level is Long-Cycle maintenance (LCO), which consists of maintenance activities that have an interval larger than 3 years. The main activities are revisions, replacements of parts, repairs of parts (NS, 2023).

When the train set is delivered, the supplier provides an initial maintenance concept. This has to be followed in order to maintain the warranty. However, there is some room for improvements based on experience and knowledge of maintenance engineers of NS, based on other rolling stock types for example. Furthermore, when the train set is delivered experience from practice is gained which can provide insight into potential adaptations to the maintenance concept. Also, the concept of the supplier is often considered to be very safe, which leads to possibilities to optimize the concept as well. NS is included in an early stage of the development of the maintenance concept of the supplier, but there are still possibilities to make adaptations nevertheless.

Adaptations to the maintenance concept often include shortening or extending the prescribed maintenance interval. In the case of shortening, materials that might still function properly are discarded too soon, which means that unnecessary costs are made. In the case of extending the maintenance interval, risk of failure and the effects of this failure could increase. When making decisions on adapting the maintenance interval, these considerations play an important role. For digital systems specifically, the maintenance approach is often prescribed by the supplier of the system and NS will make sure these prescriptions are met by implementing the activities in the appropriate maintenance level, based on the required frequency, to maintain the warranty. Because of the random failure component, there is a smaller possibility to apply preventive maintenance by predicting when the system will fail.

Data from sensors can play an important role in supporting decision making processes about shortening or extending the maintenance interval. Currently, different types of data are used. First, digital systems are used to register which failures have occurred and which maintenance activities have been done. This makes it possible to reflect on the current prescribed maintenance activities and to determine whether these are appropriate. Furthermore, data plays a role in the maintenance research which is about monitoring the current state of the rolling stock, systems, and components. The failures that are registered are used to determine the state of the rolling stock. The registry of the passed failures and alarms is called diagnostic data. Another type of data is measurement data, which consists of measurements of specific indicators over time.

Examples of how data is used currently include using cameras and sensors in the tracks to determine the level of degradation of the wheels. Sensors are used to determine the saturation of the filters surrounding certain computers on board of the train. Furthermore, the train operator is able to check the systems in the train in a small test before the train is started to check if everything is working properly. This has many advantages compared to the situation without these digital checks. The train can start much quicker, no daily visual inspections are required to test these systems and maintenance can be done more focused when a check states a failure.

There are also examples in which humans provide input in the maintenance process. For example, the mechanic communicates with the Rolling Stock manager about the feasibility of the prescribed maintenance. Furthermore, there is communication between the Reliability Engineer and the Service and Operations department, representing the train conductors and train drivers. Here the problems that are experienced by the service personnel are discussed and the feasibility of making adaptations to solve these issues is evaluated.

The aim for the future is to work towards more condition-based maintenance. However, currently the operations are focused on scheduled maintenance. This is visible in the fact that maintenance engineers are trying to fit all the maintenance activities into the current (scheduled) maintenance cycle. Changing this approach required flexibility in all aspects of the operations, which is very complex. Furthermore, it requires a common goal for working towards flexible condition-based maintenance, which is not noticeable yet.

<u>Availability indicators:</u>

There are several indictors that are used to monitor the performance of the rolling stock. The number of available train sets is determined by the entire fleet minus the number of train sets that is scheduled to be in the maintenance facilities. For unscheduled unavailable rolling stock the following indicators are used. First, TVTA (Te Verklaren Trein Afwijkingen), which is short for train deviations to be explained. These are the technical failures that occurred during the operations. Furthermore, the punctuality is considered, which is determined by the number of minutes of delay per million driven kilometres per coach. If a train is cancelled due to the delay a standard of 30 minutes is measured. Lastly, the safety is imported which is measured in the number of safety related failures per million driven kilometres per coach.

4.3.2. Port of Rotterdam: RPA-12

<u>Asset:</u>

Port of Rotterdam is responsible for the development, construction, and management of the port and industrial area of Rotterdam. The port area is monitored and inspected in several ways. One of which are inspection vessels, which are used to inspect the water area and act upon calamities, such as fires. One example of such a vessel is the RPA-12 (Rotterdam Port Authority).

FIGURE 16: RPA-12 INSPECTION VESSEL (VERENIGING DE BINNENVAART, 2023)

<u>Actors</u>

There are different actors involved in the maintenance process of the RPA-12 inspection and calamities vessels. First of all, the asset owner is the Port of Rotterdam itself. Furthermore, The Harbor Master (DHMR) uses the vessels and is responsible for first-line maintenance, which includes tasks such as lubricating parts, inspecting motor oil and fuel levels, cleaning the vessel, and reporting defects. The suppliers of the components of the vessel are included in the process for larger maintenance activities. The Technical Service (TD) is the first point of contact when a defect or failure occurs, and corrective maintenance has to be done. The Technical Service is called upon when a defect is reported by any of the parties. An inspection is carried out to determine whether the Technical Service can maintain it or if the supplier of the specific component needs to be engaged.

The asset manager is responsible for optimizing the operations, and thus the maintenance of the assets. The asset manager is supported by the D&IT (Data and IT) department for all data and IT-related aspects. The Data & IT department of the Port of Rotterdam also ensures secure connections and facilitates the transfer of signals from the sensors on the vessels to the shore. For example, a dashboard has been made by the asset manager and the colleagues at D&IT in which insights in the state of the fleet is visible. The Asset manager looks at potential improvements, based on the available data. The aim is to determine how potential risks of failures, or the effect of the failure scan be reduced, by predicting the occurrence of the event. Furthermore, the asset manager has to determine how the maintenance approach should look like, in terms of activities and frequencies, to reach the desired effects and minimize the risks.

The asset owner is responsible for the strategic side of asset management, in which the costs, performance and risks are considered. In the case of the Port of Rotterdam, the asset owner is responsible for the entire asset base of the company. The main focus of the asset owner is to determine how the asset management process should look like, which supporting systems are required and how the strategic goals of the company are translated into maintenance activities.

The role of the Reliability Engineer is to improve the maintenance process of the asset. The RE examines the Preventive Maintenance plans, focusing on the effect of specific maintenance on the type and frequency of failures. Analyses are conducted to determine the impact of maintenance on reliability and whether it falls within acceptable risks and costs. Additionally, the role of technology in this process is assessed. Data can play an important role in this process, as it can be used to support certain decisions.

Agreements

The main agreement that plays a role is the Service Level Agreement (SLA) between the Port Master (DHMR) and the Port of Rotterdam in which agreements about the availability of the vessels are described. The agreement is that at all times at least 5 vessels have to be available to use by the Port Master. A derivation on this agreement is that every vessel should be available 92% of the time. Here available is measured as: ‘no maintenance is required to the vessel’. There is frequent communication between these parties as there are some challenges about the availability measures, and when a vessel is considered to be available.

After the warranty period (1-2 years), in case of defects, the original parts' supplier is contacted for repair or replacement. Sometimes there is a larger contract in place. For example, all engines come from the same supplier, so this supplier is contacted in case of engine defects.

This frequent communication also includes feedback about the prescribed maintenance as DHMR also does the inspections to determine which maintenance is required, and how the maintenance is executed. There are no other examples of information that is acquired via human input that cannot be obtained by using a sensor.

Furthermore, the Port of Rotterdam ensures that the port has ownership over all the data from all the assets, while keeping in mind that relevant data can be shared with different parties to improve the efficiency of the operations in the port.

Approach

The vessel crew (DHMR) reports a malfunction using an app (ServiceNow), this report is converted into SAP and exported to PowerBI weekly by the Reliability Engineer. Corrective maintenance is done by the Technical Service. They work by using an on-call service, so when an incident occurs an employee is called by the HCC (Port Coordination Centre) and is sent directly to the incident.

For preventive maintenance, each vessel comes in twice a year for major maintenance and 1 or 2 times a year for a pit stop, depending on the number of hours worked. Previously, vessels came in for maintenance four times a year, but experiments and data support have reduced it to 2 maintenance occasions. The maintenance intervals are longer because additional maintenance tasks have been added.

Maintenance on the sensors themselves is minimal since they are continuously providing output. If this output stops, it indicates a problem, and the sensor is not functioning correctly. Sensor data is validated by comparing it to the analogue meters on board the vessel.

Currently, there are few sensors on board that provide data for maintenance. The Reliability Engineer is working on Asset Performance Management (APM) and Predictive Maintenance, with some practical examples already in use. Alerts are generated for issues such as water in the ship and triggering of fire alarms. The goal is to expand this to monitor a continuous status and detect trends, not just individual alerts. Currently, they are looking at engine data and how to translate it into a dashboard, including monitoring fuel levels, lubricating oil, cooling water levels, and vessel speed.

Sensors are installed to validate the prescribed maintenance and determine the optimal maintenance frequency. They are also exploring the information required, how it should be visualized, and how trends can be identified. This is likely to involve more frequent data analysis than the current weekly analysis.

The preventive maintenance is part of the asset management approach, for which the VDMXL approach is used. VDMXL is short for Value Driven Maintenance and this approach is designed by Mainnovation. An overview of the pillars can be found in figure 17. The idea is to apply maintenance properly to create value. This is done by increasing the performance of the asset, or by reducing the costs that are involved. Furthermore, a risk analysis is made by the reliability Engineer by determining which failures can occur and what the potential effects of those failures could be. By using a risk matrix, certain values are assigned to specific risks and effects. This is based on financial risks, image, people, environment, and core business.

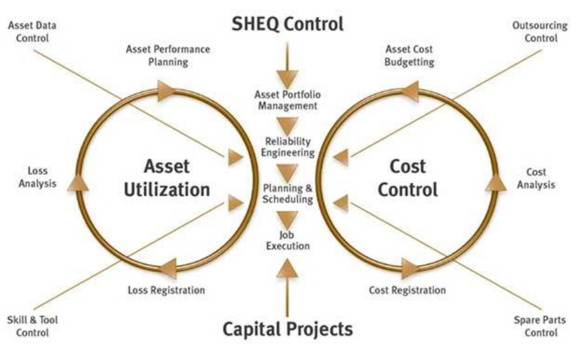

FIGURE 17: VDMXL APPROACH (MAINTWORLD, 2016)

The general maintenance approach is derived from the Strategic Asset Management Plan (SAMP). Risks with high costs, or large effects are identified by an FMECA (Failure Mode Effect & Criticality Analysis). For each of these risks an approach is designed to mitigate and reduce the potential risks. These mitigation measures are the base for the maintenance approach.

Currently, not all data that can be used from the vessels is available to analyse. The aim was to start investigating the most expensive and most frequently occurring failures. One effect of using data is that the number of maintenance moments has been reduced from 4 to 2. This was done by experimenting with different frequencies and evaluating the effects on the risk matrices.

The goal for the future is to predict failures and let AI-systems predict the best moment to apply maintenance, while considering the available capacity of the maintenance facilities and employees. Furthermore, using data and sharing it in a good way with global partners allows the Port to communicate and work together with global parties as efficiently and effectively as possible. For example, arrival times can be shared very specifically which makes scheduling easier and makes it possible to optimize the schedule as well.

An example of how data is used to prevent failures from occurring are the filters in large vessels. The filters filled up quickly, which required maintenance. However, a trend between the acceleration and the fullness of the filter could be identified from the data. This meant that by accelerating more when the filter was almost full, could burn all the excess dirt out of the filter, resulting in the fact that maintenance was not required anymore.

The decision to add additional sensors to a vessel is made in consultation with the Asset manager. A cost-benefit analysis is conducted to assess the potential impact on reliability, availability, and critical or expensive components.

The primary effect of digitalization is reducing the need for physical vessel inspections. This saves time and reduces emissions. The vessel's status can be analysed from a safe office environment, eliminating safety risks and external factors (e.g., noise, weather, air quality, vibrations). While there are currently few visible effects in practice due to limited data, except for the reduction in maintenance occasions, the main challenge lies in establishing and securing the digital infrastructure.

The main challenges for predictive maintenance and using data are as follows. There needs to be knowledge and expertise about what needs to be measured and what data is required. Also, which sensors are needed to acquire that required data and how the data is translated into information. Furthermore, knowledge on how the connectivity between the asset and the computer should be organized and where and how the data should be stored is necessary. Lastly, a plan should be made about data ownership and how data can be shared with different parties while maintaining the ownership.

<u>Availability indicators</u>

Availability is closely related to reliability. Reliability aims to minimize unplanned downtime, thereby improving both reliability and availability. Currently, there are some challenges in how the availability is measured because there is no clear definition of when a vessel is available. This is the case because different systems are required for different incidents. For example, the fire extinguisher is not required to work for an inspection round. There is frequently communication between DHMR and the port to make clear agreements. They are currently working towards defining different levels to make a distinction between which systems are available and which are not. Furthermore, there is currently too little available data to determine the effect of digitalization on the availability of the vessels.

4.3.3. Rijkswaterstaat: Kreekraksluizen

Asset:

Rijkswaterstaat responsible for public works, water management, railway projects and traffic management in the Netherlands. Currently, Rijkswaterstaat is gaining experience in data-driven asset management for six "movable" objects in the Netherlands. These include locks, pumping stations, movable bridges, and tunnels. One of the assets that is part of the program is the Kreekraksluizen. This is a slot consisting of two elements that is located on the connection between Rotterdam and Antwerpen.

The pilot program is established to gain experiences with data-driven work and asset management using data from the locks, including data from the lock's control system and additional sensors. The goal of the program is to ensure that the involved departments of RWS and the relevant market parties able to apply data-driven working in asset management for water structures, movable bridges, and tunnels in two years. The desired result is to reduce unplanned disruptions for users and to increase the control over performance, risks, and costs of the assets.

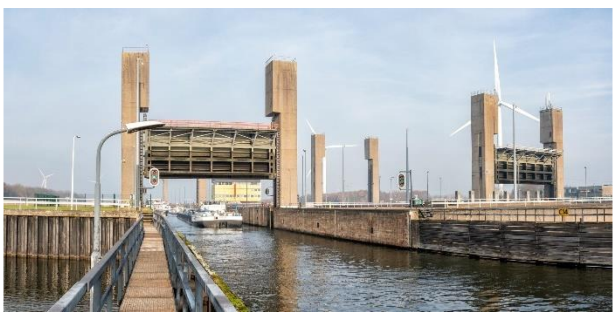

FIGURE 18: KREEKRAKSLUIZEN (RIJKSWATERSTAAT, 2023)

Actors

Ministry of Infrastructure and water management is the Asset Owner of all the assets in the Netherlands and Rijkwaterstaat is the Asset Manager. Within Rijkswaterstaat, there are regional organizations responsible for the assets in their regions as asset managers. Furthermore, there are several national services within Rijkswaterstaat, in of which is Programs, Projects, and Maintenance (PPO). PPO serves as a link between the regional asset managers and the market as a service provider. The main focus of PPO is to support in discussion concerning contract details (including maintenance quality) and technical discussions in case of incidents. For the Kreekraksluizen, Scaldis is the service provider, which is determined by a tender. The contract for the tender runs between 5-10 years (7 years with the option of extending for 2 years).

Agreements

Between the Ministry of Infrastructure and Water Management and Rijkswaterstaat agreements about performance are made, which are called pins (performance indicators). The agreement is as follows: 0.8% planned downtime and 0.2% unplanned downtime. Routine maintenance and inspections are carried out by the service provider, Scaldis. This is done continuously to ensure routine maintenance. Variable maintenance, such as renovations, is carried out through a bidding process by Rijkswaterstaat.

The data extracted from the asset is owned by RWS, even though, in this case, Scaldis performs the inspections and uses and supplements the data. Analyses and results are entered into the systems of Rijkswaterstaat. It is not clear whether data obtained by suppliers from their product analyses can become the property of Rijkswaterstaat if it is included in their structures.

There are six assets where data-driven asset management is applied. Lessons are shared and improvements are made within the project through a community of practice, allowing colleagues to learn from each other. This takes place once every three months, with experiences shared from the six assets. Relevant external parties can also attend. Additionally, documentation is produced quarterly, highlighting implementations and their outcomes, and lessons learned are gathered.

Approach

The current maintenance regime primarily focuses on corrective and preventive maintenance. Risks are calculated using FMECA (Failure Mode Effect & Criticality Analysis) and ORA (Optimal Risk Analysis), based on failure mode, effect, criticality, and redundancy. Based on the outcome, decisions are made regarding the necessary control measures and whether a component should be maintained preventively or correctively, always supported by inspections and surveys.

For DDAM (Data Driven Asset Management), FMECA is also used as a basis, supplemented by expert judgment, to determine which components are eligible for condition-based maintenance and monitoring based on (sensor) data. Criticality, MTTR (Mean Time to Repair), and remaining service life are also considered in this evaluation, along with a cost-benefit analysis.

From 2017 to 2021, there was a program within Rijkswaterstaat called "vital assets,". The aim of the program was to gain a better understanding of the condition of assets and to aim at keeping assets in a healthy state by performing correct and timely maintenance, to potentially extend the lifespan of assets. This program mainly focused on smart and condition-based maintenance and was more operationally oriented. In 2022, the program transitioned to data-driven asset management, in which the tactical asset management level was included in the scope as well. RWS is improving their asset management approach to be able to manage and maintain the networks quantitatively and qualitatively in the future in a professional way, using a predictable and centralized organization and control. Data-driven asset management helps in this task.

Working more data-driven in asset management means using new IT techniques and new data sources that allow for better monitoring of performance, usage, and condition. This allows Rijkswaterstaat to have more information available and to work with up-to-date data on performance, usage, and condition of assets. This results in the ability to make informed choices at different stages of the asset management process. Data usage is considered to provide additional tools for operational, tactical, and strategic asset management processes.

Audits in recent years have revealed that RWS's current asset management approach is less professional than originally thought. To address this issue, the program Asset Management 2.0 (AM2.0) is created. The development and improvement of the asset management program 2.0 runs in parallel with the development of the data-driven asset management program, and the goal is to integrate the developments and results from both programs. AM2.0 primarily focuses on the strategic and tactical asset management level. The DGAM program mainly focuses on the operational and tactical asset management level. Together, it creates a complete strategy.

Digitization has a positive impact on the availability of an asset. However, the organization must have the capacity and quality in place to effectively manage it. People need to be adequately and properly trained. Digitization enhances availability by providing insights into the actual lifespan of components, enabling proactive management. Moreover, it can reveal both positive and negative aspects, including insights into previously unknown issues. Ultimately, it leads to increased availability because it allows for proactive actions before failures occur. However, this impact is expected to be realized in the long term, not immediately after implementation.

Availability indicators

In asset management, the focus is more on risk than on performance. While agreements are made in which performance plays a central role, the performance indicators are less relevant in practice. Availability is assessed by looking at passing times, and at Kreekraksluizen, consisting of two locks, it is available when only one lock is open for ship passage. However, passing times are longer during peak times. Therefore, passing time is a relevant KPI for measuring asset availability.

Another indicator that is used is functional Downtime Hours. This refers to the time the lock is actually closed for shipping. There are developments within Rijkswaterstaat to explore a different indicator to measure availability as well. These are the hours that are lost due to (unscheduled) maintenance when a vessel wants to pass. When the lock is functionally closed, but there is no ship traffic that needs to pass through, it's not as critical. The "vessel loss hours" indicator would take this into account and combines technical functional downtime with shipping demand into a single performance indicator (PIN).

Several important points are relevant here. Firstly, the primary agreement is that the lock cannot be unavailable for more than 1% of the total time. This PIN doesn't consider whether there is shipping demand or not. Furthermore, it's already challenging to perform a proper risk analysis and align maintenance programming for the simpler "functional downtime hours" indicator. Using a more complex indicator to express availability requires even more input and insights that may be limited. For example, the variable "shipping demand" needs to be made transparent.

"Vessel loss hours" is currently used in the policy side of Rijkswaterstaat because it is relevant to the Netherlands as a whole. The goal should be to first address functional downtime and set up the data analysis before moving on to use a new indicator. It's essential to have clarity about when the first indicator is well-understood, so the transition to the second indicator can be made. The key factors include having a valid and reliable model, maintaining, and regularly checking and improving the model where necessary, and ensuring that maintenance is carried out and inspected properly. Additionally, data related to shipping demand should be accurately and reliably recorded, and systems containing all this data should be integrated to provide a comprehensive picture.

The last point presents an additional challenge: both execution and inspection are currently carried out by the same party, which may lead to a lack of transparency regarding the quality of their own work. Rijkswaterstaat is exploring adjustments to the inspection strategy to avoid such circumstances. Ideally, inspection and maintenance should be separate activities carried out by different parties.

4.3.4. Prorail: Kap van Barendrecht

Asset:

ProRail is the infrastructure manager of the Dutch rail network. ProRail is responsible for the trackside of the rail operations. For the case study, the Kap van Barendrecht is analysed. This tunnel consists of 5 tubes, in which 9 rail tracks are located. Of these 9 tracks, two are used for the high-speed line, three are used for freight transport and the other four are used for passenger transport between Rotterdam and Dordrecht. This is the only tunnel in the Netherlands where the high-speed line, freight transport and passenger transport are using one tunnel.

This tunnel is a so-called land tunnel, which means the land goes over the tracks, rather than the tracks going underground. However, this is still considered to be a tunnel, which means the rules and regulations for tunnels apply. Furthermore, the general (data-driven) maintenance approach and system administration is the same for all tunnels owned by ProRail in the Netherlands.

FIGURE 19: KAP VAN BARENDRECHT (STRUCTURAE, 2005)

Actors

In the maintenance process of the tunnel, several actors are involved. First, the asset owner is ProRail. The organization uses a matrix system with nine geographical regions, each having a regional manager and specialists. It also categorizes different types of technology or assets, such as ERTMS, train security, CT&U (Civil Engineering and Utility), and rail switches and geotechnics. ProRail has a separate department for ICT and automation that focuses on the digital aspects of assets, and another department that specifically looks at the civil part, including materials and asset structure.

In each region, there are specialists because each area has unique assets. National policies are also translated at the regional level. Central policies and regulations are created and then adapted to the nine separate regions. In Utrecht, there are system specialists who have knowledge and expertise in specific areas to develop national policies. Regional implementation is carried out by subject specialists.

Maintenance contractors are responsible for maintaining a predetermined level of performance by maintaining and monitoring the assets properly. Because maintenance contractors have a more immediate interest in a rapid digital transition (as they are commercial companies), they invest heavily in digitalization. ProRail's pace in this regard is significantly slower. Nevertheless, both parties must reach an agreement. The use of data can sometimes be part of Performance-Based Maintenance (PGO). However, the goal is to make all data the property of ProRail, with maintenance contractors having access to it for the purpose of performing and optimizing maintenance.

Agreements

Contracts with maintenance contractors are standard and run for five years through a tendering process. For each of the nice geographical regions, a tendering process is done, and a maintenance contractor is selected for the region. In the case of the Kap van Barendrecht, Volkerrail is the maintenance contractor.

Communication takes place with various external parties, one of which is Rijkswaterstaat. The Centre for Underground Construction (COB) is good example, as it facilitates knowledge sharing among various parties.

Approach

Currently, there are 20 tunnels that are managed and monitored but don't have continuous data extraction and analysis yet. This means that data is only stored and analysed in the case of a failure. Once the failure is resolved the data is discarded. The Kap van Barendrecht has a new control system, making it suitable for remote monitoring. This has been in place since May 2023.

The current maintenance cycle has two routes. The first route is long-term and primarily involves preventive maintenance based on manufacturer instructions. The second route is known as Performance-Based Maintenance (PGO), where the maintenance contractor is responsible for achieving specified performance levels and must organize the maintenance themselves. This is determined by regional contracts, and the assets included, and maintenance planning depend on the region. ICT has a shorter lifespan compared to civil assets. An inspector from ProRail inspects all assets, and every five years, an external party determines the need for major maintenance. ProRail specialists are called in to establish the maintenance strategy and planning.

Current sensors only report failures and alarms (e.g., high temperature), and data is discarded. The goal for the future is to store relevant data to analyse trends over time. This will help inspectors in identifying the causes of failures and applying targeted maintenance. Initially, the focus is not on adding new sensors but on examining what data can be extracted from the existing systems and identifying information needs. This process begins with the ventilation system, which is the most significant cost component. The long-term goal is to establish a generic approach for all tunnels in the Netherlands, allowing data extraction and analysis to compare tunnels. Sensor maintenance is not currently part of the process. Typically, sensors are integral components and are replaced when the system is replaced. The strategic plan for maintenance at ProRail is developed from practical experience. The long-term plan is being written, and input for maintenance activities is derived from practical experience. This differs from other companies where the approach is often the opposite.

The bridge's components have been divided into two categories: civil engineering components, such as concrete and steel, and installations, as well as IT systems. Components of Civil Engineering and Installations include energy systems (e.g., high-voltage cables), rail systems (e.g., switches), and train security systems that measure factors such as air quality and visibility in a tunnel. This division is made because different systems exhibit different failure behaviours. IT systems become obsolete more quickly and therefore require different maintenance. For example, they may be replaced with a new system sooner, while civil engineering components often only need repairs and have a longer lifespan.

Data quality doesn't play a significant role yet, but cybersecurity standards are considered. The aim is to ensure data can only be read in one direction, and no unauthorized data can be sent into the systems. Data ownership is also a significant consideration to ensure that data remains the property of Prorail.

The effect of digitization on PGO might change how digital functions and failures are handled, potentially altering the form of PGO. Contracts will focus more on providing fault services and ensuring readiness rather than just conducting maintenance upfront. The effect of digitization is that ProRail seeks more control over data ownership concerning faults and issues. Additionally, there is a consideration to remove specific objects like bridges and tunnels from contracts.

Digitalization can help in predicting failures more accurately because it provides insight into the status of a component and allows for analyses of failure behaviour. It also enables benchmarking and increases the efficiency, safety, and speed of maintenance.

Availability indicators

Availability is measured using various indicators, but the primary focus is the percentage of time when trains cannot pass through the tunnel due to unplanned maintenance. It distinguishes between "hinderklasse 1 and 2" (hinder classes 1 and 2), indicating the level of disruption. Prestige requirements that must be met are defined in agreements with the Ministry. Indicators are outlined per theme on prestaties.prorail.nl: passenger transport, freight transport, infrastructure, safety, and environmental sustainability.

4.4. Final maintenance aspect framework

Based on the input from the interviews, some adaptations to the framework have been made, which means that there are some changes compared to the version of the framework that has been presented in chapter 3. After all the aspects in the different blocks of the framework were evaluated, the interviewee was asked if relevant aspects were missing, or if aspects should be adapted and how. The majority of the actors that were being interviewed considered the framework to be complete and no additional aspects had to be included.

The usefulness of the framework depended on the person and function that was being interviewed, because for some people it was hard to imagine how the framework would fit in their tasks and responsibilities. The purpose of the framework is to create awareness of all the relevant perspectives and to act as a checklist when designing new policies and long-term visions. For some of the actors, this is not part of their tasks and responsibilities and therefore the usefulness would be arguable. The main concern was that this picture could become part of the many frameworks and pictures that are used in the business activities. The main change to the framework has therefore been to create a model in which the important aspects all start with an A: Actors, Agreements, Approach, Application and Availability. This may lead to the fact that the model is more memorisable and therefore has a better opportunity of being applied and used. Furthermore, the purpose of the framework should be clear. The idea is to show that maintenance and digitalization are noticeable throughout the entire operational chain, and that insights on the aspects that are included in the framework are essential for a successful digitalization transition.

The framework is adapted in the approach block. The title includes applications as well. The monitoring aspect for which sensors are used, is included in input. The maintenance of the sensor itself is described by an additional block 'conservation'. By applying maintenance approaches to the sensors, itself, the data stream from the sensors is conserved. The final maintenance aspect framework is presented in figure 20. Figure 21 visualizes the difference between the initial version and the new version of the framework.

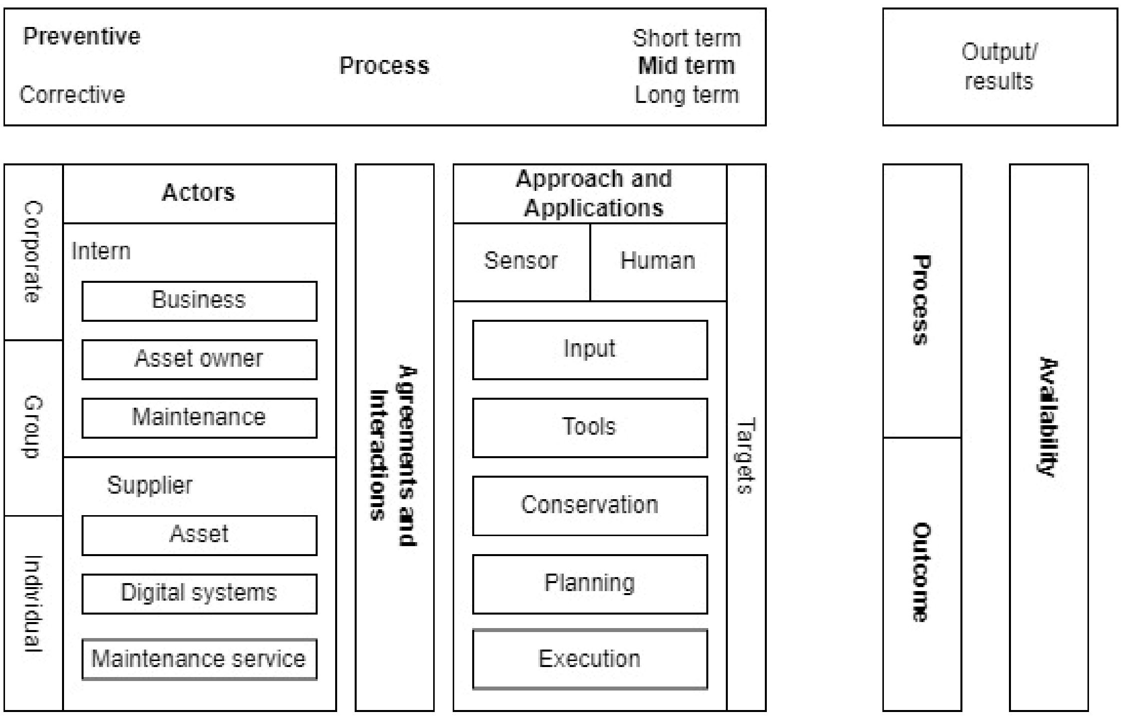

FIGURE 20: FINAL MAINTENANCE ASPECT FRAMEWORK (OWN WORK)

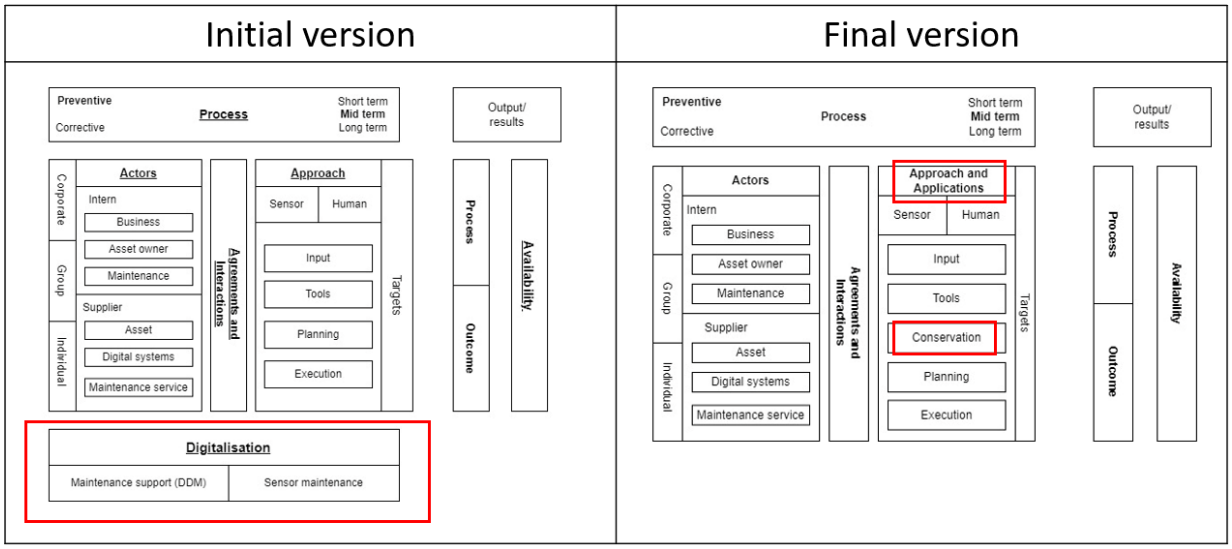

FIGURE 21: DIFFERENCES BETWEEN INITIAL AND FINAL VERSION OF MAINTENANCE ASPECT FRAMEWORK

4.5. Conclusion

Four cases were selected to be included in the research: the SNG (Sprinter New Generation) of NS, the RPA-12 (Rotterdam Port Authority) at the Port of Rotterdam, The Kreekraksluizen at Rijkswaterstaat and the Barendrechttunnel at ProRail. The interviews provided much information, and several insights can be derived from these interviews. These insights are discussed in chapter 5, where the cases will be compared to each other and the literature. The maintenance aspects framework has been adapted, based on the feedback from the interviews. There is more focus how the framework can be designed to be memorized easily, in order to recognize the aspects and to consider the effects. This is essential for the framework to be useful for the intended purpose. The purpose of the framework is to act as a checklist to reflect on current policies and long-term visions and ensure that all relevant aspects of maintenance of digitized assets are included in new policies and long-term visions.

5. Results: case comparisons

In this chapter, the outcomes of the cases will be compared to each other and to the original literature that was presented in chapter 2. This will highlight the differences and similarities between the literature and the effects that are experienced in practice. The cases will be compared with each other to determine the actual effects per aspect of the maintenance aspect framework. Each section in this chapter will evaluate one aspect of the framework. The chapter is concluded with patterns that can be established based on the nature of the assets or the organizations that have been evaluated.

5.1. Actors

Shift in responsibilities of the Asset Management roles

When comparing the organizational structures of the involved companies it can be seen that, in general, all parties work with the known asset management roles. These roles include an asset manager, asset owner and a service provider. This is consistent with the description of the asset management in the literature, as described by van den Boomen et al. (2012) and van der Velde et al. (2013). Van der Velde et al. (2013) described the responsibilities as follows: the Asset Owner is responsible for making strategic decisions and the trade-off between long-term and short-term investments. The Service Provider does the operational maintenance actions and is responsible for reliability, availability, maintanability and safety. Lastly, the Asset Manager is the link between the asset owner and the service provider. The main effect that can be noted is that it can be seen that with the increase in digital system and data use, the monitoring tasks of the service provider is pulled back towards the organization, rather than the external service provider.

The asset management 2.0 program at Rijkswaterstaat is a good example of this shift. Scaldis, the tendered service provider is responsible for monitoring and maintaining a specific performance level, as is described in the pins (performance indicators). However, in the asses management 2.0 a project team of Rijkswaterstaat is determining which data and sensors are required for the specified information needs. Aspects as reliability, availability, maintainability and safety are considered to specify these information needs and to assess the costs, benefits and risks associated with replacing visual (human) inspections, with sensor monitoring.

Multiple actors for one role

Another important change that can be seen in practice is that the tasks and responsibilities of thes roles are carried out by multiple actors. The maintenance process itself is extensive, so mapping the status of the assets digitally and setting up the digital infrastructure to facilitate these activities can be considered as additional tasks. Furthermore, the data that becomes available has to be analyzed and used back in the operations. At NS and the port of Rotterdam, as the asset management team includes roles as Maintenance Engineers and Reliability Engineers who carry out the monitoring tasks of the service provider. For ProRail and Rijkswaterstaat, the division is made between national policy design, and regional policy execution. For ProRail for example, system specialists who have knowledge and expertise in specific areas to develop national policies. Subject specialists translate these national policies into regional implementation plans.

Result per asset management role

The aim for the interviews was to speak with the three asset management roles at all the included organizations. This was because of the fact different actors could have different perspectives and experience different effects as a result of digitalization. This section will address the findings that can be related to each specific asset management role. As mentioned before, in some organizations the asset management roles are fulfilled by multiple actors, so the findings that can be related to a specific role can come from multiple actors. Generally, in each company an asset manager and asset owner was included in the interviews. Therefore, this section will mainly focus on these roles.

For all four organizations the asset manager is often focused on looking back at past failures and how these could have been detected by sensors, and on the short-term future. Whereas the asset owner is often focused on the long-term effects of the sensors and digitalization effects. As a result of this difference in focus, the experienced effects of digitalization are described differently. For the asset manager role, an important effect of digitalization is the ability to support the decisions to change the maintenance strategy that is provided by the supplier. This was mainly the case for the members of the rolling stock team of NS and the asset management department at the Port of Rotterdam. These decisions are related to the moment at which maintenance is executed and the maintenance activities itself. Furthermore, the main potential advantages of digitalization is considered to be able to discover trends in the failure pattern and work towards a more condition-based maintenance strategy. These effects are mainly related to the short-term future. Another important effect, mentioned by the asset managers specifically is the ability to look at past data from failures that already occurred and to see what data is required to prevent these failures to occur in the future.

Because of the more long-term perspective of the asset owner, the effects mentioned by people with this role are different, compared to the asset managers. Data and digitalization provides the possibility to gain insight into all the assets in the Netherlands, which helps to prioritise the maintenance activities. This was mainly the case for Rijkswaterstaat, as they experience a overload on scheduled maintenance activities because of the COVID pandemic and the new nitrogen regulations. Furthermore, there is more focus on the effects of digitalization on the overall business operations. The Port of Rotterdam provides good examples, as they stated that digitalization also plays a large role in the communication with the arriving and departing vessels. This is essential for an optimal flow in the harbour area. Lastly, the focus of the asset owner was often on the acquiring of new sensors, based on advice from the asset manager. The asset focuses on what data can be retrieved from systems that are already present currently. The data and information that cannot be retrieved yet, is translated into the advice for new sensors that is provided to the asset manager.

Development in required knowledge

The increasing number of digital systems requires a different approach for the maintenance activities and the required knowledge and tools. In all fours cases is became apparent that computers are and will be a vital tool in the maintenance approach. Not only because this will be the first step to determine the required maintenance, but also because it has to be used for the maintenance itself, in the form of software updates. The latter was not as apparent in practical examples. Furthermore, more digital systems require different knowledge from the actors that are involved in the maintenance process. Challenges that were often mentioned are about determining which data can be used to make certain predictions about the state of a component. It was often described as the connection between the traditional mechanical approach and the IT systems. Furthermore, knowledge how to execute more digital maintenance tasks, such as finding bugs and faults in software requires different knowledge as well.

The role of the Asset User

Singh et al. (2019) introduced the role of the asset user, which is used by NS. The responsibility of the asset user is to determine the long-term plans, regarding network design, timetables and asset demands and employment. Currently, this role is fulfilled by the Network Design and Development department (N&O). In the other cases, these responsibilities seemed to be executed by the asset owner, which raises the question why a separate asset management role has to be distinguished. The transition towards data driven maintenance is a long-term process and therefore, has to be included in the long-term plans, which are made by the asset user according the the definition of Singh et al. (2019). The role of the Asset Owner, according to the definition is to make decisions based on the long-term and short-term plans. In the case of the Port of Rotterdam, the responsibility of the Asset User is included in the responsibilities of the Asset Owner. When comparing the two cases, the added value of a separately defined asset management role is hard to detect. In other words, the tasks can be done by two different parties but the added value of the separate role of asset user in practice is hard to uncover. The effects on the interaction within the organization of this additional role will be discussed in section 5.3.

5.2. Approach

In general, in all four cases a similar transition can be observed. In every case, there are examples of corrective and preventive maintenance. For the preventive maintenance, the aim is to use data to support the transition from periodic, or scheduled maintenance to condition-based maintenance.

Change in maintenance frequency

According to the literature, the increase in digital systems will result in more maintenance moments, as digital systems include more software, which needs frequent updates. It is interesting to see that currently this is not (yet) the case. More digital systems are being included and once they have been implemented and working, they can be updated regularly. Therefore, it is interesting to see that in the case of the Port of Rotterdam, the number of maintenance cycles have been reduced, as a result of more digital systems. This is the case because the systems provided insights that showed that less maintenance cycles would be sufficient, rather than the digital systems needed to update. Nevertheless, the example shows that there could be an intermediate phase in which the number of cycles is going down, before it has to be increased again.

Timeline of digitalization transition

Additionally, a general timeline of the transition process can be made which includes challenges and pitfalls that are relevant for all the organizations. All the cases can be located at this timeline, based on the challenges and pitfalls that have been overcome. Figure 22 shows a schematic visualization of such a timeline. All the challenges that have been identified in the interviews are included in the form of troughs. Also, the four organizations are plotted in the timeline to show the progress of each organization in the transition process. The time line is designed with a stair-like pattern, because once a part of the transition process has been completed, there is some time to get used to the new situation and determine a plan to start the next phase of the transition process. This is indicated with a horizontal phase in the time line. The framework that is presented in chapter 4 can support organizations in this transition process, by functioning as a checklist and guideline for the plan to reach the next phase. A more specific description of how the framework can be used for this purpose will be provided in the implementation plan in chapter 6.

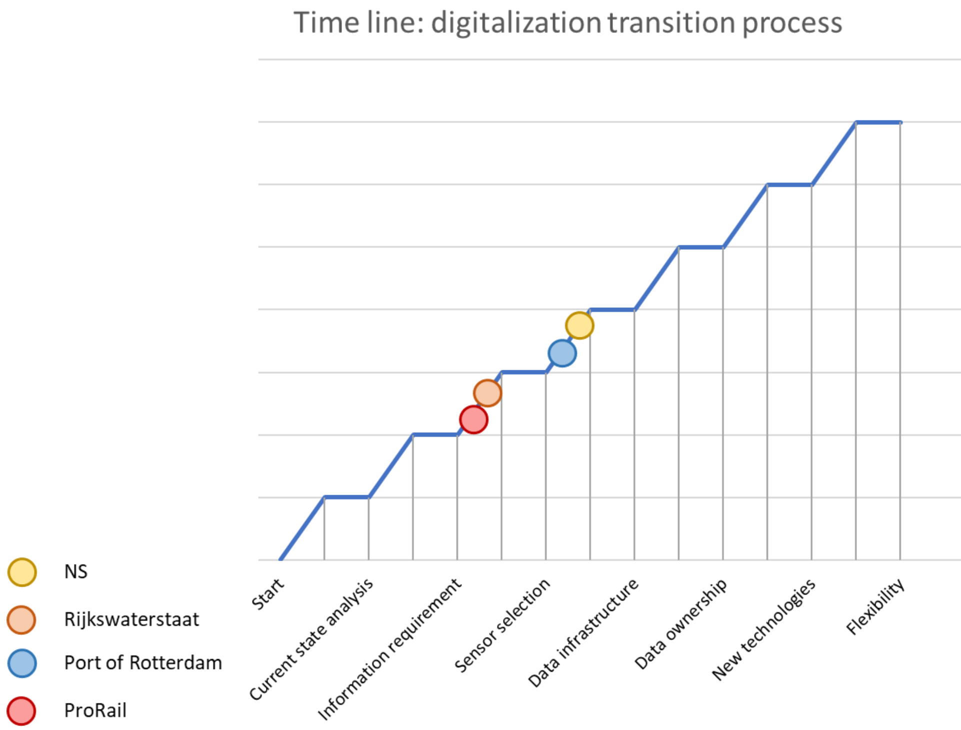

FIGURE 22: TIMELINE: DIGITALIZATION TRANSITION (OWN WORK)

The challenges that are included in the timeline start with a thorough analysis of the current state of the asset. In this phase, the available information on the asset is collected and analyses. This includes information such as the age, the building materials and all maintenance that has been done to asset. Additionally, the missing information is identified, and specific actions are set up to track down this information. This is the information requirement. The next step is to determine how the data can be retrieved and how the data can be translated into information. In the case of information about the current state of the components of the asset, a sensor can be used. Before applying the sensor, the missing information should be linked to possible data output from a sensor and the method of translating this output to useful information which can be included in the information file of the asset and support to create a comprehensive image of the asset. During the whole process of identifying missing aspects, determining how the missing aspects can be acquired, the acquisition process and the managing all the data, information and knowledge, the knowledge management rainbow (Herder et al., 2004) might provide useful guidance. It emphasizes the fact that it is a process to transition from data to information to knowledge and that it plays a role in all the levels of an organization.

Another important aspect, which is often overlooked, is the input that can be obtained from the users of the asset. Based on the findings by Seely Brown and Duguid (2002) the human input has be considered in order to have a succesful maintenance approach. It is also included in the idea of knowledge mapping in te Knowledge Management Rainbow (Herder et al., 2004), where it is investigated which knowledge and expertise is present among the actors within the company. Human users can provide inisghts that cannot be obtained by a sensor. For example, the cab driver of the train, or a mechanic in a tunnel. Their knowledge and more important, their experiences in practice can be useful input to improve the maintenance strategy. Additionally, human input can be used as a maintenance tool. For example, NS uses a telephone connection for the cab driver in case of a defect to support the driver in fixing the issue. Seely Brown and Duguid (2002) mention the example of Xerox in which mechanics dicuss the defects they have experienced which results in a very effective maintenance approach, compared to a maintenance manual. Defects can be better detected and fixed quicker and more effectively.

Another important aspect to consider is the required data quality and how this quality can be measured. Based on the data, important decisions will be made. Moreover, during the interviews it became apparent that the long-term goal for the organizations is to work towards a form of asset management, in which decisions are based on data only. Therefore, it is important to have clear agreements within the entire company on what the requirements for data quality are and what indicators will be used to measure the data quality, as is suggested by the CGI levels in the knowledge management rainbow (Herder et al., 2004). These agreements are not fixed, because of the many effects that play a role in the transition process. For example, the quantity of data will change, and the data infrastructure will adapt, which means the requirements need to be adjusted according to the surroundings and environment. The importance of the company-wide agreements is also underlined in the fact that there should be a general trust in the reliability of the data in the entire company. If this is not the case, people might not follow the predetermined procedures as they do not trust the data.

When a plan for information acquisition has been made, a plan for the data infrastructure should be made. Since this step occurs more often than once, as the beginning of the set up needs to be a base for all the digital systems in the future. A proper infrastructure is therefore vital for a successful digitalization transition. Part of this infrastructure is to think about how issues like cybersecurity play a role and how these risks can be mitigated.

The next step is to make agreements with the collaborating parties on the data ownership. Again, this can change as the environment changes, but it is important to consider this and fix this contractually. In the next phase, new technologies are considered. Examples are the use of Artificial Intelligence (AI), Augmented and Virtual Reality (AR and VR). Often these new technologies need sufficient and reliable input in order to be effective. Therefore, this can be considered after the data input stream is secured and the reliability is guaranteed. The last aspect of the timeline is flexibility. As mentioned earlier, many agreements and decisions have to be made several times and adjustments need to be made according to the environment. An organization needs to be flexible to be able to manage these adjustments properly.

It is important to note that this is a schematic visualization. Even though it is called a timeline, often the events do not occur as sequentially. Furthermore, flexibility is required throughout the whole process, similar to properly skilled and trained employees. In order to make decisions in each step, the required knowledge has to be present, or it has to be acquired first. Lastly, throughout the timeline, many decisions have to be made, which will need a vision or strategy as a base. This strategy needs to be clear throughout the whole process and organization. Furthermore, the timeline is visualized as a line with peaks and troughs to represent the process with peaks and pitfalls. Naturally, the shape of the line depends on the context and the organizations' ability to deal with pitfalls, learn from it and apply it in practice.

Position of the organizations in the timeline

The four cases are plotted in the timeline, as can be seen in figure 23. As mentioned before, the transition process is not as sequential as is visualized in the timeline. Some activities and phases can be done simultaneously, and activities and phases have to be executed multiple times. This is important to keep in mind when considering the position of the organizations in the timeline. Being in front of the line, does not necessarily mean that this organization is the furthest ahead in the transition process. Nevertheless, some notes on how the positions in the plot are determined can be made.

The position of all cases is relatively close. However, it can be seen that NS and the Port of Rotterdam have passed the challenge of sensor selection and are currently working in the data infrastructure. This is based on the fact that these parties have assets which already include many digital systems and data providers, resulting in the fact that the focus lies on extracting what is already present in the asset. Whereas Rijkswaterstaat and Prorail are placing separate sensors on top of the existing systems, which means they have to select which data has to be extracted and which sensor can be used for that.

An important distinction that can be made between the organizations is the priority of data quality. NS has been positioned most upfront, as they have a specific list of indicators which is used to measure the quality of data. This is done for internal data and information and will be done for information coming from the sensors. For the Port of Rotterdam, Rijkswaterstaat and ProRail, such indicators were not available. Furthermore, the interviews showed that establishing standards for data quality and define rules on what the minimum levels have to be are not the highest priority currently. This is why these organizations are positioned at an early stage in the timeline.

In chapter 6, an implementation plan will be provided that describes how that framework can be applied to proceed to the following phases in the time line.

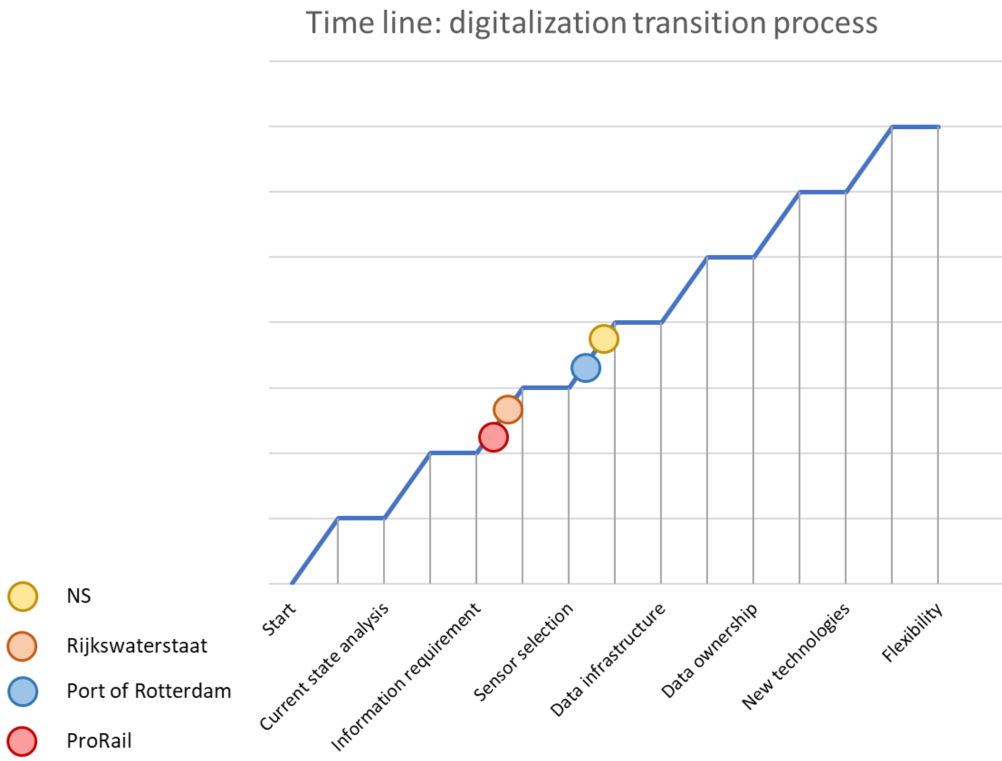

FIGURE 23: TIMELINE: DIGITALIZATION TRANSITION (OWN WORK)

Driver behind the maintenance activities

The actual maintenance activities have been described for each case in section 4.2. For the comparison of the cases, it is interesting to consider the driver behind the current maintenance approach. As can be seen in the timeline a clear strategic vision is important, but for each case an additional motivation became clear from the interviews. For NS, the main important aspect in each decision or consideration is safety. Sometimes the overall attitude can be reluctant to take risks as this could endanger the safety that must be guaranteed. In practice this can be seen in the fact that Maintenance Engineers and Reliability Engineers evaluate data to improve the maintenance cycle. There is more potential for extracting data from the rolling stock towards these actors, but the impression exists that this is not the highest priority. For ProRail, the driver to work towards more condition-based maintenance is to keep up with the other parties in the sector. Maintenance contractors benefit from properly installed digital system and being able to adjust the maintenance approach to the data from the system, as they can earn more money. The Port of Rotterdam wants to maintain status as global port and therefore needs to facilitate relevant information to the parties that they collaborate with. Retrieving this information can be done by using sensors. Lastly, Rijkswaterstaat has a lot of assets that are due for maintenance in the near future, but they do not have the capacity to execute all these maintenance activities. To make supported decisions on what maintenance activities can be postponed, data is required. For many assets of Rijkswaterstaat, the maintenance activities and state of the asset has not been documented properly, so there is a lot of missing information.

The role of data quality

According to van der Velde et al. (2013), adequate data quality is essential for successful asset management. This can be reached by using the three instruments: objectives and standards, plans and contracts. Objectives and standards are often included in the long-term plans designed by the headboard of the company. In all four of the cases the transition from tactical to strategic to operational level can be seen in specified documents. One important note can be made however, the method of this translation is not always straightforward, or known on all levels of the company. Namely, some of the actors that were being interviewed did not have knowledge on how this process is done. Another important aspect of including data quality in the company-wide standards is that this contributes to a general trust in data quality and reliability of the data. This allows employees to use the data in the business processes and to allow decisions being made, merely based on the data. This is especially important when companies intend to work towards processes that are managed by artificial intelligence (AI) tools, which only use data as an input. During the interviews, the case of the Port of Rotterdam showed that AI was definitely a tool that was considered to be part of their future operations.

The next instrument is plans, which includes documentation on how budgets are determined and assigned, how the network can be optimized and what the maintenance plans are. Again, insight on how these plans are determined could be improved in some cases. Moreover, most of these plans are being redesigned such that data use and digitalization is included. The last instrument are the contracts, which includes service level agreements (SLA) and internal agreements. These agreements are being affected by digitalization as well and are therefore redesigned as well. The next section will elaborate on this aspect. In practice, data quality was not the highest priority for three of the four companies. Only NS could show a list of indicators which is used to determine the data quality. They check data by six dimensions, which are the following complete, accurate, time-bounded, valid, consistent, and uniform.

The plans that are mentioned as one of the instruments are also the basis for the establishment of the maintenance planning. For all four cases, major changes to the maintenance planning itself have not been made yet. The framework, proposed by Coetzee (1999) is based on the trade-off between reliability estimation and maintenance costs. This trade-off was an important aspect of the maintenance strategy, based on the interviews. Furthermore, this trade-off is also used to determine which sensors can be used to increase the reliability of the asset, for a manageable price.

5.3. Agreements and Interactions

Data ownership

As mentioned in section 5.1, the responsibilities of the service provider are executed by multiple actors. As a result, the relationship between the organization and the service provider is changing. The digital infrastructure is built, and the requirements are established by the organization and the exact role of the service provider is currently established. Issues such as data ownership plays an important role, which can be seen in the cases as well, because all four organizations aim at being the owner of the data coming from the assets. The service providers have the authority to use the data and analyse it to execute and optimize the maintenance activities.

Duration of maintenance contracts

As a consequence, the agreements between the different asset management roles are changing. A general trend can be seen in the duration of the contracts. Digitalization is considered to be a long-term process and setting up the digital infrastructure properly and to identifying trends in the outcoming data, requires time. Furthermore, the process of digitalization starts at the design process of an asset. This aspect of the process was considered to be out of scope; however, it forms the basis of a more long-term agreement between the supplier and the organization as the supplier offers more support in all phases of the process. In the design process, there is more collaboration on the possibilities on what technology can be included in the new asset. Since digital systems develop quickly and the design and tender process can be elaborate and lengthy, some flexibility is required to deliver an asset with the latest technology. Once the asset is delivered, these systems need to be maintained such that the warranty from the supplier is retained. Furthermore, the supplier often has much knowledge and expertise about the (digital) systems, which is useful for proper maintenance. All of these long-term interactions are included in so called Service Level Agreements, in which the service from supplier is contractually secured.

Translation of long-term plans into maintenance activities

As mentioned in section 5.1. the role of the asset user is only formally denoted within NS, which raises the question whether it is necessary to distinguish this additional asset management role. Furthermore, is there a noticeable effect as a result of this distinction. Generally, it can be seen that the overall vision of the company is translated into estimated requirements for the assets. For example, if a company wants to grow, more train sets or vessels are required. These requirements are included in a set of long-term plans which are developed on a national level in all four cases. Specifically for maintenance and asset management, the long-term plans are translated into a so-called Strategic Asset Management Plan (SAMP). In practice, it can be seen that at NS this is done by the asset manager, whereas at The Port of Rotterdam this is done by the asset owner. Even though, tasks are done by an actor with a different role, the process is similar in all four cases.

Interactions between the asset management roles

Important to note is that a potential effect does not only depend on if all the tasks are executed. Especially, in the case of a large number of assets and a variety of assets, it is important that the asset management plan is specific enough to be able to translate it into maintenance activities for a specific asset. Again, the Port of Rotterdam and NS prove to be a good example to clarify this. A schematic representation of the Asset Management roles and responsibilities is visualized in figure 24. It can be seen that in the case of NS, the translation of the long-term plans to the SAMP and into maintenance activities is done by the asset manager level, whereas this is done by the asset owner and the asset manager at the Port of Rotterdam. Asset specific translations are done by the actors in the level that is closer to the operations at NS. It could be argued that this leads to more asset specific strategic targets in the SAMP as the actors with knowledge on specific assets are creating the SAMP. In the case of the Port of Rotterdam, the asset owner is responsible for all the assets of the organization. To come to a successful result, there has to be a good communication between the involved parties is essential. Looking at the schematic representation, it could be argued that the structure of the port is more straightforward, which makes maintaining the essential communication line much easier.

Therefore, it is concluded that in practice there no specific effect of an additional asset user role in between the asset owner and asset manager could be identified. It can be said that because maintenance and asset management is an extensive process, many actors are required to execute all the tasks and activities. However, too many roles could also result in the loss of overview resulting in activities not being done or no insights in responsibilities.

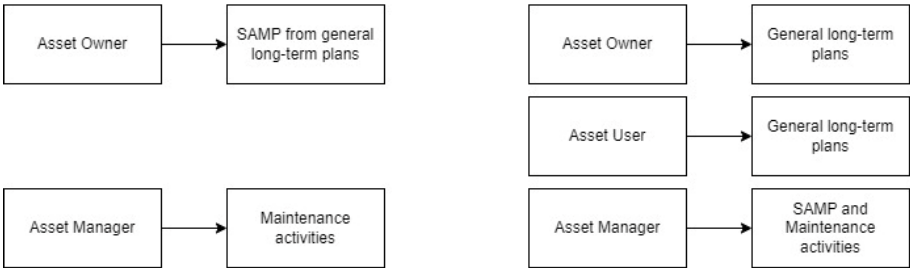

FIGURE 24: ASSET MANAGEMENT ROLES AND RESPONSIBILITIES OF PORT OF ROTTERDAM (LEFT) AND NS (RIGHT)

Asset management in different organizational structures

Apart from the asset user as an additional asset management role, a difference in the approach of asset management can be observed for the cases. In some cases, the asset is compartmentalized, and tasks and responsibilities are assigned accordingly. Figure 25 shows the organizational structure related to the asset management for each case. It can be seen that at NS the organization is divided for all train set types and for all production chains, or systems. This is represented in a matrix-like structure in the top left figure in figure 25. For ProRail the organization is divided over geographical regions, and for each region the asset management is done. Similar to NS, a division is made between the different systems and structures that are present in the assets. For ProRail this is called, Civil Engineering structures and digital installations. This is represented in a matrix structure in the bottom left figure in figure 25. At Rijkswaterstaat, the asset is considered as a whole and managed by people from national and regional departments. At the port of Rotterdam, the assets are divided in categories, but for the vessel that is considered, the asset is managed as a whole.

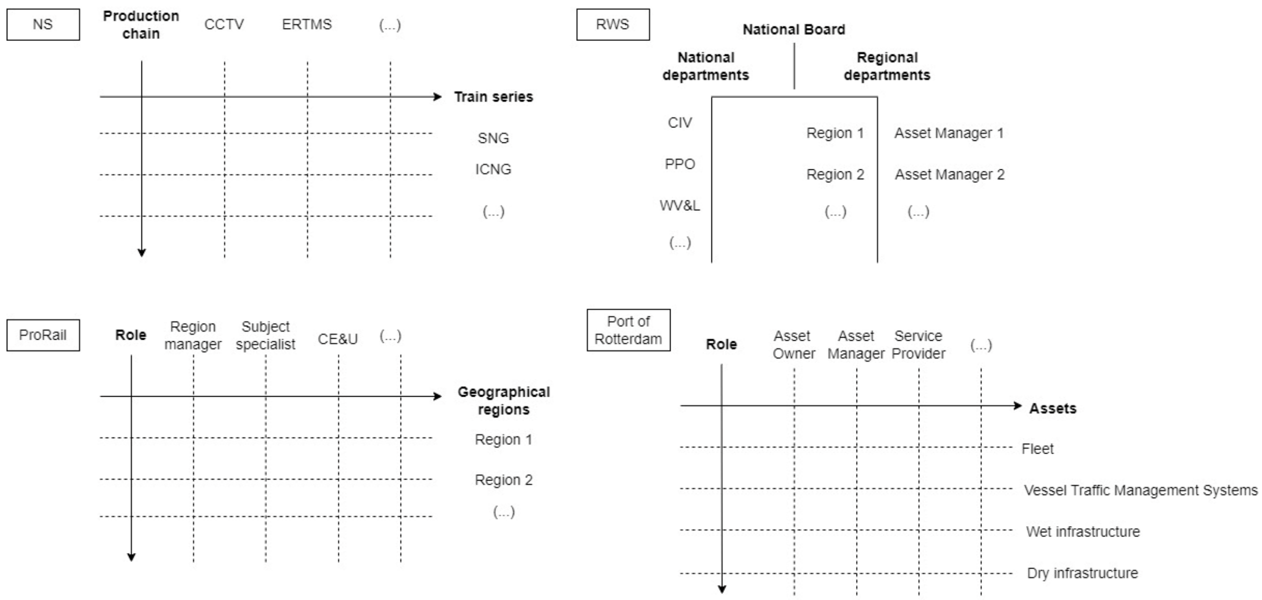

FIGURE 25: ORGANIZATIONAL STRUCTURE ALL CASES (OWN WORK)

From these insights, different notes can be made. First, the organization by geographical regions at Rijkswaterstaat and ProRail requires the actors to have knowledge of different types of assets in a region, rather than knowledge of a specific asset type. For NS and the Port of Rotterdam the division is made, based on the asset type, and at NS even on the system within the asset type. This provides very specific knowledge but requires more actors that are involved in the process. The effect of digital systems in these operations can be seen in several aspects. First, digital systems make it possible to share knowledge between different regions on similar assets. For example, data of a tunnel in Groningen can be compared with a tunnel in Maastricht. Moreover, if the contracts allow, data can be shared with different parties. For example, ProRail and Rijkswaterstaat would be able to share knowledge on tunnels in the Netherlands. Another effect of digitalization can be seen in the required knowledge of the specialists. New digital systems could add actors to the matrix, which can increase the complexity of the organizational structure. For example, for NS, more vertical lines have to be added to the matrix.

5.4. Availability

For all assets availability is an important performance indicator. It is measured differently for each asset, which often means it is measured by multiple different indicators. These indicators have been discussed in chapter 4. When comparing the approach of the four cases it can be seen that availability is indeed an important aspect, but often other aspects play a role. In the comparison of the maintenance approach in section 5.2. this issue was already described. However, the effects of the different drivers behind the maintenance approach can be observed in the availability measurement. Moreover, depending on the role in the maintenance process, actors even work towards different performance measures than availability. Examples can be minimizing risk, such as limiting specific defects with a high risk, or minimizing costs, by evaluating which sensor has to be implemented on an asset. The main conclusion is therefore that availability is not the only important performance measure for asset management.

5.5. Additional comparisons: similarities

Between the cases some similarities noted and therefore couples between the cases can be established. These relationships might result in more interesting insights that are more related to the sector or the type of asset. A table with the comparisons can be found in figure 26. The four organizations are represented at the top row and the asset features are represented in the left column. The features that are included are the asset type, the sector, the level of influence by the government, the number of types of assets owned by the organization and the party that is executing the maintenance.

	NS	**Port of Rotterdam**	**Rijkswaterstaat**	**ProRail**
Asset	**Train**	**Vessel**	**Lock**	**Tunnel**
Asset type	Moving	Moving	Fixed	Fixed
Sector	Rail	Port	Water	Rail
Government	No	No	Yes	Yes
# types of assets	Few	Many	Many	Many
Categorization	Type	Type	Region + type	Region + type
Maintenance	Inhouse	Inhouse	Tender	Tender

FIGURE 26: ADDITIONAL COMPARISONS (OWN WORK)

First the asset type might influence the effects of digitalization on the maintenance approach. In the cases that were considered, two moving assets (NS and Port of Rotterdam) and two fixed assets (Rijkswaterstaat and ProRail) were considered. The main difference in practice is that for maintenance is brought to the asset of the asset is brought to the maintenance. Mobile maintenance could be an implemented for moving assets, which results in different effects on the operations as the train or vessel does not have to be brought to a maintenance facility. For fixed assets, the only option to apply maintenance is already to bring the service provider to the asset, so the fixed type of asset has less options. The possibility to bring the service provider to the asset, and the asset to the service provider for moving assets could lead to more opportunities to optimize the maintenance process, based on data. If it is possible to predict failures accurately and there is no space in maintenance facility to apply maintenance, there is still the possibility to send a mobile maintenance crew to the specific asset. For fixed assets the location cannot be changed, which leads to a restriction for the optimal (dynamic) maintenance process.

Another distinction that can be made is the sector in which the assets are being operated. Two assets belong to the rail sector (NS and ProRail), one asset in the port sector (Port of Rotterdam) and one the in the water management sector (Rijkswaterstaat). In the interview few specific sector related effects were observed. However, some examples were mentioned about how actors work together in the same sector and learn from each other and even work together. For example, ProRail uses measuring equipment in trains of NS to determine the state of the tracks and vice versa. Rijkswaterstaat and ProRail work together in organizations like COB (Centre for underground building) to share best practices. A conclusion that can be made is that different collaboration is possible and might also be required. As stated earlier, ProRail and NS use each others equipment to measure the state of their assets, which is a form of collaboration that will likely increase as the digital systems on board of the assets increase. The first steps of these sorts of collaboration and data exchange will likely stay within the sector, but might expand and include multiple sectors. For example, the Kreekraksluizen might include cameras to monitor the exterior of the vessels that pass through the locks.

Furthermore, the influence of the government is for some of the cases larger than for other cases. Since all assets operate in the public domain, some governmental influence is present for all assets. This was visible at Rijkswaterstaat for example, where the sensor was selected by a different department to make sure a national approach was maintained. At the Port of Rotterdam for example, this was not the case, and the decisions can be made by same actors that make the requirements and evaluation for the sensor. Potential effects of high levels of governmental influence could affect the types of sensors that are used and how they are used. For example, budget could play a role which could lead to less frequent measurements, or lower quality measurements. This could play a role in the collaboration between organizations that are mentioned earlier, as these organizations could become less popular to collaborate with if the data quality is insufficient. More of these potential effects could be possible.

Additionally, the number of different types of assets within an organization can have an effect. More different types of assets means that more knowledge has to be present in the organization or has to be acquired. Furthermore, it has an effect on whether it is possible to apply a similar procedure to all assets or not. For digitalization this means that different approaches and sensors are used for different asset types. For example, NS can use a similar sensor in all trains the measure the roundness of the wheels. Rijkswaterstaat on the other hand, can use sensors to measure the level of the water for locks. However, these sensors might not provide relevant information when applied in tunnels or bridges. In practice, this could mean that for multiple types of assets, multiple strategies have to be developed, whereas for one type of asset, one strategy might be sufficient. Furthermore, it might be easier for employees of an organization to follow one strategy, in stead of keeping multiple strategies in mind.

Lastly, an important difference can be seen in the decision if maintenance is done inhouse or, if is outsourced to a different party. When maintenance is outsourced, specific knowledge on the asset or component is part of the maintenance agreement, which can be advantageous. This knowledge does not have to be present within the company and employees do not have to be trained or educated to gain the new knowledge. On the other hand, this requires contractual agreements which are especially complex with the addition of data use and data ownership. The effects of doing the maintenance inhouse and digitalization could be that these agreements are not necessary and that the contact between the mechanic and the maintenance designer could be more frequent and accessible. For the digitalization transition, it is important to determine what knowledge is present inhouse and what the focus of the organization is. If maintenance is done inhouse, there should be knowledge about the IT-systems and the mechanical systems and this knowledge should be maintained and kept up to date. There also has to be a sufficient number of mechanics and facilities with proper tools to execute the maintenance. These decisions are closely related to the number of types of assets that are present, because the more types of assets there are, the more divers the requirements for the knowledge, mechanics, facilities and tools are.

Generally, based on the features of the asset and the organization, the current approach of the four organizations that have been considered is in line with the expected maintenance strategy. All the organizations are approaching the digitalization transition in their own way, but they seem to follow a similar path, which is represented by the timeline, described in figure 23. Based on the features, more specific conclusions can be drawn about the expected and actual maintenance strategy. The fact that NS and the Port of Rotterdam have moving assets allows these organizations to move the asset and the maintenance crew. For both parties, the combination these options is included in the possibility to optimize and adapt the maintenance strategy. For the fixed assets of ProRail and Rijkswaterstaat, there is only the possibility to move towards the asset. This insight can be connected to the tendered maintenance, the categorization of the assets and the number of types of assets, owned by these organizations. There are many assets, with fixed locations all over the country and the maintenance of these assets is assigned to a external service provider. It can be argued that this is the expected approach, because of three reasons. First, the country can be divided into regions, which is the case for ProRail and Rijkswaterstaat, which makes it easier to access the assets more quickly for the service provider. Furthermore, there are less assets in the region, which makes it easier to monitor the state and required maintenance of the all these assets. Lastly, when there are less assets in the region, less knowledge and resources are required. This can be different, when there are different types of assets in a region that require specific knowledge, rather than one type of asset in one region. Nevertheless, less assets means that overall less information is required.

5.6. Conclusion

Many of the aspects that are mentioned in the literature can be considered to be relevant, based on the interviews. In all four cases, the focus on the trade-off between reliability and costs was clearly noticeable. This was the case for considerations about the maintenance activities and how these should be prioritized and executed, but also for the sensor selection. The four organizations are in a similar position in which they are shifting from a combination of corrective and scheduled preventive maintenance towards condition-based preventive maintenance, with the aim of reducing the unexpected failures and therefore having no corrective maintenance. A general timeline can be made, which includes the phases and activities that organizations go through during the digitalization transition.

Furthermore, some conclusions can be made on the effects that are experienced and described, based on the asset management role. During the interviews the two main roles that have been included are the asset manager and the asset owner. The main focus of the asset manager was related to events that have occurred in the past and the events that will happen in the near future, whereas the focus of the asset owner was more on the overall operations of the entire organization and the long-term business processes. The effects that were mentioned by the asset managers for example include applications such as looking back at failures that have already occurred and investigating if this could have been prevented, based on the available data. Effects that were mentioned by the asset owner are for example the possibility of monitoring the state of the assets in the entire country and being able to prioritize the maintenance activities.

The cases have been compared based on similarities between the features of the asset or the organization. The features that are included are the asset type, the sector, the level of influence by the government, the number of types of assets owned by the organization and the party that is executing the maintenance. Because this was not the main focus of the interviews, there is limited possibility to make hard conclusions, but some notes have been made. The moving assets allow for more possibilities to apply maintenance, as the maintenance crew can go to the asset, or the asset can go to the maintenance facility. This can be advantageous when working with a more data-driven, or condition-based maintenance strategy. Digitalization of assets in the same sector could lead to a different form of collaboration between the involved parties. For example, NS and ProRail use each others equipment to measure the state of their assets. This collaboration also allows to learn from different parties. In the future this new form of collaboration and learning possibilities might expand over multiple sectors. Also, the level of influence by the Dutch government could play a role, as they might set rules and regulations for which sensors to use or which procedures to follow. Furthermore the number of types of assets that are present in an organization could play a role. When there is only one type, or the assets are similar, one vision might be sufficient, whereas this might not be possible for multiple types of assets. Creating a long-term vision has proven to be a complex process, as many aspects of the digitalization transition are uncertain. Lastly, the fact whether maintenance is done inhouse or outsourced is considered. Because of the new and different knowledge is required for the digital systems and maintenance requires many resources, this decision needs to be made based on many considerations.

When inspecting the table with similarities, based on the features of the assets and the organizations, some expectations for the maintenance approach can be made. Particularly, there seems to be a connection between the following features: the tendered maintenance, the categorization of the assets and the number of types of assets, owned by these organizations. It is expected that maintenance is outsourced, because of the numerous types of assets, or the location of the asset, because it could require too much specific knowledge and resources to be able to manage the maintenance process from within the organization that owns the asset.

The main difference between the literature and the cases is the focus on having a uniform strategy and vision, which is noticeable throughout the entire company and the decisions. To some extent a vision is present, but often not all employees are aware of what the vision is. Moreover, the process of how this vision is translated into decisions is often unclear. Furthermore, data quality is considered to be an aspect that will be dealt with once the data infrastructure is ready, however it is suggested that this has to be considered simultaneously as part of the data infrastructure, to guarantee that the data from the sensors is useful and reliable for basing maintenance-related decisions on.

6. Implementation plan and recommendations

This chapter will describe how the findings from the interviews and the comparison of the interviews can be translated into recommendations and an implementation plan. The implementation plan includes a description on how the recommendations should be implemented and who should be responsible. The findings from the interviews and comparisons will be reflected on the current maintenance vision of NS. This is done because of two reasons. First, the way of working is represented in this vision, which makes sure that recommendations are more likely to be implemented. People are already working towards these goals and the base of the strategy does not have be reinvented. Secondly, this allows to point out which aspects are already present in the vision, which can be advantageous, because it is good to know that the organization is already working towards the desired direction.

6.1. Implementation plan

This section describes how organizations in general can use the framework to progress in the digitalization transition timeline. The implementation plan will include specific actions and considerations that can be derived from the framework. The structure of the framework will be the base of the plan. Therefore the structure of the section will be in the following sequence: process, actors, agreements and interactions, approach and application and availability. Figure 27 shows the framework again to provide an overview of the aspects an the concepts that are part of each aspect. Figure 28 shows the time line and the phases that are included to be able to connect it to the implementation plan.

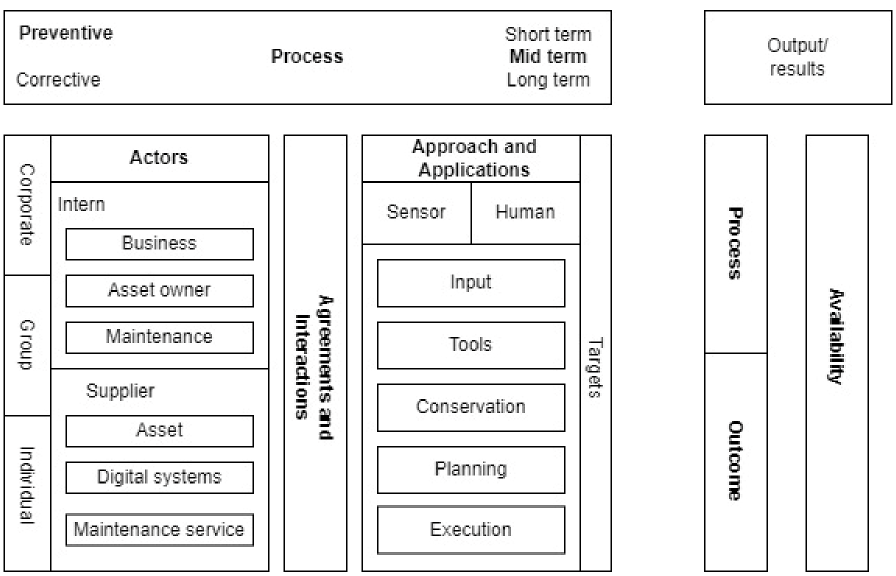

FIGURE 27: FINAL MAINTENANCE ASPECT FRAMEWORK (OWN WORK)

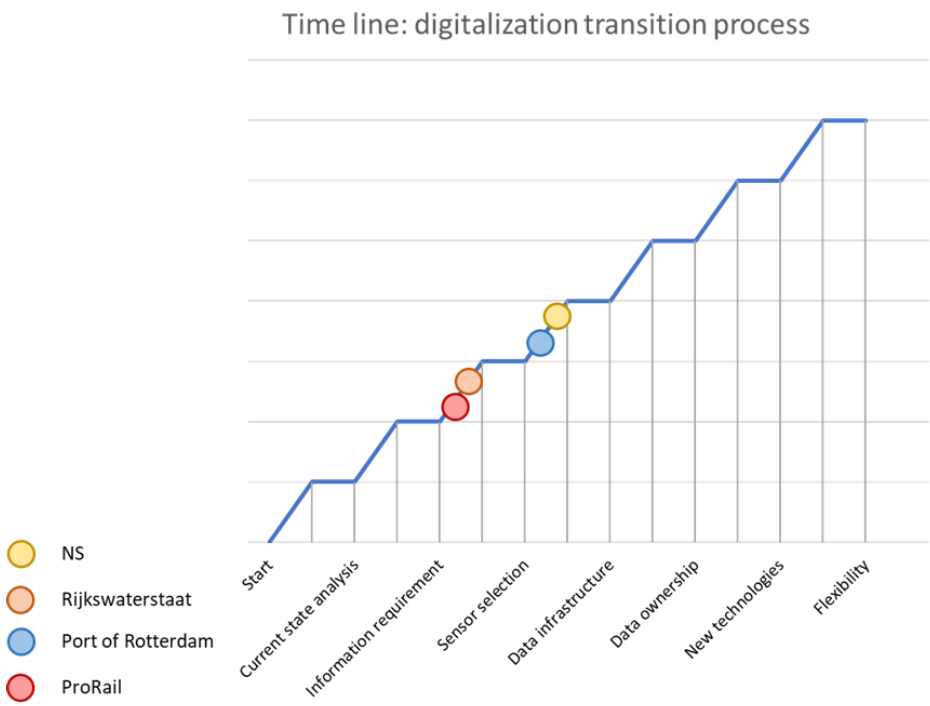

FIGURE 28: DIGITALIZATION TRANSITION TIMELINE (OWN WORK)

Process

This part of the framework includes creating an overarching visualization of the process. This can be used for the upcoming steps and it allows to zoom out between throughout the evaluation process and consider the entire process as a whole.

The first step is to do a current state analysis, because this is the first phase in the time line. In order to do so, a visualization of the entire process has to be made. The steps that are included are.

- Sketch out the entire process. Define a clear beginning and end of the process and visualize all the process steps that take place in between the beginning and the end. The framework is created with a focus on preventive maintenance and mid-term perspective, so it is advised to used the same scope. Otherwise, the process mapping process might become too complex, or elaborate. It is important to include all the activities, because even the smallest activities have to be included in the evaluation.
- Describe the tasks and activities that are executed during all the process steps. This helps to identify all the actors that are involved and what interactions take place.
- Describe which data is used, created and passed on to the next process step. Mapping the data flow can help to show where in the process data is translated into information and into knowledge. These point are important, especially combined with the actors that are involved in this translation process, because valuable information or knowledge is created.
- Identify the value streams in the process. In addition to the previous point, it is important to map where in the process value is added to the process. As said before, this can be in the form of translating data into information, but also by combining information to create a more elaborate overview. To do so, it is important to determine what is considered valuable by the company.

Actors

When the process is visualized, the actors that are involved in the process can be included in the process map. Furthermore, more information on these actors can be included in the process map.

- For each activity in the process map, determine which actors are involved.
- Describe per actor the following aspects:
  - Function title and the standard asset management role that is most closely related to this function. In the framework, this is included as business (asset manager), asset owner and maintenance (service provider) for internal actors. For external actors, this is related to the supplier of asset, supplier of the digital systems and the maintenance service.
  - Position in the organization. Once multiple actors have been identified, groups can be created, based on which actors work together. This can be linked to the CGI-levels that have been described by Herder et al. (2004) in the knowledge management rainbow.
  - Tasks and responsibilities of the actor. What activities are executed by this actor, and equally important: why is this actor in particular doing these activities? This is important to determine the added value of the process steps. Making evaluations like this could provide insight into activities that are not necessary, or do not play a role in the value streams of the company. Additionally, which information is required for these activities and is this information already accessible. Answers to these questions can be used for the information requirement phase.

Agreements and interactions

Van den Boomen et al. (2012) underlines the importance of communication, agreements, and interaction as the are required to establish and maintain a successful maintenance strategy. Therefore, in this part of the implementation plan the agreements and interactions are evaluated. Once all the actors are identified, the interactions and agreements between the parties can be mapped and included in the process map.

- Determine the interactions that are included in the process. Consider different types of interactions, such as vocal conversations and meetings, but also information exchange via emails. For each interaction, determine which actors, or groups are involved, with which frequency the interaction takes place, why the interaction takes place and if it necessary. These questions help to determine if the interaction is contributing to the value stream.
- Determine what the specific goals and objectives are for agreement and if the agreement are actually contributing to the goals and objectives, that are included in the strategy of the company. Furthermore, the indicators to measure how goals and objectives are planned to be reached can be evaluated. Determine how these are selected and if they provide relevant information.
- The knowledge rainbow and the strategies that are described by Herder et al. (2004) provide relevant information about interactions between the different levels within the organizations. Based on the actors that have been identified in the previous step, the most suitable strategy can be used as a guideline for the relevant aspects.

Approach and application

For this aspect, the framework distinguishes sensor and human related factors. It is recommended to follow this approach and evaluate the aspects separately.

- The second phase in the time line is the information requirement. Based on the current state analysis, which is a combination of the information and evaluation of all the previous steps, the missing information can be identified. For each type of missing information, it should be determined how this information can be retrieved: by a sensor, or a human and whether additional tools are required. These decisions are related to the sensor selection phase in the time line.

Up until this point in the evaluation process, the current process and the process map have been the leading elements. However, when looking at the future, this process might change. This is where the value streams that have been identified are essential. The value streams are by definition processes that contribute to the vision and mission of the organization and should therefore stay in the process. However, the process can be adapted while maintaining these value streams. Changing the process requires planning and a specific vision. The final goal should be clear and should be something that can be reached in the end.

- Decisions on the maintenance approach are a good example of these considerations. For example, will the focus be on scheduled or condition based maintenance. Both approaches can be used to maintain the value streams, but the approaches require different information and therefore different sensors, or actors that provide this information. Select the general approach that is in line with vision and align it with the information requirement. Specify how the information should be retrieved.
- Since data ownership was one the most frequently mentioned challenges related to interactions during the interview, extra focus can be added to this aspect. When selecting the sensors and considering the infrastructure that is required for the sensor, the possible parties that should have access to the data should be identified. For each actor and the tasks of each actor, the required information has already been identified, so that information can be used here as well.
- Define the role and responsibilities of each actor. When it is determined what approach will be used, the activities can be scheduled along with the actors that will do these activities. It is important to schedule activities that add to the value streams of the organization, in order to avoid unnecessary work.

The next phase in the timeline is data infrastructure, in which the physical and digital infrastructure that is required for the selected sensors is created.

- For each sensor, determine the required infrastructure. Furthermore, keep in mind that more system might have to be added to the infrastructure. So, some room to expand and include additional systems has to be included as well. When considering the possibilities for these future additions, new technologies and innovations have to monitored closely.

Availability

The final block in the framework is about availability. In order to measure the availability, indicators have to be determined.

- Determine the indicators to measure the availability. Furthermore, determine the method to measure and the level of significance. This has to be included in the sensor selection process, as the sensors might add limitations to the desired measuring methods and significance levels.
- Describe how the availability indicators are linked to the overall vision and mission of the organization. Check if the indicators actually represent information that demonstrates the added value to the organization.

6.2. Current Maintenance Vision

The maintenance vision is an internal NS document. Specific details are therefore not shared. The main points of the vision are used as a starting point. These main points include: Helpdesk, repairs, service, maintenance, R-service (revision service), modification and modernization. Using the main points might lead to discarding nuances which are important. Nevertheless, awareness on how the main points are interpreted and which aspects need additional attention or reconsiderations based on these interpretations could be relevant. The document discusses a schematic vision on the coming 10 years and which developments are important. In this section a brief description of the main points is provided. The next section will reflect the findings of the interviews and comparisons of the interviews on these main points.

The first point is a helpdesk with real time monitoring. Real Time Monitoring (RTM) is a collection of systems that allow to monitor and inspect the state of the asset continuously at all times. The aim is to use RTM to support the operations and to make decisions. A helpdesk employee is able to help during the operations with a live connection. There will be a transition from reactive to proactive and preventive actions. ERTMS is introduced which leads to more support requirements from the helpdesk. After the introduction period of the systems, the number of support requests will reduce. The transition towards RTM will require more knowledge on IT systems, especially on detecting failures, defining business rules and design maintenance advice.

The next point is repairs, which are the operations and processes to restore defects or breakages that have occurred to the asset. For repairs, the main focus points are flexibility and an effective process with the goal to have quick and good-quality maintenance. The train has to go to the nearest location with the proper equipment and personnel. This location does not have to be a specific maintenance facility, as it is possible to let the mechanic go to the train. Specific maintenance facilities are adapted to handle more and different train sets to add flexibility. Furthermore, standard components need to be present at these maintenance locations. This approach requires different knowledge of mechanics, which is solved by educational requirements and specific education for subsystems. Furthermore, the mechanics will be supported by engineers.

The third point is service, which is mainly about inspecting and cleaning the train sets. Cameras in the tracks will be used to do checks, regardless of the time and location. Cleaning will be done during the day, which creates capacity during the night. Furthermore, it prepares the organization for more train sets that will need to be cleaned during the day in the future. Furthermore, the role of the mechanic will change from checking and inspection to more repairing.

The fourth point is about maintenance, mainly focused on preventive maintenance and preventive cleaning of the train sets. Generally, these activities are part of the short-cycle maintenance process (KCO). New train sets require less short-cycle maintenance, or less maintenance activities that are currently part of the short-cycle maintenance service (KCO). Additionally, revision services are excluded from the KCO, which creates space for the increasing number of train sets. This different approach requires less time, which means train sets are shorter extracted from the operations. The maintenance activities are more IT (Information Technology)/OT (Operational Technology) – related maintenance, which leads to different tasks for the mechanic. Lastly, the different types of rolling stock will be distributed over multiple maintenance facilities, whereas specific rolling stock types are currently maintained in specific maintenance facilities.

The fifth point is specifically about the R-service, or the revision service. In the revision service parts of the train sets interior and exterior is replaced with new equipment. Because this is a large operation, it can be time consuming. In the future these revision services will take place in the new maintenance hall in Haarlem, which creates space in the other maintenance facilities. The R-service will be done every 6-7 years, and this will replace the long-cycle maintenance (LCO).As a result, more facilities will be available for future IT/OT related maintenance, such as software updates or upgrades.

The sixth point is about modifications. Modifications will be done when they can be scheduled, focusing on minimal extraction from the operations. Modifications are often divers, which results in the fact that this is not always possible to schedule and execute. In new train sets, the number of IT/OT modifications will increase. Modifications will therefore be combined with scheduled maintenance activities as much as possible. Software updates will be done remotely. Furthermore, integral management and procedures for modifications is required as the modifications need to be uniform, while being done in different facilities.

The last point is modernization. In the new train sets, it is expected to have fewer modernizing activities to mechanical parts, but more focus on IT/OT components. This will be done in collaboration with the OEM (Original Equipment Manufacturer). Functional changes to the rolling stock will become more complex, based on the regulations and the norms for accessibility to the Dutch railway network.

6.3. Reflections on the NS vision

This section addresses the aspects that are considered to be missing from the maintenance vision, described in section 6.1, based on the findings described in chapter 5.

First and foremost, in addition to the maintenance vision, there is a data management vision. This document mainly focuses on data quality. This section will not reflect on that vision document as specifically as the maintenance vision, because maintenance is the core topic of this research. However, an important reflection to make is that data management and the maintenance process of digitized assets is closely related, which is why it can be argued that these visions should be combined into one vision. More details on the recommendations for NS will be described in the next section.

Generally, the vision covers the aspects that are included in the framework and are relevant for the digitalization transition of the maintenance strategy. For example, for each main point, there is a specific focus on process and on the people that are involved in the process. This is in line with what is emphasized in the literature that the role of the actors is important. As is stated by van den Boomen et al. (2012), communication, agreements, and interaction is required to establish and maintain a successful maintenance strategy. However, some notes can be made. First, the focus is often on the effect of the changes in the process on the people in process, and not what the role of the people in the process will be. For example, often the change in required knowledge of the mechanics or engineers is mentioned, but there is less explanation on differences in operations and activities.

Furthermore, especially for the mechanics, many statements are made on required changes, but these are quite divergent. For example, mechanics need to be educated for specific subsystems, but there is also need to all-round mechanics with broad knowledge. The link on how maintenance activities are changing and what knowledge and skills are therefore required is missing. Furthermore, the actors that are involved in the parts of the process and the changes in their roles are relatively neglected, as the focus is mainly on the mechanics, engineers, and suppliers. This can be linked to the knowledge management rainbow, described by Herder et al. (2004), in which three levels organizational structures are described. In order to develop a successful knowledge management, all three levels should be considered. By only including the mechanics, engineers and suppliers, the focus is mainly on the Group (G) level for the interactions with the (external) supplier and the requirements for the group of mechanics. The Corporate (C) and individual levels are therefore neglected, which results in a limited scope for the vision document.

Lastly, during the interviews the idea of condition-based maintenance seemed to be the goal for digitalization. However, in the vision this concept is not mentioned once. This indicates that there is a difference in the vision of the employees that were included in the interviews and the departments that are included in the formation of the vision. The findings from van den Boomen et al. (2012), about the significance of communication, agreements, and interaction that required to establish and maintain a successful maintenance strategy underline the fact that the difference between the interviews and the vision could delay the development of a successful maintenance strategy.

For the main points of the vision, some notes can be made as well. Firstly, in several points, it is stated that there should be focus on more IT knowledge for mechanics and engineers. This is consistent with the literature and the interviews as it is a challenge that was often mentioned. As stated by Seely Brown & Duguid (2002), the right skills and pre knowledge has to be available in order to translate data into information and information into knowledge. What is missing however, is the focus on the communication between the mechanic and the engineer. Both actors work together, and knowledge is acquired in practice, for example when a failure occurs. Both actors have a different educational background, so how the acquired knowledge shared and documented so it can be used again, and also that it can be shared with different mechanics and engineer. This challenge can be related to the knowledge management rainbow, presented by Herder et al. (2004), especially the third strategy ‘Transfer and Integrate’. Here the focus is on how information is shared between facilities, or actors and ensuring that information reaches the people that are able to use it properly. The challenges that have been identified, such as the different educational backgrounds, have to be accounted for to establish proper knowledge management.

Furthermore, the requirement for more IT-related knowledge seems to be too limited. The challenge that was often mentioned in the interviews was not only IT-related, but mainly on the connection between IT-systems and the current mechanical structures. For ERTMS, it is stated that the number of support request from the service desk will increase, but once the introduction phase has passed, this will reduce. It is good to know that

ERTMS is also a digital system, which could result in not only more support requests, but also more IT-related of the support requests.

It is stated that sensors, like for example cameras will be used to monitor the situation on the tracks, regardless of the time and location. Some more in-depth statements about the procedures that will be put into motion when the cameras do not work (properly) are missing. Especially, the level of dependency is unclear. In other words, how dependent will the maintenance approach be on these cameras and what are the consequences if one doesn't work. This has to be considered in the construction as well. For example, systems can be built in redundantly, which means multiple systems are included, with the same function. If one of the sensors breaks down, there is a back-up system that still works. Furthermore, it is unclear if the cameras are owned by NS and therefore maintained by NS, or if this is the responsibility of ProRail. The significance of communication, agreements, and interaction between actors, described by van dan Boomen et al. (2012) emphasizes that these questions need to be clear in order to create a successful maintenance strategy.

The removal of the revision service (R-service) out of the short-cycle maintenance shows that there is more focus on the shorter development cycle of digital systems, which is good. This shows the flexibility in the maintenance that is required to deal with the changes that come with the increasing number of digital systems. The maintenance facilities are adapted, and the goal is to frequently used components and mechanics available at maintenance facilities, and even let mechanics do maintenance during the operations. This is also part of the increasing flexibility that is required.

The statements in the vision document clearly showcase the change in the collaboration with the supplier. The IT/OT systems can be modified, maintained, and modernized but this needs to be done together with the supplier. This is in line with the findings in the literature and the interviews.

The reflections mentioned in this section will be summarized into recommendations in the next section 6.4.

6.4. Recommendations for NS

In this section, a summarized list on recommendations based on section 6.3. is provided. These recommendations will be connected to the implementation plan and the maintenance aspect framework, described in section 6.1.

Create a clear vision for the goal and all the intermediate steps. During the interviews the idea of Condition-Based Maintenance (CBM) seemed to be the goal of digitalization, as many of the actors that were being interviewed mentioned CBM as a future goal. However, this is not represented in the vision documents of NS. Both ideas should be aligned to form one objective and to make sure that all parties work towards the same goals. As stated by Boomen et al. (2012) and van der Velde et al. (2013), common objectives and standards which are communicated clearly as essential for a successful digitized maintenance strategy. The fact that CBM is part of the goals of the employees, but not part of the vision of the company indicates that there is room to improve the common objectives and standards.

Identify all the involved actors and determine the role and the responsibilities. The vision mainly focuses on engineers, mechanics, and suppliers, but there are more actors involved for which the role in the maintenance process will change. Since the maintenance process is a process that has an effect on the entire operational chain, this point might be very elaborate. It is recommended to start with the actors that are part of the three departments that are responsible for the maintenance vision. These departments are NS Technology (NS Techniek), Train Modernization (Treinmodernisering) and Maintenance & Service (Onderhoud & Service). For the identification process, the framework and the knowledge management rainbow, described by Herder et al. (2004) could provide guidance. In both of these models the focus lies on internal and external actors, as well as different levels within the organizations that are involved. This is included in the second part of the implementation plan.

Determine a standardized method for collaboration between the mechanic and the engineer. It is stated that the mechanic and the engineer need to collaborate and need to share knowledge on issues regarding maintenance. According to the literature, these collaborations are essential for efficient and effective business processes (Seely Brown & Duguid, 2002) In order to use this knowledge again later and to share it with different mechanics and engineers, this needs to be documented. This is where the concept of knowledge mapping can support, as it describes the location of knowledge and expertise in the organization.

Clarify the requirements for the mechanics. In the vision, it is stated that the knowledge of mechanics should be specific and more focused on IT/OT systems, but it should be broad and generic to shape all-round mechanics. It could be possible that the idea is to have mechanics of both types, but in that case a more elaborate plan on what the role and responsibilities of each type of mechanic will be needs to be included in the plan as well.

Expand the requirement on more IT knowledge. It is true that with the increasing number of digital systems, more knowledge on these systems and the mechanisms behind it is essential. However, in the interviews the issue related the required knowledge was more elaborate. Namely, the complexity lies in the connection between the ‘new’ IT/OT-systems and the ‘current’ mechanical systems. Furthermore, for the analysis activities, knowledge on the current mechanical systems and on the IT-systems is required to determine which data can be used to monitor the performance of the mechanical systems.

Determine the level of sensor dependency and create a maintenance plan accordingly. There are examples of how sensors are used to support the maintenance strategy, and in the vision, cameras are mentioned as an example. It is unclear if there are agreements about the level of sensor dependency and how these levels are determined for each sensor. Furthermore, a plan for sensor maintenance has to be established. Taking these steps contributes to the progress in the time line. These considerations require to connect the sensor selection to the overall goals and value streams of NS.

Data quality requirements have to be clearly defined. Despite the fact that NS has clear measuring indicators to determine the quality of data, it needs to be which quality level is necessary to be able to base decisions on this data. This is related to the level of dependency of the sensor. If the sensor is the only data source about the state of a component or a system, this output has to be reliable. The minimum level of reliability and the method of measuring the reliability has to be clear. This is also related to the maintenance strategy of the sensor. In order to provide reliable data sensors have to be maintained properly. The required reliability therefore determines when maintenance or replacement of the sensor is required. Data quality is included in the data management vision document, but the fact that this is a separate document and no references between the documents are included shows that these strategies might not be aligned properly. As stated by van der Velde et al. (2013), adequate data quality can be reached by using the proposed three instruments: objectives and standards, plans and contracts. Data quality is therefore connected to the objectives and plans and should therefore be included in the maintenance vision.

Maintain good communication with the supplier throughout the entire process. From the design phase, until the train is fully operational the supplier will play a more important role in the support of the maintenance activities. Therefore, a good communication is essential. This is already well included in the vision.

Maintain flexibility in the maintenance strategy. There is more focus on short cycle maintenance, to account for the shorter development cycle of software. Due to the shift towards more short cycle operations, there is more room for flexibility because new developments can be implemented during maintenance moments sooner. This flexibility should be maintained, which required changes in facilities, capacity, and logistics.

6.5. Conclusion

In this chapter, an implementation plan has been presented which connects the framework, presented in chapter 4, with the timeline, presented in chapter 5. Furthermore, the current maintenance vision document of NS is evaluated, based on the framework. The implementation plan is designed to be applicable to many organizations and provides a guideline for what steps and considerations need to be taken to progress in the digitalization transition. The recommendations based on the maintenance vision are made specifically for NS. These recommendations for NS are focused on where the vision might need more attention and which aspects are already well formulated based on the findings from the literature and the interviews.

7. Conclusion

This chapter will provide the answers to the research questions that were stated in chapter 1. First the sub research questions will be answered, and the chapter is concluded with the answer to the main research question.

7.1. Sub-research Questions

What are the standards and definitions of the maintenance process in the current literature?

Maintenance is defined as: “activities that are executed to keep a product in a reliable state and operable. This is done by repairing faults, regulating the environment in which the product operates, and anticipating potential risks and mitigating these risks” (Karki et al. 2022)

Maintenance can be divided into corrective and preventive maintenance. Corrective maintenance is applied after a failure has occurred and preventive maintenance is applied before a failure has occurred. Preventive maintenance can also be divided into two types. The first type is condition-based maintenance in which maintenance is applied whenever the condition of a component has degraded to a predetermined level. The other type is time-based, or scheduled maintenance, in which maintenance is applied after a certain amount of time has passed, regardless of the condition of the component.

Additionally, another classification for maintenance can be made. Maintenance can be divided into maintenance actions, policies and concepts. Maintenance actions are the tasks that are executed. Maintenance policies, are the triggers for the maintenance actions. Finally, maintenance concepts are the set of policies and procedures that are used to do the maintenance.

Maintenance has developed over the passed decades, as the systems, machines and components that need to be maintained have changed as well. The most important addition to the concept of maintenance is the idea of predicitive maintenance. This idea aims at predicting when maintenance is required, based on information from the process and operations. This requires continuous monitoring, data collection, data analysis and the use of diagnostic and prognostic tools. Furthermore, the number is feedback loops that is required is reduced, which can save time. Furthermore, the point at which human intervention is required, is much later in the process. As a result of this information use and requirement from the entire process, maintenance has become a much more important part of the operations. Finally, the use of information from the operations and using it for the maintenance strategy has formed a base for new technologies and innovations, such as big data, Virtual Reality (VR) or 3D printing. These innovations could allow modifications to the maintenance approach such as remote repairs, or creating components that are hard to acquire, or that break easily.

What are the differences between the traditional maintenance approaches for mechanical and analogue systems and digitized systems according to the literature?

Because of the increasing use of digital systems in many business processes, the maintenance process is digitizing as well. This development is noticeable for several aspects. The main aspects that have changed can be noted are the cycles, the role of the actors, the interactions between the actors and the tools that are used in the maintenance activities.

The establishment of a maintenance process and the initial cycle can be represented by two processes. A strategic process and an operational process. The strategic process consists of a management planning and management measurement. The management planning process consists of sub-processes such as determining the maintenance policy, the maintenance procedure, and objectives. The maintenance procedures can be seen as an extension of the maintenance policy, to make sure that tasks are aligned and standardized. The management measurements are aimed at evaluating the performance of the processes of the management planning.

Often the number of cycles is determined based on a trade-off between the reliability estimation and maintenance costs. The actual number that is selected is based on the priorities of the organization and what they consider to be more important: risks or costs. Methods such as Failure mode, effects, and criticality analysis (FMECA) and Reliability Centred Maintenance (RCM), where the RAMS(HE) (Reliability, Availability, Maintainability, Safety and Health) indicators are assessed, are used to determine these risks and the related costs, to be able to make an evaluation. In the initial strategy, the distinction between corrective, preventive and predictive maintenance is made. An important development is the focus on short-cycle maintenance, as a result of the Software Development Life Cycle. Software is developed quickly by using short cycles, which results in frequent update releasing. The maintenance cycle has to be aligned to this higher frequency, in order to include the most recent version of the software in the components.

For Asset Management, standard roles are specified: the asset owner, the asset manager, and the service provider. The Asset Owner is responsible for making strategic decisions and the trade-off between long-term and short-term investments. The Service Provider does the operational maintenance actions and is responsible for reliability, availability, maintainability, and safety. The Asset Manager is the link between the asset owner and the service provider. The literature also mentions the role of the Asset User at NS, who is responsible for the long-term plans, regarding network design, timetables and asset demands and employment. However, in the other cases these responsibilities are done by one of the other asset management roles, so the added value of a specifically designated Asset User can be argued. For vehicles in the rail sector, other roles are specified: Entities in Charge (ECM). There are four levels: The ECM 1: Management function, ECM 2: Maintenance development function, ECM 3: Fleet management function and ECM 4: Maintenance delivery function.

Between the actors, there are many interactions and agreements. The contents of these agreements and interactions are based on the actors that are involved and context. Generally, it can be said that a clear vision and policy has to form the base for all the communication. From this vision, the objectives can be derived, which form the base for tender requirements, maintenance plans and financial plans. Furthermore, a framework with criteria for assessments and inspections can be obtained from the vision. This framework can be used for the entire operational chain. Lastly, agreements will be shaped differently, based on the developments. Agreements will be more long-term, and the supplier will often be involved for a longer period. Agreements will be in the form of service level agreements (SLA), in which the supplier will support in the maintenance processes with, for example knowledge or parts. Furthermore, the contents of the contracts will change, as issues such as data ownership will have to be included.

To conclude and answer the research question, the differences between the traditional maintenance approaches for mechanical and analogue systems and digitized systems are the number of cycles and the length of the cycle. Software and updates to the software are created and offered with a high frequency, which results in the fact that maintenance have to be aligned with this higher frequency in order to maintain a properly working digital system. Furthermore, the agreements between organizations and suppliers are different. The duration of the contract has increased and the supplier is included in the earlier in the process and will provide service for a longer period after the product has been supplied. Lastly, the contents of the contract between different parties has changed. New elements are included, which were not relevant in the traditional maintenance approach. For example, data ownership has become an important issue with the increasing number of digital systems and data that is provided by these systems.

What is effect of digitalization of the asset on the maintenance strategy of a public asset in practice?

Based on four case studies a general picture on the maintenance strategy and the effects in practice can be made. For all four cases applied that the organization was still at the beginning of the transition and investigating what the future should look like and what would be needed for that.

In general, it can be said that the maintenance cycle is often based on the instructions of the supplier(s) of the asset. By using knowledge and experience from practice, the maintenance cycle is adapted and optimized. Based on the components of the asset, the surroundings it has to operate in and the performance requirements the performance of the asset is measured with predetermined indicators and these indicators are used to determine the quality of the maintenance.

With the introduction of data and digital systems, some aspects have changed. First, data is added as input value to monitor the performance of the asset and to measure these indicators more precisely. As an effect, adaptations to the maintenance cycle can be made quicker and more reliably. Furthermore, the addition of digital systems has allowed for better documentation on which maintenance is executed. Furthermore, from the performance data points over time and the information on the executed maintenance, trends can be deduced, which allows for predictive maintenance.

Because of the increasing number of digital systems, the tools that are required for the maintenance activities have changed. Instead of the conventional toolbox for the mechanical components, computers are often used for maintenance activities. On the one hand computers are used to visualize the data that is extracted from the asset into a dashboard. This dashboard can be used to make analyses to determine the required maintenance activities. On the other hand, computers are used for these maintenance activities as it requires changes to software more often, which has to be done with a computer.

As a result of the computer being a maintenance tool, the specifications required knowledge for mechanics and engineers has changed. Mechanics need to be able to use the computer as a maintenance tool in order to do the repairs and required updates. Engineers or analysts need to establish links between available data and the mechanical works of the asset. In other words, they need to recognize which data explains, or represents the physical state of the asset. In order to create these links, proper knowledge on IT-systems and the mechanics of the asset is required.

Another trend that could be observed is a more long-term collaboration between the organization and the suppliers of the assets. In stead of only providing the product and the spare parts for the components, the collaboration is changing into a service, in which the supplier plays a supporting role. This difference also results in another effect, namely changes in the contracts. In addition to the longer terms for which the contracts apply, new elements have to be included. For example, agreements on data ownership play an important role. The sensors in and on an asset are owned by one party, but the data might be used by other parties as well, to optimize the maintenance activities.

The effect of digitalization on the availability of the asset is generally considered to be advantageous in the long term. At the beginning of the data gathering process, there is a lack of knowledge on the current state of the asset. Insights from the data might reveal information on the asset that was unexpected. The effect on the availability might therefore be negative on the short-term as more maintenance is required than expected. However, on the long-term the effect is considered to be positive as the improved ability to monitor the asset allows for better predictions and scheduling on when maintenance is required, which makes it possible to optimize the maintenance planning and therefore increase the availability.

Digitalization also brings some challenges. The change in the required knowledge has already been addressed. Another challenge is determining the prioritization for the information acquirement. There are many sensors available, and much data can be derived from an asset. However, organizations need to determine what data has to be extracted and in which sequence this has to be done. The prioritization needs to correspond with the vision and goals of the company. Another challenge that plays an important rule is the fact that this transition is a new development, and the future can be uncertain. The decisions that are made now, have an effect on the future and the goal is to build a data infrastructure that is resilient against the uncertainties. Furthermore, the infrastructure has to be secure and protected against potential cyber risks.

Which findings from the case studies can be translated into recommendations for the maintenance strategy of train operators, such as NS?

NS has created a maintenance vision, which describes the main focus points for upcoming developments that NS will have to face. Some reflections on these main points have been made. The reflections are translated into recommendations for NS on where the vision might need more attention and which aspects are already well formulated. These recommendations are based on the findings in the literature and the interviews. The recommendations can be prioritised, based on the framework and the timeline, as this represents the transition process. The recommendations are as follows:

- *1: Create a clear vision for the goal and all the intermediate steps*. Within the organization there should be one vision, which is translated into the activities and decisions in the operational chain. All actors should be aware of this vision in order to maintain an aligned approach. According to Boomen et al. (2012) communication, agreements, and interaction is required to establish and maintain a successful maintenance strategy. This emphasizes the importance of a vision that is known throughout the entire organization.

- *2: Identify all the involved actors and determine the role and the responsibilities.* The current vision does not include all the parties and does not cover roles and responsibilities on different level in and outside of the organization. Since maintenance is an elaborate process which is present in different levels internally and externally, these roles should be addressed. This is important, because insights like this are essential for proper knowledge management (Herder et al., 2004). Data can be transformed into information and into knowledge, only if the right pre-knowledge and skills are present. This transformation process of data into knowledge is required for the normal operations, but also to improve these operations.

- *3: Determine a standardized method for collaboration between the mechanic and the engineer.* The vision states that there should be knowledge sharing between these actors. To ensure that this knowledge is not lost, and that other mechanics and engineers can apply it as well, it should be documented properly. This is also part of knowledge management, which is explained by Herder et al. (2004). Data, information and knowledge should be stored and transferred properly to use it for the operations.

- *4: Clarify the requirements for the mechanics*. The change in the required knowledge leads to changes in the specifications for the skills and prerequisite knowledge for the mechanic. In the vision there is no uniform picture on what the role of the mechanic should be and what skills and knowledge are required for that role. Similar to the previous point, part of proper knowledge management is to make sure that the right skills and pre-knowledge is available to translate data into information into knowledge. As a part of this process, it is important to determine what pre-knowledge should be available and what is therefore required of the mechanics.

- *5: Expand the requirement on more IT knowledge.* There is a large focus on the increased requirement for knowledge on IT-systems. However, according to the findings in the interviews, the main challenge is the connection between the IT-systems and the mechanical systems. The requirement should therefore be expanded, to include this link as well.

- *6: Determine the level of sensor dependency and create a maintenance plan accordingly*. Sensors are currently used to support the maintenance process and to have additional information as an input source. In the future, the organization might rely more on these sensors and therefore the level of dependency and the risks that come along with this should be addressed per sensor. Investigating this dependency helps to proceed in the time line, as it is part of the sensor selection and the corresponding considerations that have to be made.

- *7: Data quality requirements have to be clearly defined*. When using the information of a sensor to base decisions on, the data quality should be evaluated. NS already has specific indicators to do so, but threshold values, and the relationship with the dependency level has not been addressed yet. Van der Velde et al. (2013) emphasize the critical role of sufficient data quality for effective asset management, which can be attained through the utilization of three key tools: objectives and standards, plans, and contracts. This can be connected to the first recommendation in which the importance of a general known vision is underlined.

- *8: Maintain good communication with the supplier throughout the entire process.* In the vision, the change in collaboration with other parties is mentioned and the proposed approach is already well-formulated. Nevertheless, this should be maintained properly.

- *9: Maintain flexibility in the maintenance strategy*. Similar to the previous point, the need for flexibility has been addressed in the vision already, but should remain to be one of the main focus points.

Based on the framework (figure 29) and the time line (figure 30) that have been presented in this research, a prioritization for these recommendations can be provided. The points about the communication with the supplier and the need for flexibility throughout the entire process, were already included in the vision document, but should stay a focus point when implementing the other recommendations. The other recommendations should be prioritized as follows. First the clear vision, mentioned in the first recommendation is the base on which all the decisions will be made and should therefore be the first priority. Next, the second recommendation in which the actors will be identified. This also allows to expand the eighth recommendation, in which good communication is maintained. Next, the data quality indicators have to be set, because this is related to the sensors that will be selected, as is stated in recommendation 7. If sensors cannot provide a certain level of reliability, they cannot be used. Based on these indicators, the level of dependency can determined, which is described in recommendation 6. Based on the selected sensors and indicators, the requirements for the mechanics can be described, as it is known what systems the mechanics have to work with. Lastly, the third recommendation, in which a standard method for collaboration is described, can be executed. This requires decisions on data storage, which is related to the IT infrastructure, which is the following phase in the timeline.

7.2. Main Research Question

To conclude the research, the main research question is answered, based on the combination of the answers on the sub research questions, the literature and the findings from the interviews.

The research aimed at investigating what effects the digitalization process and the increasing usage of digital systems has on the maintenance strategy of large public assets. The main research question was therefore formulated as follows:

"What is the effect of digitalization on the maintenance strategy of large public assets?"

The effect of digitalization can be explained by looking at five aspects: actors, agreements, approach and applications and availability. This is combined into a framework which is presented in figure 29.

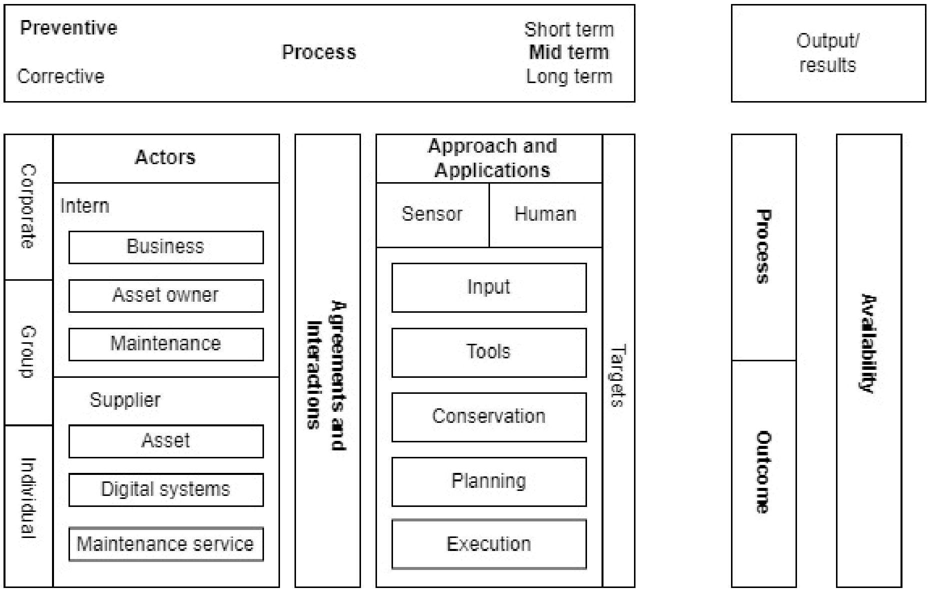

FIGURE 29: FINAL MAINTENANCE ASPECTS FRAMEWORK (OWN WORK)

The actors in the maintenance process often follow the asset management roles, similar to the situation before digital systems were present in the operations. So, there is an Asset Manager, Asset Owner, Asset User, and the Service Provider. The role of Asset User is only used by NS and the added value of a specifically designated Asset User is arguable. A new development as a result of digitalization is the additional task of data analysis. This can be done by the organization, but also by the Service Provider, or a combination of both parties. This depends on the agreements between the parties. In the cases that were included in the research, the data analysis was often done by the Asset Manager of the case organization. From these analyses, specific maintenance tasks were determined which are executed by the service provider.

Another development is the changed requirements for the knowledge of the actors that are involved in the process. Depending on the role of the actor, the requirements are different. However, in general, it can be said that all actors need to have more knowledge IT-systems and how they work. Furthermore, one of the main challenges that has been described is detecting connections between the mechanisms that are already in the assets and the IT-systems. It has to be determined which data can be used to provide information on the physical state of the components of the asset.

The effect of digitalization on the agreements in the maintenance process is visible in two aspects. First, the agreements are often more long-term, compared to earlier contracts. There is more communication with the supplier in an earlier phase of the process. For example, during the design phase, many discussions and conversations are taking place with the supplier. Furthermore, as soon as the asset is operational, the supplier is often still involved and providing services such as support in the maintenance process, releasing and updating new software and providing spare parts. The collaboration is service based, which is secured in a Service Level Agreement (SLA).

Another development are discussions and agreements about data ownership between the asset owner and the external service providers. In all the cases the owner of the assets wants to have full ownership of the data coming from the asset. However, for some sensors this is not the case yet. Furthermore, not only the ownership is relevant, but the aspect of data sharing in order to use the data to optimize the maintenance activities are relevant as well. These issues often play a role between the asset owners and the service providers.

The effect in the maintenance approach can be described as a transition from corrective maintenance to preventive and predictive maintenance, in the form of scheduled or condition-based maintenance. In the cases that have been considered, the sensors are applied, or the systems that are already available are being analysed. The approach is to slowly transition into using more data, considering the required knowledge, setting up the data infrastructure and evaluating the risks of making the operations more dependent on sensor output. Another effect, which is already more visible, is the fact that maintenance actions can be recorded in digital applications by the mechanics or service providers. This already creates a more detailed picture on the current state of the asset, as recent maintenance, replacements, and updates are visible. The short-term aim is to create a comprehensive picture of the current state of the asset and the composition of the asset.

The impact of digitization on asset availability is generally seen as beneficial in the long run. Initially, during the data collection phase, there may be limited information about the current condition of the asset. Analysis of the data might unveil unexpected insights about the asset. Consequently, in the short term, the impact on availability could be negative as it may necessitate more maintenance than originally anticipated. However, in the long term, this effect is considered to be positive. Enhanced asset monitoring capabilities enable more accurate predictions and scheduling for maintenance needs, ultimately optimizing maintenance planning and increasing asset availability.

The transition process can be represented as a timeline, in which organizations can be placed. Based on the progress in the transition process, and which steps already have been taken. For the case studies that have been done for this research, a timeline has been created and the organizations that were used in the case studies. This timeline is presented in figure 30. This timeline can be connected to the effects of digitalization that were mentioned earlier in this section. The effects of digitalization are summarized below, along with the connection to a phase in the timeline.

- Additional task of data analysis: as a result of the sensor selection, actors need to translate the data from the sensors into information. Based on the current state analysis, it is determined that the information is missing and needs to be acquired by a sensor, after which it can be analysed.
- Different required knowledge: in order to do an information requirement and sensor selection, knowledge is required to determine what information is missing and what sensors can fix that.
- More long-term contracts with earlier involvement and providing service during the life time of the asset: during the considerations in the data infrastructure phase, decisions need to be made about who has access to the data. Because of these different contracts, external parties have to be included in these considerations.
- Data ownership is important: this is a separate phase in the process, which is a result of the previous point. When it is determined who needs access to the data, the data ownership needs to be considered and included in contracts with external parties.

- Transition from corrective maintenance to preventive and predictive maintenance: data is used to discover trends and failure patterns. This transition is represented in the shift between the current state analysis phase an the information requirement phase, as in the latter the information to be able to discover trends is identified.
- Positive impact on availability: when all the decisions are made and executed properly, the information and knowledge that can be derived from the data, retrieved by sensors and humans, could optimize the operations. As a result of optimal business processes, the availability will likely increase as well. This is represented by the timeline as a whole and the guidance it can provide to properly make and execute decisions.

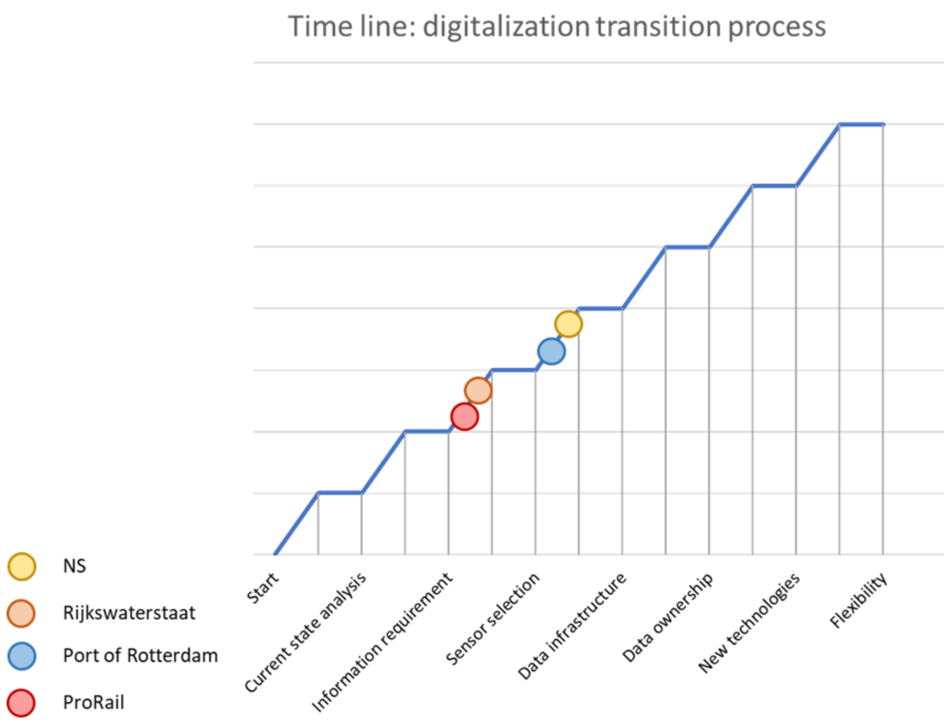

FIGURE 30: DIGITALIZATION TRANSITION TIMELINE (OWN WORK)

7.3. Additional takeaways

In addition to the answer to the main research question, some takeaways from the research can be stated.

Since the digitalization process is a relatively new development, there is not much literature on what the process exactly looks like. Furthermore, the process is filled in differently for different organizations. The sequence of the steps that are might be different, based on the focus of the organization. However, the overall process is similar, because in general, the same steps are taken. These steps are included in the timeline.

Another important note is that it is positive to see that organizations expect that the use of digital systems has a positive effect on the availability. In the problem identification of this research, one of the challenges was that people might be aversive towards new systems. However, this positive attitude shows that this issue might not play a large role in the transition process.

The outcomes of the case studies were often in line with what was presented in the literature. However, there was one example in the case studies, in which the actual result was opposite of what was described or expected. The number of maintenance cycles is expected to increase, as digital systems have to be updated regularly. In the case of the Port of Rotterdam the number of cycles has decreased based on the data, which was unexpected. After further investigation, this result could be explained. This reduction of maintenance moments is a short term effect, and the reduction is not related to the maintenance of the digital system and the higher update frequency. Therefore, it is expected that once more digital systems have been implemented in the vessels, the maintenance frequency increases again. This examples showcases that the effects of digitalization are long-term effects and are often not noticeable yet.

8. Discussion

This chapter provides a reflection on the executed research. Furthermore, a description of the contributions and the relevance of the thesis will be given. This will be divided into two sections: contributions to the theory and existing research, and contributions to practice. Furthermore, the limitations and the possible effects of decisions that have been made are explained. The chapter is concluded with recommendations for further research and some final remarks.

8.1. Contribution

In this section, the contribution of the research to the current theory and existing research is described. Additionally, the contribution of the research to practice is described. This will be done, based on the research gap that has been identified at the beginning of the thesis. The research gap was described as the fact that with the increasing number of digital systems that is used in business processes, such as the maintenance process, the maintenance of the systems itself is often neglected. Especially, the role of data quality and the need to ensure that the data that is provided by the sensors is reliable as a result of the maintenance of the sensors. In order to fill the research gap, the effects of digitalization on the maintenance process as a whole have been evaluated. This is done to determine why the maintenance process of the digital systems has not been researched yet and which complexities play a role.

8.1.1. Contribution to theory

Maintenance is a very elaborate process, which is unique for every organization, or asset that is being maintained. However, some general aspects of the maintenance have been described and this research has found more aspects that be generalizable for the maintenance process of large assets.

First, the maintenance aspect framework describes the aspects that are relevant for the maintenance process of digitized assets. Even though these aspects are derived from existing literature, a combination of these aspects has not been presented yet. Furthermore, the relevance of the aspects has been reflected in the case studies in which the actual effects of the aspects is reviewed. The similarities and differences that have been stated in this research can be seen as an added value to the existing literature. Examples of these differences are the importance of a general vision and the emphasis on data quality. For both of these examples, the literature already stated the importance and this was not noticeable as much in practice. This also shows that there were no examples of aspects that were considered to be important in the literature, which were not considered to be important in practice. This shows that the literature is up to date with the relevant aspects.

Secondly, the literature describes the role of the asset user in practice. The case studies have shown that in other organizations the tasks and responsibilities of the asset user are done by other roles, which makes the added value of a specific asset user in addition to the other asset management roles arguable. Currently, there are only sources that address that this role exists, but there is no research that represents a voice of discussion on whether this role is useful or not. Therefore, this research could act as a starting point to determine the added value of assigning an asset user as an asset management role.

Furthermore, the maintenance approach for all of the cases have been compared to each other. In order to make the results comparable to some degree, similarities between the nature of the assets, or the organization have been identified. This allowed for making conclusions based on the possibility to move the asset, the sector in which the asset operates, the level of influence of the Dutch government, the number of types of assets of an organization, the categorization method, and the decision on doing maintenance inhouse, or outsourced.

The possibility to move an asset provides multiple opportunities for applying maintenance. Maintenance teams can either go to the asset or the asset can be transported to the maintenance facility. In the same sectors, digitalizing assets results in a different type of collaboration among involved parties. For instance, NS and ProRail utilize each other's equipment to assess their asset conditions, fostering mutual learning opportunities. This evolving collaboration might extend across various sectors in the future. Additionally, the Dutch government's influence in setting sensor standards or procedural regulations could impact this landscape. The variety of asset types within an organization could also influence strategy formulation; a singular vision might suffice for uniform or singular asset types but not for a diverse range. Crafting a long-term vision amidst the uncertainties of digitalization proves to be intricate, especially considering whether maintenance is handled internally or outsourced. Given the need for specialized knowledge and resources for digital systems, this decision entails numerous considerations.

This research shows that there is possible connection between the following features: the outsourced maintenance, the categorization method of the assets and the number of types of assets. It is expected that maintenance is outsourced, because of the numerous types of assets, or the location of the asset, because it could require too much specific knowledge and resources to be able to manage the maintenance process from within the organization that owns the asset. These conclusions can be researched into more detail to identify more similarities, trends, or best practices for the specific category. These findings can be added to the existing literature.

Lastly, a timeline has been created in which the phases of the digitalization transition are represented. The evaluated cases have been plotted into this timeline to show how far they currently are in the transition process. A timeline like this has not been presented in the current literature yet and can therefore be considered as a contribution to the current research. The digitalization process has not been mapped as a general process description, and this time line can considered to be a base on which more research on the general process can be done. This additional research can also be used to validate and verify if the timeline is correct and applicable in the current form.

8.1.2. Contribution to practice

In addition to the contributions to the current literature, this research provides some interesting aspects that are relevant for the application in practice. The findings from the literature review and the interviews have been reflected to the long-term plans and specifically translated into recommendations for NS, based on the current way of working and the vision that is created. Nevertheless, other companies or organizations can do this in a similar way and reflect the long-term maintenance plans, based on the findings of this research. The maintenance aspect framework can provide a base for these reflections, which makes the framework itself useful for application in practice. An implementation plan has been presented which explains how to use the framework to proceed in the schematic timeline that has been presented.

Furthermore, the framework can be used as a checklist to determine if future plans are complete and include all the relevant information. Additionally, this concept also allows for the framework to be used as a guideline to reflect on previous policies and visions when challenges and failures occur. This way organizations can learn from their own mistakes and prevent them from occurring in the future.

The timeline that is presented can also be considered as a contribution to practice as it provides insight into the position of organizations in the process. This could allow companies to determine which companies have already tackled certain challenges, and how this can be done. Even without other companies being plotted in the graph, the timeline can be useful as it can be seen as a suggested road map, in which the general phases for a digitalization transition are included. This could reduce the uncertainty about what challenges can be expected in the future. Organization can anticipate on these challenges and therefore manage these challenges more easily.

8.2. Limitations

Despite the interesting findings and conclusions, some remarks are necessary about the limitations of this research and what the effects of these limitations are on these findings and conclusions.

In the research four organizations are considered. During the selection of the organizations and the cases from these organizations, the features of the organization and the assets itself were considered. The goal was to find at least three other organizations, in addition to NS, which could provide an example of an asset which has been digitized recently. Due to the recent digitization, the case could provide relevant information and examples from practice. In all of the cases, the organization provided an example of an asset which was considered to be a good example. In the end this resulted in a divers set of assets, which can be seen as a advantage or a limitation. Because of the diversity, it was often complex to compare the cases, as many factors play a role. If similar assets had been selected, some of these factors could have been excluded. This could mean that when doing a similar research with more similar assets, more detailed conclusions might be drawn. Nevertheless, some similarities could be found which allowed for making some conclusions.

The number of cases that was considered yielded in much information, as the aim was to interview at least all of the asset management roles to create a comprehensive picture of each asset and organization. For each interview, a summary is made, which is send to the interviewee to check if the information that is used for the research is correct and complete. This reduces the risk of misinterpretations from the interview. Furthermore, missing information could be added. Nevertheless, there could still be relevant information missing from the interview, as it was filtered out by summarizing the interview. This could lead to findings being excluded from the research and therefore not included in the conclusions and to a lack of nuances that could have been added to the conclusions that have been drawn.

Additionally, relevant information could be missing because relevant actors were not interviewed. Scheduling interviews takes time and requires time from the interviewer and the interviewee. Furthermore, in this case it required investigating for four companies which actors were relevant to select for an interview. In the case of this research circumstances such as holidays, illness and late responses resulted in the inability interview all the desired actors. Therefore, it can be the case that relevant perspectives are not taken into account. This is mitigated as much as possible by interviewing actors with a similar function for other assets, or actors that previously had the role of the desired actor.

On top of missing perspectives of the actors that have not been included in the research, it is also important to note that the perspectives of the actors that are included in the research can affect the outcomes of the research. As stated earlier, the aim was to include the three asset management roles for each asset to create a comprehensive picture. Nevertheless, in many of the cases these responsibilities of these standard roles are fulfilled by different actors. The perspective and position of the actor in the process could steer the interview. For example, criticism against actors that are on a higher hierarchal level might not be shared, even though it could be relevant. Furthermore, the sequence of the interviews could influence the outcomes, as information is gathered throughout the interviewing process. This could result in new questions that are included in the interviews, which are therefore missing in the previous interviews.

Also, in some interviews the actor has recently transitioned to the current job. This means that the actor is also acquiring knowledge and experience from this function, which can therefore not be shared during the interview. By interviewing multiple people and including the question on what other actors might be relevant to interview as well, this risk was mitigated as much as possible.

The distribution of interviews is also important to point out. Since the research is done for NS, more interviews have been conducted with employees of NS. This was due to the fact that scheduling interviews was a smoother process, since the communication was quicker, and it was easier to contact the required actor. Furthermore, the organizational structure was clear much earlier in the research process, which resulted in the fact that it was clear who the relevant actors were. As a result of this uneven distribution, more detailed information was available which makes it possible to add nuances for the case of NS which is not possible for the other cases. This was very useful for the establishment of recommendations for NS. The uneven amount of information resulted in the fact that comparisons could not be made as detailed as the available information was, as specific details and nuances were missing from the other three cases.

Another important limitation is that no actual service providers or mechanics were interviewed. This was mainly due to the fact that there was no interest to collaborate in this research, or the interview could not be scheduled to limited available time. Perspectives on the effect of digitalization on the actual maintenance activities from inhouse mechanics, or external parties is therefore missing. Even though this is part of the maintenance process, and the role of these actors is very important, it could be seen that the data analysis tasks are often not done by these parties. For the effects of digitalization in the sensor selection and analysis aspect, this limitation does not play a role. The effect of digitalization on the required knowledge on IT systems and how this plays a role in practice could have been emphasized by the inclusion of the service providers. Furthermore, including these parties might have revealed challenges that are not considered in this research, which can be seen as a limitation of this research.

Lastly, the moment of doing this research can be seen as a limitation, because all the organizations that were considered were just starting with digitalization. This means that there were not many examples of the effects of digitalization, as they have not occurred yet. This added some complexity to compare the literature with the effects in practice, as there were not many effects in practice yet. On the other hand, the moment for this research is right as companies are still in an early stage of the transition process. This means that adaptations can be made and the recommendations from this research can actually still be implemented.

8.3. Recommendations for further research

Based on the limitations and aspects that were considered to be out of scope for the research, some suggestions for further research can be made.

First, research focusing on the service provider and the effects that can be observed on in the execution part of the maintenance process can be done. As mentioned by the previous section, the service providers were not included in the research, which resulted in a potential neglection of relevant effects. In follow-up research, these effects can be identified, and it can be evaluated whether there are additional effects and whether the effects that are mentioned in this research also play a role in the perspective of the service provider.

There is also a research possibility in the question of the added value of the asset user. Currently, there is only research which states that the role exists. This research argues the added value of the role, and further research can validate the added value. Moreover, it could be interesting research the effect of digitalization on the asset management roles in general, and whether these roles and responsibilities evolve with the digitalization transition. It could lead to conclusions about the added value of additional roles, such as the asset user, or a change in the standard responsibilities that are associated with an asset management role.

During the interviews, the link with the acquisition phase of the asset was often made. Since this research was focused on the maintenance process, this was considered to be out of scope. However, this connection is very relevant, because the decisions that are made during the acquisition phase, have an effect on the maintenance process. An interesting aspect that was most frequently mentioned is researching the Return on Investment (ROI) for specific requirements for digital systems. Assets are delivered with many digital systems and therefore many possibilities to extract data from the asset. Since the purchasing process and the maintenance process are often considered as two different processes, there is little insight on the effects of the decisions that are made in the purchase process. These insights are very relevant, but they can also be applied in future purchases.

In this research five aspects of the maintenance process of digitized assets are considered. Further research can be done to investigate whether more aspects are relevant, later in the digitalization transition. Another option could be to investigate whether one of these aspects will play a more prominent role in later parts of the process. Furthermore, each of the aspects can be researched in more detail, to identify more specific effects. Additionally, other companies can be included to determine if other cases result in different effects. It could be the case that there are organizations that are already further in the digitalization transition that can be used to identify the potential other effects, or to identify the effect of the aspects at a later moment in the process.

Based on the features of the asset and the organization, some similarities between the case have been identified. Potential effects of these features on the digitalization process were described, but further research can be done to investigate whether these potential effects actually play a role and what this role is. Furthermore, additional effects can be discovered which might be used to expand the maintenance aspect framework.

Many of the interviews showed that the final goal includes using new techniques such as Artificial Intelligence (AI) in the maintenance process. Data would suggest the most optimal maintenance planning, based on the conditions that are given as input values. Furthermore, it would have the ability to learn from mistakes and adapt the strategy accordingly. It could be interesting to research how and to what extent these possibilities are influencing current decisions. Furthermore, examples of using these techniques and the effects on the maintenance strategy would be interesting to see as well.

Data quality was considered to be important in all cases, but it was not the highest priority currently. Often the focus was more on the sensor selection and information requirement. More research on how data quality can be measured and the potential effects of insufficient data quality on the performance of the asset can be done. Furthermore, the link between the data dependency and data quality can be researched for these cases. This could lead to knowledge on when the data quality is sufficiently high that it is possible to only rely on sensor output.

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Appendix

i. Scientific paper

Digitalization: Everything starts with an A
Evaluating the impact of digitalization on the maintenance strategy of digitized assets

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Keywords: Maintenance, Digitalization, Effect, Sensor, Asset

Abstract -The number of digital systems that is used for business processes in many organizations is increasing. These digital systems can be used to support decision-making in the maintenance process. In this research the effects of digitalization on the maintenance process are evaluated. This is done by focusing on five aspects: actors, agreements, approach, applications and availability. By comparing the recent knowledge described in the literature with the experiences from practice, a maintenance aspect framework is designed. The experience from practice is obtained from conducting interviews at four organizations. These organizations are: NS (Nederlandse Spoorwegen), Port of Rotterdam, Rijkswaterstaat and ProRail. At each of the organization, one specific asset is selected for which the effects of digitalization are evaluated. The findings of the comparisons are reflected on the features of the asset and the organization to generalize the conclusions. Furthermore, an implementation plan and recommendations on how to use the framework to ensure that all the relevant aspects are included in future policies, are derived from the findings. The implementation plan is designed to be applicable in general, and the recommendations are made for NS specifically. In the recommendations, advice is provided on which aspects should be prioritized more and which aspects are already well formulated in the long-term plans. Lastly, a time line is presented in which the phases of the digitalization transition process are represented. The implementation plan can be used as a guideline to determine in which phase an organization is currently in, and what steps should be taken to proceed to the next phase.

1 Introduction

The number of digital systems that is used in business processes and daily operations is increasing. These systems rely on sensors, networks, and wireless connections to generate data. The data can be used for two purposes: to enhance efficiency of everyday processes, and to predict when maintenance is required. However, the maintenance strategy of the data-providing sensors, networks, and connections themselves is often overlooked. This is important to guarantee a level of reliability, which makes it possible to base decisions on the acquired data and to generate a certain level of trust in the data. In order to determine why this aspect is often overlooked and what challenges arise during the maintenance process of digital systems, the effects of digitalization on the maintenance process of digitized assets are researched.

In this study, four examples are included of different assets at different organizations: the sprinter new generation (SNG) at Nederlandse Spoorwegen (NS), the RPA-12 (Rotterdam Port Authority) at the Port of Rotterdam, the Kreekraksluizen at Rijkswaterstaat and the Kap van Barendrecht at ProRail. By interviewing relevant actors that included in the maintenance process of each of these assets, the effects of digitalization that are experienced in practice will be evaluated. These effects will be reflected on what is described in the current literature to determine why the maintenance process of digital systems is not included in research often and what challenges play a role.

The goal of this research identify what the effect of digitization is on the maintenance process of digitized assets. To structure the research and to fill the identified research gap, the following research questions have been stated:

“What is the effect of digitalization on the maintenance strategy of large public assets?”

What are the standards and definitions of the maintenance process in the current literature?

What are the differences between the traditional maintenance approaches for mechanical and analogue systems and digitized systems according to the literature?

What is effect of digitalization of the asset on the maintenance strategy of a public asset in practice?

Which findings from the case studies can be translated into recommendations for the maintenance strategy of train operators, such as NS?

This paper describes the highlights of the research process and results of the research in the following way. In chapter 2, a summary of the current body of knowledge is described, which provides an answer to the first research question. In chapter 3, the first version of the maintenance aspect framework is presented, based on the findings of the literature review. This will form the basis for the interviews that will be done to build the case studies, which are described in chapter 4. In chapter 5, the outcomes of the case studies will be compared to the information that is stated in the literature. Based on the similarities and differences the framework is adapted and a implementation plan is created. Furthermore, a general description of the digitalization transition process is made, in the form of a timeline, in which all the case studies will be plotted. The paper is concluded with the conclusions that can be drawn from the findings (chapter 7) and reflections on the methodology and the contributions of the research (chapter 8). A more detailed description of the all these chapters can be found in the thesis of this research.

2 Literature Summary

During the problem identification process of the research, a representation of the problem context has been created. This is presented in figure 1. For each of these aspects (cycles, availability, actors and roles, new system, specific system and twofold role of data) the current knowledge on the effect on the maintenance process is evaluated. A more detailed version of the problem context can be found in the appendix.

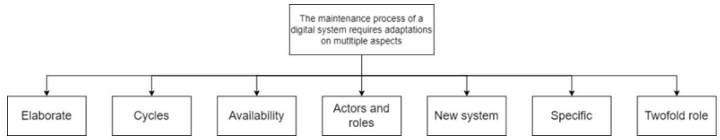

FIGURE 31: PROBLEM CONTEXT

The literature review is used to determine which standards and definitions are used in the maintenance process. Furthermore the development of the maintenance process, as result of more data usage is evaluated. The literature review is also used to investigate which aspects of the maintenance process play a role and how they are affected by digitalization. Lastly, the role of data, information and knowledge is researched.

2.1. The definition of maintenance

Maintenance is defined as “activities that are executed to keep a product in a reliable state and operable. This is done by repairing faults, regulating the environment in which the product operates, and anticipating potential risks and mitigating these risks” (Karki et al., 2022).

There are two main approaches for the maintenance process: before and after a failure has occurred (figure 2). The approach that is used before a failure has occurred, is called corrective maintenance. The approach that is used after a failure has occurred, is called preventive maintenance. Preventive maintenance can be split further into two categories as well: condition-based maintenance and predetermined maintenance (Lind & Muyingo, 2012). Condition-based maintenance is applied once the condition of the component has reached a specified level. Predetermined maintenance is applied once a specified amount of time has passed (Lind & Muyingo, 2012).

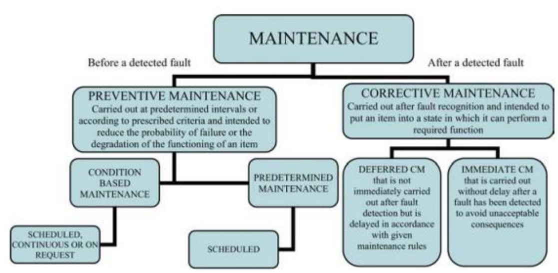

FIGURE 32: OVERVIEW OF MAINTENANCE CATEGORIZATION (LIND & MUYINGO, 2012)

Another method to distinguish different elements of maintenance is presented by Kobbacy and Prabhakar. (2008). In this method, three terms of maintenance are distinguished: maintenance actions, which are the tasks that are executed; maintenance policies, which are the triggers for the maintenance actions; and maintenance concepts, which is the logic and the set of policies and procedures that are used to do the maintenance. In the research of Kobbacy and Prabhakar. (2008), five maintenance policies have been described. These are failure-based, time-based, condition-based, opportunity-based and design-out. The latter policy is about the re-design or re-assembly of a component to prevent recurrent failures (Muganyi et al., 2018).

2.2. The development of maintenance

As a result of the increasing use of data and digital systems in the business processes, such as the maintenance process, an additional category of maintenance approach is added. Besides the corrective and preventive maintenance approaches, preventive maintenance approaches are possible. In this approach, data is used to determine predict when failures will occur and thus work towards the optimal maintenance strategy for a component (Karki et al., 2022).

The main differences between the traditional maintenance approach and the digital maintenance approach have been identified by Karki et al. (2022). The traditional maintenance approach entails that a failure is detected, because the processes are disrupted. The mechanic has to travel towards the site, or asset where the failure has occurred and has to inspect manually what caused the failure. The digital approach consists of less activities and therefore takes less time from a human mechanic. By using a digital system, the cause is often already identified. The mechanic can fix the defect off-site, or can travel towards the defect with the required equipment and knowledge. This reduces the time to fix the defect and human intervention is required later in the process.

Another development that has been described in the literature is that the maintenance process is becoming part of the strategy, or management methods (Muller et al., 2008). This can be related to the aspect in the problem context about the fact that the maintenance process is elaborate. This development includes the monitoring activities, the diagnosis and prognosis process, the decision-making process and control processes throughout the entire process. This development often results in a new term for the maintenance process. Examples include digital maintenance (Karki et al., 2022), e-maintenance (Muller et al., 2008) and Smartenance (FESTO, 2023). Furthermore, more and more new technologies are introduced in the maintenance process. These systems help to collect data more efficiently, or more reliably and allow improvements in the repair methods. Marquez (2022) lists examples of new technologies such as digital twins simulations and augmented reality (AR). Furthermore, the development of 3D printing allows to print spare parts, which can increase the productivity of an organization (ATS, 2023).

2.3. Aspects that play a role in the maintenance process

<u>Maintenance cycles</u>

In addition to the extensiveness of the maintenance process, more aspects have been identified in the problem cluster (figure 2). The first aspect is the maintenance cycle. The maintenance cycle is established, based on two processes (Coetzee, 1999). The two processes are the strategic process (outer circle) and the operational process (inner circle), which are represented in figure 3. The strategic process consists of a management planning and the management measurement. The management planning consists of the maintenance policy, the maintenance procedure and objectives (Coetzee, 1999). The management measurements are aimed at evaluating the performance of the operational processes and ensuring the alignment between all the decisions.

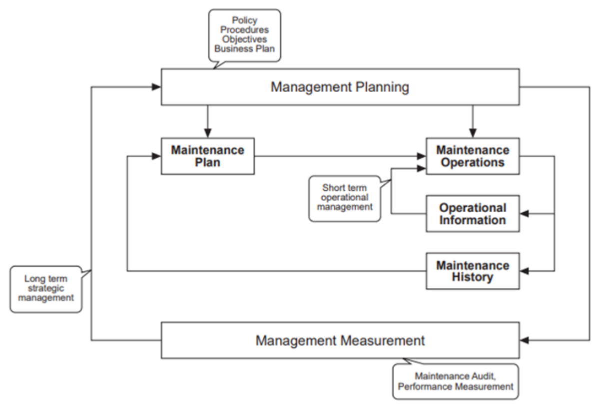

FIGURE 33: ESTABLISHMENT OF MAINTENANCE CYCLE: STRATEGIC OUTER CIRCLE AND OPERATIONAL INNER CIRCLE

In addition to the establishment of the maintenance cycle, the optimal number of cycles is studied as well. Faccio et al. (2014) describe the general phases of the establishment of a maintenance policy, which includes the optimal number of cycles. The main finding is that the optimal number of cycles is based on the tradeoff between the reliability estimation and the estimated maintenance costs. Based on the objectives of the organization, decisions are made for the optimal number of cycles.

The reliability component of the tradeoff is important for the maintenance strategy. Singh et al. (2019), van Dongen (2015) and Rausand and Vatn (2008) emphasize this importance and propose to use RAMSHE (Reliability, Availability, Maintainability, Safety, Health and Environment) and FEMCA (Failure Mode Effect and Criticality Analysis) as part of RCM (reliability centered maintenance) to identify the reliability and the risks that are related to the failure of a component. The goal is to define and measure risk (i), provide an overview of the potential risk (ii), use the probability of failure to optimize the inspection schedule (Bhatia et al., 2019).

The optimal number of cycles is changing as a result of the increasing presence of digital systems. Digital systems include software and an important feature of software is the short development cycle. The Software Development Life Cycle (SDLC) is based on the agile methodolgy, which uses short cycles and (Gillis, 2019) constant customer input (Outsystems.com, 2023). This means that updates and upgrades are available with a high frequency and the maintenance cycle should be aligned with this higher frequency, in order to implement these updates and upgrades.

As a conclusion, it can be said that instead of applying maintenance to the system at a predetermined frequency, maintenance is applied when it is required according to the data. Therefore, the maintenance frequency can be different throughout the life cycle of the system, depending on what is required according to the data.

Actors and roles

The maintenance process is part of what is often called asset management. In the concept of asset management, three standard roles are identified. The Asset Owner, who is responsible for making strategic decisions and the trade-off between long-term and short-term investments. Secondly, the Service Provider does the operational maintenance actions and is responsible for reliability, availability, maintainability and safety. Lastly, the Asset Manager is the link between the asset owner and the service provider (van der Velde et al., 2013). Singh et al. (2019) include a fourth role in the asset manager structure: the asset user. The asset user determines the long-term plans, regarding network design, timetables and asset demands and employment.

In the rail sector, there is an additional set of standard roles, related to the maintenance process of assets. In this approach, an entity is assigned to all railway vehicles to ensure that they maintain a safe state and are operational. The ECM (Entities in Charge of Maintenance) provides a description of the maintenance strategy, which activities are included and how these activities are inspected. The maintenance activities can be outsourced, but the ECM will stay responsible at all times (ILENT, sd)

Interactions and agreements

Between the roles that have been identified in the previous section, communication, agreements, and interaction is required to establish and maintain a successful maintenance strategy (van den Boomen et al., 2012). Additionally, reliable asset data is required for successful asset management (van der Velde et al., 2013). This can be obtained using three instruments: objectives and standards, plans and contracts (van der Velde et al., 2013). The literature does not specify which interactions and agreements are required specifically, as this depends on the asset.

Maintenance activities

The main differences between the traditional maintenance approach and the digital maintenance approach are the intervention moment and the time the overall process takes (Karki et al., 2022). Additionally, different maintenance activities are required for the maintenance process of digital systems. In general digital systems require more software, which requires maintenance in which a computer is involved, rather than mechanical tools. In addition to different tools, the maintenance activities often include more programming and debugging software, rather than repairing mechanical components.

Additional aspects

The literature review yielded no relevant aspects in addition to the existing aspects: cycles, actors, interactions, and activities. However, the concept of data sharing and ownership was considered to be an important development according to the literature (Zhu & Liyanage, 2021) (Jägare et al., 2019). Furthermore, the challenges related cybersecurity can be linked to this aspect as well. All the asset management roles require insights in the data to execute their tasks and responsibilities. Data sharing and publications can lead to potential security risks, which is why attention is required to mitigate potential risks and create independence and resilience (Zhu & Liyanage, 2021). Jägare et al. (2019) provide some guidelines to deal with these issues, which mainly advice to consider that data as an asset by itself. Furthermore, considerations about data sharing, data ownership and cybersecurity should included in the contracts with external parties.

2.4. The role of data, information and knowledge

Data, information and knowledge are three different concepts. Data consists of symbols (Chen, et al., 2009), or can be described as raw material for information and knowledge (Zins, 2007). Information is processed data in such a way that that it is considered to be useful. It can be used for answering “who, what, where, when and how”-questions (Chen, et al., 2009). Knowledge is related to the skills, abilities and habits of mind of people (Seely Brown & Duguid, 2000), which means that until the information is received by the people with the proper skill set, or the required pre-knowledge, the information is useless.

Because of this transition, and the requirements of skills and pre-knowledge to transition data into information into knowledge, it is not necessarily the case that more data always leads to more information and more knowledge. Roetzel (2019) even describes the possibility that the decision-making performance decreases as the information load increases, due to information overload.

Data plays an important role in many business processes, which requires for the data to be managed properly. A concept that is often mentioned in the literature is knowledge management. Knowledge management is defined as "the capacity to manage information, including gathering knowledge from internal and external sources, transforming it into new strategies or ideas, and implementing and preserving it" (Idrees et al., 2023). The objective of knowledge management is to distribute the data, information and knowledge throughout the entire organization, to make sure it can be used effectively (Sarka et al., 2019).

Herder et al. (2004) have visualized the concept of knowledge management as the 'knowledge management rainbow', which is presented in figure 4. Each of the segments of the rainbow represents a part of the method to distribute the information and to support the transition from information to knowledge.

The horizontal axis of the rainbow represents the transition from information to knowledge. On the horizontal axis, three levels are indicated: Corporate (C), Group (G) and Individual (I) (Herder et al., 2004). The five segments represent knowledge management strategies: Store and retrieve, Tracking and Analyze, Transfer and Integrate, Connect and Explore and Network and Cooperate. By applying knowledge management properly, relevant data is selected to be transitioned into information. This information is thereafter moved to the right location where it can be used effectively.

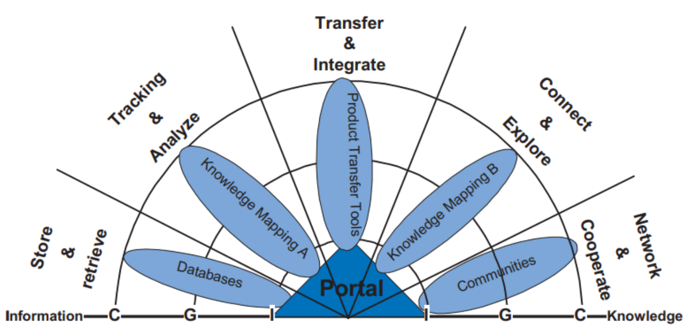

FIGURE 34: KNOWLEDGE MANAGEMENT RAINBOW (HERDER ET AL., 2004)

In addition to proper knowledge management, data quality is considered to be essential for digital asset management (van der Velde et al., 2013). Ensuring data quality involves planning, obtaining, storing and sharing, maintaining applying and disposing of data (POSMAD), which is also known as the data life cycle (McGilvray, 2021). Data quality is often assessed using dimensions, or attributes (Cichy & Rass, 2019). The dimensions that are used most often are completeness, accuracy, timeliness, consistency and accessibility (Cichy & Rass, 2019). The framework and attributes that are used to measure often depend on the organization and the sector in which the organization operates.

3 Framework

A framework is developed which visualizes the relevant aspects of the maintenance process, based on the findings in the literature. The framework includes five aspects, which are represented in blocks. The purpose of the framework is to show the relevant aspects and to act as a checklist for organizations when creating policies. The framework is presented in figure 5. A larger version of the framework can be found in the appendix.

The aspects that are included in the framework, in the suggested sequence are process, which focuses on the preventive maintenance approach and a mid-term perspective. Next, the actors are evaluated. This is split in internal and external parties for which their role in the organization and process is evaluated. Next, the interactions and agreements between all the parties are discussed. Furthermore, the approach towards using more digital systems is included. Here is focus is on the digital tools as well as the human input towards the maintenance process. The digitalization aspect is included in the form of support tools, in which sensors are used to monitor the condition of an asset and provide information for condition-based maintenance. The other aspect is the maintenance process for the sensors itself. Finally, the framework is concluded with the availability. For each asset this is a common goal, even though it is measured and expressed differently. The framework will form the basis for the interviews that are done.

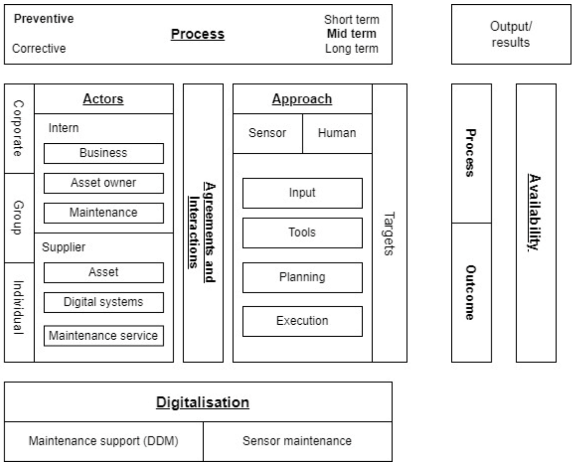

FIGURE 35: INITIAL VERSION MAINTENANCE ASPECT FRAMEWORK

The framework is verified based on the literature research and the interviews that are done in the case studies to confirm that the framework is complete and all relevant aspects are included. The combination of literature and interviews is essential, because this ensures the input from research and practice. The framework is validated based on the interviews that are done in the case studies. This is important in order to ensure that the framework is useful in practice.

The decision to divide the framework into different blocks is made to support the purpose of the framework. This way a clear overview of the relevant aspects is provided and it is easy to check if all the aspects have been evaluated, when designing new policies and long-term visions. Furthermore, the suggested sequence of the aspects, as is described earlier allows organizations to follow a structured approach in which no aspects are neglected. Furthermore, information from the one aspect can be used in the considerations for the next aspects.

4 Case studies

Four cases were selected to be included in the research: the SNG (Sprinter New Generation) of NS, the RPA-12 (Rotterdam Port Authority) at the Port of Rotterdam, The Kreekraksluizen at Rijkswaterstaat and the Barendrechttunnel at ProRail. Each case will briefly be addressed. A more detailed description can be found in the thesis.

The roles that have been interviewed are presented in figure 6.

Company	Roles
NS	Maintenance Engineer, Reliability Engineer Rolling Stock Manager, Manager Maintenance Engineering, Lead architect, Manager Maintenance Development, Aspectmanager IT/OT
Port of Rotterdam	Asset Owner, Asset Manager, Reliability Engineer
Rijkswaterstaat	Asset Manager, Smart Maintenance Manager, Consultant Industrial Automation
ProRail	Asset Manager Civil Engineering and Utilities, Asset manager Infrastructure Innovations

FIGURE 36: OVERVIEW OF INTERVIEWED ROLES

SNG (Sprinter New Generation) at NS

The SNG is one of the sprinter train sets that is used by NS to cover regional train transport. For each train set type, a rolling stock team is assigned to monitor the performance of the rolling stock type and optimize the processes that are related to the operations, such as the maintenance process. These optimizations are often based on the data that is retrieved from the rolling stock, or the operating staff on-board.

NS is operational in the rail sector, which means that there is an ECM for each train set type. The ECM tasks are divided into four categories, which are all covered by NS departments.

The train sets are supplied by external suppliers, which means there is a contract with these partners. Important aspects of these contracts are the warranty agreements, and the effect of adapting the prescribed maintenance on these warranty agreements.

The maintenance process is divided into three types: daily maintenance (DO), short-cycle maintenance (KCO) and long-cycle maintenance (LCO). For each of these types, specific maintenance actions are determined.

The availability of the rolling stock is determined by several indicators. In short, it is the total number of train sets minus the number of train sets that is scheduled for maintenance. In other words, the number of train sets that can be used for the operations. The unscheduled unavailable rolling stock is the factor that affects the availability. This can be measured by the number of failures, or the number of minutes delay, both per million driven kilometers per coach.

The goal of digitalization is to use data effectively and efficiently, to reduce the number of safety-related failures and prevent failures from occurring. Furthermore, the aim is to work towards a more condition-based approach.

RPA-12 (Rotterdam Port Authority) at the Port of Rotterdam

The RPA-12 is an inspection vessel that is used for inspections, or when calamities occur on the harbor terrain. The vessels are used by The Harbor Master (DHMR), and are owned by the Port of Rotterdam.

The asset management approach with the standard asset management roles are used, with the addition of reliability and maintenance engineers. This way the maintenance process and resulting reliability can be optimized. For each asset type, an asset manager is assigned. The asset owner is responsible for all asset types. The maintenance is done by the Port itself, and the supplier of the specific component is included if the maintenance is too complex.

Preventive maintenance consists of two major maintenance moments and 1-2 additional pitstops. This interval has been reduced from four to two maintenance moments, based on the data, retrieved from the vessels.

Digitalization has played a role in creating more insight into the actual availability of the vessels, as not all the required information is known to determine an accurate representation of the availability. Additionally, it allows better communication with foreign parties who want to use the harbor. One example is that the arrival of each vessel can be determined and shared accurately and easily. Furthermore, the goal is to work towards the application of techniques such as AI to let data determine the optimal maintenance schedule.

The Kreekraksluizen at Rijkswaterstaat

The Kreekraksluizen are part of program to gain experience in data-driven maintenance and to apply data-driven maintenance in the asset management of Rijkswaterstaat in two years. The Kreekraksluizen is a set of slots consisting of two elements that is located on the connection between Rotterdam and Antwerpen.

The asset owner of all the assets of Rijkswaterstaat is the Ministry of Infrastructure and water management. Rijkswaterstaat is the overall asset manager, but the tasks and responsibilities divided over national services and programs. One of which is Programs, Projects, and Maintenance (PPO).

For the Kreekraksluizen, Scaldis is the service provider, which is determined by a tender for a duration of 5-10 years. This includes routine maintenance and inspections, which is done continuously to ensure routine maintenance. Variable maintenance, such as renovations, is carried out through a bidding process by Rijkswaterstaat. The goal is to have Rijkswaterstaat as the data owner of all the data that is retrieved from the assets, but let parties such as Scaldis use the data for optimizing the maintenance activities.

Audits in recent years have revealed that RWS's current asset management approach is less professional than originally thought. To address this issue, the program Asset Management 2.0 (AM2.0) is created, which runs parallel to the development of the data-driven asset management program, and the goal is to integrate the developments and results from both programs to create a complete strategy.

Digitization leads to increased availability because it allows for proactive actions before failures occur. However, this impact is expected to be realized in the long term, not immediately after implementation.

To measure the availability of the locks, two indicators are used: passing time and downtime hours. In the future, vessel loss hours might be used. In order to use this KPI, the right data has to be available.

Barendrechttunnel at ProRail

The Barendrechttunnel consists of 5 tubes, in which 9 rail tracks are located. These tracks are used for the high-speed line, freight transport and passenger transport between Rotterdam and Dordrecht. This tunnel is a so-called land tunnel, which means the land goes over the tracks, rather than the tracks going underground. However, this is still considered to be a tunnel, which means the rules and regulations for tunnels apply.

The overall asset owner is ProRail. The Netherlands are divided into nine geographical regions, each having a regional asset managers and specialists. External maintenance contractors are responsible for maintaining a predetermined level of performance. The current maintenance cycle has two routes: long-term, which involves preventive maintenance based on manufacturers instructions, and Performance-Based Maintenance (PGO), where the maintenance contractor is responsible for achieving specified performance levels and must organize the maintenance themselves.

ProRail’s digitalization pace is slower than the pace of the maintenance contractors, because the contractors are commercial parties that invest heavily in digitalization. In the case of the Barendrechttunnel, Volkerrail is the maintenance contractor.

This means that data is only stored and analyzed in the case of a failure. Once the failure is resolved the data is discarded. The goal for the future is to store relevant data to analyze trends over time and to create a generic approach for all tunnels. Initially, the focus is not on adding new sensors but on examining what data can be extracted from the existing systems and identifying information needs, which is started with the ventilation system, the most significant cost component. Sensor maintenance is not currently part of the process. Sensors are integral components and are replaced when the system is replaced.

The goal is to make ProRail owner of all the data, with maintenance contractors having access to it for the purpose of performing and optimizing maintenance. Digitalization can help in predicting failures more accurately by providing insight into the status of a component and allowing for analyses of failure behavior. It also enables benchmarking and increases the efficiency, safety, and speed of maintenance.

Based on the findings in the interviews, the framework is adapted and the cases will be compared in more detail. This will be described in the next section.

5 Results

In this section, the results of the research will be described. First, the adjusted framework is discussed. The additional comparisons are presented. Also, a time line that represents the digitalization transition process is discussed. Additionally, the implementation plan that follows from the framework and the timeline explained. Furthermore, the findings from the literature and the interviews are reflected on the current maintenance vision of NS, resulting in a set of recommendations. These recommendations can also be linked to the general implementation plan.

5.1 Framework

The maintenance aspects framework has been adapted, based on the feedback from the interviews. It is presented in figure 7. A larger version of the framework can be found in the appendix.

The purpose of the framework is to act as a checklist to reflect on current policies and long-term visions and ensure that all relevant aspects of maintenance of digitized assets are included in new policies and long-term visions. In the new version, there is more focus how the aspects in the framework can recognized and memorized more easily. All the aspects therefore start with the letter A and the digitalization. The sensor maintenance block is included in the approach, under applications, because it is part of the entire process, rather than a separate block.

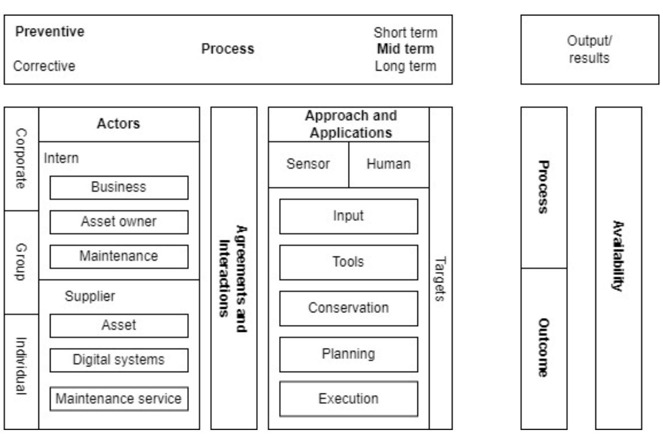

FIGURE 37: FINAL VERSION MAINTENANCE ASPECT FRAMEWORK

In all four cases, the focus on the trade-off between reliability and costs was clearly noticeable. This was the case for considerations about the maintenance activities and how these should be prioritized and executed, but also for the sensor selection.

During the interviews the two main roles that have been included are the asset manager and the asset owner. The main focus of the asset manager was related to events that have occurred in the past and the events that will happen in the near future, whereas the focus of the asset owner was more on the overall operations of the entire organization and the long-term business processes. The effects that were mentioned by the asset managers for example include applications such as looking back at failures that have already occurred and investigating if this could have been prevented, based on the available data. Effects that were mentioned by the asset owner are for example the possibility of monitoring the state of the assets in the entire country and being able to prioritize the maintenance activities.

The interaction between the actors are similar for all cases. The effect of digitalization on the interactions and agreements between the actors are mainly related to the duration of the contracts and the inclusion of new developments such as data ownership.

The effect of digitalization on the approach is represented by a timeline, which will be discussed in section 5.3.

Availability is an important performance indicator for each asset. Generally, it is considered that digitalization has a positive effect on the availability on the long term, as it could result in more insights and a more accurate representation of the availability levels. Furthermore, the interviews showed that many perspectives play a role when determining the availability. Examples can be minimizing risk, such as limiting specific defects with a high risk, or minimizing costs. This means that the single availability indicator does not provide a complete picture of the performance of the maintenance process.

5.2 Additional comparisons

The cases have been compared based on similarities between the features of the asset or the organization. The features that are included are the asset type, the sector, the level of influence by the government, the number of types of assets owned by the organization and the party that is executing the maintenance. This is presented in a table in figure 8.

	NS	Port of Rotterdam	Rijkswaterstaat	ProRail
Asset	Train	Vessel	Lock	Tunnel
Asset type	Moving	Moving	Fixed	Fixed
Sector	Rail	Port	Water	Rail
Government	No	No	Yes	Yes
# types of assets	Few	Many	Many	Many
Categorization	Type	Type	Region + type	Region + type
Maintenance	Inhouse	Inhouse	Tender	Tender

FIGURE 8: ADDITIONAL COMPARISON: SIMILARITIES BASED ON THE FEATURES OF THE ASSETS

The moving assets allow for more possibilities to apply maintenance, as the maintenance crew can go to the asset, or the asset can go to the maintenance facility. This can be advantageous when working with a more data-driven, or condition-based maintenance strategy. Digitalization of assets in the same sector could lead to a different form of collaboration between the involved parties. For example, NS and ProRail use each others equipment to measure the state of their assets. This collaboration also allows to learn from different parties. In the future this new form of collaboration and learning possibilities might expand over multiple sectors.

Also, the level of influence by the Dutch government could play a role, as they might set rules and regulations for which sensors to use or which procedures to follow. Furthermore the number of types of assets that are present in an organization could play a role. When there is only one type, or the assets are similar, one vision might be sufficient, whereas this might not be possible for multiple types of assets. Creating a long-term vision has proven to be a complex process, as many aspects of the digitalization transition are uncertain. Lastly, the fact whether maintenance is done inhouse or outsourced is considered. Because of the new and different knowledge is required for the digital systems and maintenance requires many resources, this decision needs to be made based on many considerations.

When inspecting the table with similarities, based on the features of the assets and the organizations, some expectations for the maintenance approach can be made. Particularly, there seems to be a connection between the tendered maintenance, the categorization of the assets and the number of types of assets, owned by these organizations. It is expected that maintenance is outsourced, because of the numerous types of assets, or the location of the asset, because it could require too much specific knowledge and resources to be able to manage the maintenance process from within the organization that owns the asset.

5.3 Timeline

A general timeline can be made, which includes the phases and activities that organizations go through during the digitalization transition. This timeline is presented in figure 9. A larger of the timeline can be found in the appendix.

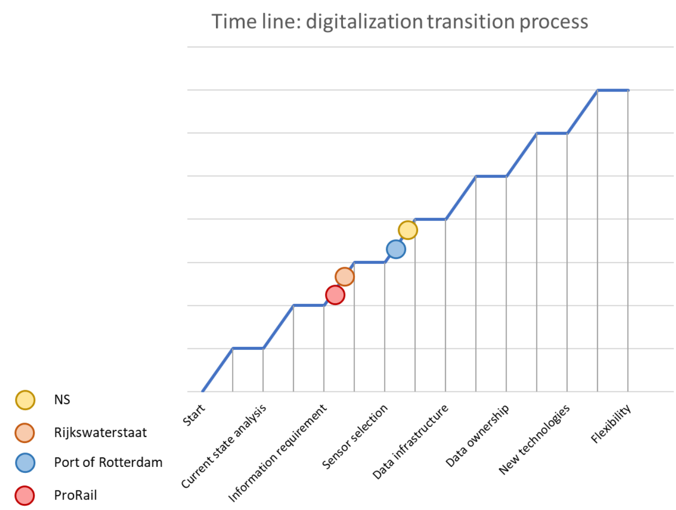

FIGURE 9: TIMELINE DIGITALIZATION TRANSITION PROCESS

The phases in the timeline represent large challenges that organizations are facing during the digitalization transition. The first phase is to create a current state analysis, which describes the available information on the asset, such as the age and recent maintenance. This provides insight in what data is missing, how this can be retrieved and translated into information, which is represented as the information requirement phase in the timeline. To retrieve missing information, sensors and human sources can be used. The knowledge management rainbow (Herder et al., 2004) might provide useful guidance as it emphasizes the fact that it is a process to transition from data to information to knowledge and that it plays a role in all the levels of an organization.

The selection process for sensors and human sources, is represented as the sensor selection phase. Each of the selected sensors requires infrastructure to work properly and to ensure the required quality. Based on the selected sensors, this infrastructure has to be created. Issues such as data sharing and data ownership have to be considered during this phase as the infrastructure determines what the sharing possibilities are. These considerations are represented in the data ownership phase.

In the next phase, new technologies are considered. Examples are the use of Artificial Intelligence (AI), Augmented and Virtual Reality (AR and VR). Often these new technologies need sufficient and reliable input in order to be effective. Therefore, this can be considered after the data input stream is secured and the reliability is guaranteed. The last aspect of the timeline is flexibility, which is required throughout the entire transition, because many factors play a role and decisions might need to be taken several times. An organization needs to be flexible to be able to manage these adjustments properly.

The timeline shows that NS and the Port of Rotterdam have passed the challenge of sensor selection and are currently working in the data infrastructure. These organizations are already able to extract and analyze data from their current systems. Rijkswaterstaat and Prorail are placing separate sensors on top of the existing systems, which means they have to select which data has to be extracted and which sensor can be used for that.

5.4 Implementation plan

In this chapter, an implementation plan has been presented which connects the framework with the timeline. The implementation plan is designed to be applicable to many organizations and provides a guideline for what steps and considerations need to be taken to progress in the digitalization transition. The implementation plan follows the same structure as the framework (figure 7).

Process: the goal is to create a visualization of the process, which can be used for the upcoming steps. It allows to zoom out between throughout the evaluation process and consider the entire process as a whole.

- Current state analysis: draw a flow diagram of the process.
- Describe the tasks and activities at each step.
- Describe which data is used, created and passed on to the next process step.
- Identify the value streams in the process. Is important to map where in the process value is added to the process.

Actors: The goal is to create an overview of all the actors that are involved in the process, and on which levels they operate.

- For each activity in the process map, determine which actors are involved.
- Describe per actor: function title and asset management role, the position in the organization and the tasks and responsibilities of the actor.

Agreements and interactions: van den Boomen et al. (2012) underlines the importance of communication, agreements, and interaction as the are required to establish and maintain a successful maintenance strategy. Therefore, in this part of the implementation plan the agreements and interactions are evaluated.

- Check the interactions that have been identified in the first step
- Determine what the specific goals and objectives are for agreement and if the agreement are actually in line with the goals and objectives of the organization.

Approach and application: the goal of this aspect is to consider the decisions that are made during the digitalization transition. For this aspect, the framework distinguishes sensor and human related factors.

- Check which information is missing, based on the process map
- Determine how this data and information can be retrieved in such a way that it in line with the information requirement.
- Determine what maintenance approach will be used, such as scheduled or condition-based maintenance.
- Determine what parties should have access to parts of the data and which infrastructure requirements this brings.
- Define the new role and responsibilities of each actor in the desired maintenance approach. Include all the actors that have been identified.
- For each sensor, determine the required infrastructure and consider some room to expand and include additional systems in the future.

Availability: the goal is to align the indicators to measure availability to the vision of the organization. Furthermore, the sensors and human sources are used to guarantee the required reliability levels.

- Determine the indicators and the method to measure the availability.
- Describe how the availability indicators are linked to the overall vision and mission of the organization
- Check if the indicators actually represent information that demonstrates the added value to the organization.

5.5 Reflections and recommendations

Furthermore, the current maintenance vision document of NS is evaluated, based on the framework. The recommendations based on the maintenance vision are made specifically for NS. These recommendations for NS are focused on where the vision might need more attention and which aspects are already well formulated based on the findings from the literature and the interviews.

1: Create a clear vision for the goal and all the intermediate steps.

2: Identify all the involved actors and determine the role and the responsibilities.

3: Determine a standardized method for collaboration between the mechanic and the engineer.

4: Clarify the requirements for the mechanics.

5: Expand the requirement on more IT knowledge.

6: Determine the level of sensor dependency and create a maintenance plan accordingly.

7: Data quality requirements have to be clearly defined.

8: Maintain good communication with the supplier throughout the entire process.

9: Maintain flexibility in the maintenance strategy.

These recommendations can be applied in addition to the implementation plan that has been presented.

Based on the framework and the time line, there is a suggested prioritization for these recommendations. This is also in line with the sequence of the implementation plan. Recommendation 8 and 9 were already included in the vision document, but should stay a focus point when implementing the other recommendations. First the clear vision (1) is the base on which all the decisions will be made and should therefore be the first priority. Next, the actors have to be identified (2). Next, the data quality indicators have to be set, because this is related to the sensors that will be selected (7). Based on these indicators, the level of dependency can determined (6). Based on the selected sensors and indicators, the requirements for the mechanics can be described, as it is known what systems the mechanics have to work with (4). Lastly, a standard method for collaboration has to be created (3).

6 Conclusions

This section addresses the final conclusions of the research and describes the contributions of the research to current research and practice. The research questions that were stated in the beginning of the research will be answered and the research gap is addressed.

6.1 Research question

The answer to the question is structured by answering the sub research questions. The main research question is stated as follows:

What is the effect of digitalization on the maintenance strategy of large public assets?

- What are the standards and definitions of the maintenance process in the current literature?

Maintenance is defined as: "activities that are executed to keep a product in a reliable state and operable. This is done by repairing faults, regulating the environment in which the product operates, and anticipating potential risks and mitigating these risks" (Karki et al. 2022)

Maintenance can be divided into corrective and preventive maintenance. Corrective maintenance is applied after a failure has occurred and preventive maintenance is applied before a failure has occurred. Preventive maintenance can also be divided into two types. The first type is condition-based maintenance in which maintenance is applied whenever the condition of a component has degraded to a predetermined level. The other type is time-based, or scheduled maintenance, in which maintenance is applied after a certain amount of time has passed, regardless of the condition of the component.

As a result of the development of the digital systems and the increasing presence of these systems, predictive maintenance is added as a type of maintenance. Data is used to predict when maintenance is required. As a result of this development, maintenance has become a much more important part of the operations. Finally, the use of information from the operations and using it for the maintenance strategy has formed a base for new technologies and innovations.

- What are the differences between the traditional maintenance approaches for mechanical and analogue systems and digitized systems according to the literature?

The differences between the traditional maintenance approaches for mechanical and analogue systems and digitized systems are the number of cycles and the length of the cycle. Software and updates to the software are created and offered with a high frequency, which results in the fact that maintenance have to be aligned with this higher frequency in order to maintain a properly working digital system.

Furthermore, the agreements between organizations and suppliers are different. The duration of the contract has increased and the supplier is included in the earlier in the process and will provide service for a longer period after the product has been supplied. Lastly, the contents of the contract between different parties has changed. New elements are included, which were not relevant in the traditional maintenance approach. For example, data ownership has become an important issue with the increasing number of digital systems and data that is provided by these systems.

- What is effect of digitalization of the asset on the maintenance strategy of a public asset in practice?

In general, data is used as input value to monitor the performance of the asset and to measure these indicators more precisely. As an effect, adaptations to the maintenance cycle can be made quicker and more reliably. Furthermore, the addition of digital systems has allowed for better documentation on which maintenance is executed.

Because of the increasing number of digital systems, the tools that are required for the maintenance activities have changed. Instead of the conventional toolbox for the mechanical components, computers are often used for maintenance activities. Computers are used to visualize the data and to make analyses based on these visualizations, and computers are used for software updates to the digital systems in the assets.

Mechanics need to be able to use the computer as a maintenance tool in order to do the repairs and required updates. Engineers or analysts need to establish links between available data and the mechanical works of the asset. In order to create these links, proper knowledge on IT-systems and the mechanics of the asset is required.

Another effect is a more long-term collaboration between the organization and the suppliers of the assets. Instead of only providing the product and the spare parts for the components, the collaboration is changing into a service, in which the supplier plays a supporting role. This results in different agreements in the contracts between parties, including new elements such as data ownership.

The effect on the availability might be negative on the short-term as more maintenance is required than expected, due to new insights. However, on the long-term the effect is considered to be positive as the improved ability to monitor the asset allows for better predictions and scheduling on when maintenance is required, which makes it possible to optimize the maintenance planning and therefore increase the availability.

- Which findings from the case studies can be translated into recommendations for the maintenance strategy of train operators, such as NS?

NS has created a maintenance vision, which describes the main focus points for upcoming developments that NS will have to face. Some reflections on these main points have been made. The reflections are translated into recommendations for NS on where the vision might need more attention and which aspects are already well formulated. These recommendations are mentioned in the previous section.

As a conclusion, the effect of digitalization on the maintenance strategy of large public assets can be explained by looking at five aspects: actors, agreements, approach and applications and availability. These aspects can be combined into a framework which acts as a guidance for organizations to include and consider all the relevant aspects of digitalization when creating new policies. The effects that are experienced in practice are often in line with what is stated in the literature.

The main difference between the literature and the cases is the focus on having a uniform strategy and vision, which is noticeable throughout an entire organizations and the decisions that are made. Furthermore, data quality is considered to be an aspect that will be dealt with once the data infrastructure is ready, however it is suggested that this has to be considered simultaneously as part of the data infrastructure, to guarantee that the data from the sensors is useful and reliable for basing maintenance-related decisions on.

6.2 Research gap and contribution

The research gap has been identified as the fact that the maintenance strategy of the increasing number of digital systems and sensors that is present in assets is often neglected. Especially, the role of data quality and the need to ensure that the data that is provided by the sensors is reliable as a result of the maintenance of the sensors. The effects that have been identified in this research show what aspects play a role in the maintenance process and challenges arise as a result of digitalization.

The research contributes to the current research in the following ways. First, a framework is created which provides a complete overview of the relevant aspects that affect the maintenance process of digital systems. Separate aspects have been addressed, but the combined overviews is a new addition. Similarly, the complete overview of the general digitalization transition process has not been described yet. Therefore the timeline presented in this research can be considered as a contribution to the existing research. Furthermore, the added value of the role of the asset user is argued, which is not addressed in current literature yet. This provides a base for further research. Also, this research shows that there is a potential connection between the following features: the outsourced maintenance, the categorization method of the assets and the number of types of assets.

For practical applications, this research is useful as well. The combination of the framework, timeline and implementation plan allows organizations to check current policies and create new policies in a structured way, ensuring all relevant aspects are being considered.

7 Discussion

Due to restrictions and the scope of the research, some decisions resulted in limitations for the research. This section addresses these limitations and the potential effects on the results of the research. Furthermore, recommendations for further research are provided.

Limitations

A divers set of assets is used, which can be seen as a advantage or a limitation. Because of the diversity, it was often complex to compare the cases, but it also allowed to think outside the box. When doing a similar research with more similar assets, more detailed conclusions might be drawn.

Relevant information missing from the interview, as it was filtered out by summarizing the interview. This could lead to findings being excluded from the research and therefore not included in the conclusions and to a lack of nuances that could have been added to the conclusions that have been drawn.

Additionally, relevant information could be missing because relevant actors were not interviewed. This is mitigated as much as possible by interviewing actors with a similar function for other assets, or actors that previously had the role of the desired actor. Another important limitation is that no actual service providers or mechanics were interviewed. Including these parties might have revealed challenges that are not considered in this research, which can be seen as a limitation of this research.

The perspective and position of the actor in the process could steer the interview. For example, criticism against actors that are on a higher hierarchal level might not be shared, even though it could be relevant. Furthermore, the sequence of the interviews could influence the outcomes, as information is gathered throughout the interviewing process. This could result in new questions that are included in the interviews, which are therefore missing in the previous interviews.

The distribution of interviews is also important to point out. Since the research is done for NS, more interviews have been conducted with employees of NS. The uneven amount of information resulted in the fact that comparisons could not be made as detailed as the available information was, as specific details and nuances were missing from the other three cases.

Recommendations for further research

- Validation time line
- validation features conclusions

Research focusing on the service provider and the effects that can be observed on in the execution part of the maintenance process can be done. The service providers were not included in the research, which resulted in a potential neglection of relevant effects. In follow-up research, these effects can be identified, and it can be evaluated whether there are additional effects and whether the effects that are mentioned in this research also play a role in the perspective of the service provider.

There is also a research possibility in the question of the added value of the asset user. This research argues the added value of the role, and further research can validate the added value. It could lead to conclusions about the added value of additional roles, such as the asset user, or a change in the standard responsibilities that are associated with an asset management role.

During the interviews, the link with the acquisition phase of the asset was often made. Since this research was focused on the maintenance process, this was considered to be out of scope. However, this connection is very relevant, because the decisions that are made during the acquisition phase, have an effect on the maintenance process.

Based on the features of the asset and the organization, some similarities between the case have been identified. Potential effects of these features on the digitalization process were described, but further research can be done to investigate whether these potential effects actually play a role and what this role is. Furthermore, additional effects can be discovered which might be used to expand the maintenance aspect framework.

Data quality was considered to be important in all cases, but it was not the highest priority currently. Often the focus was more on the sensor selection and information requirement. More research on how data quality can be measured and the potential effects of insufficient data quality on the performance of the asset can be done.

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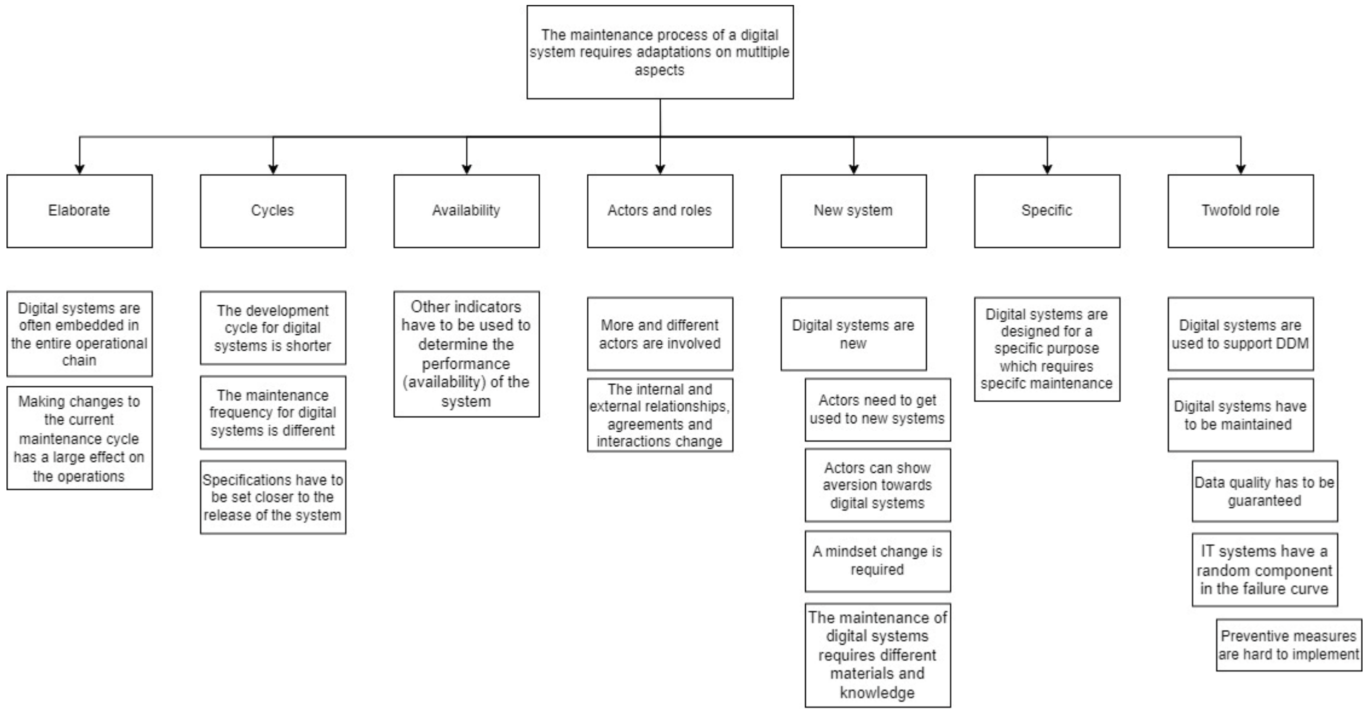
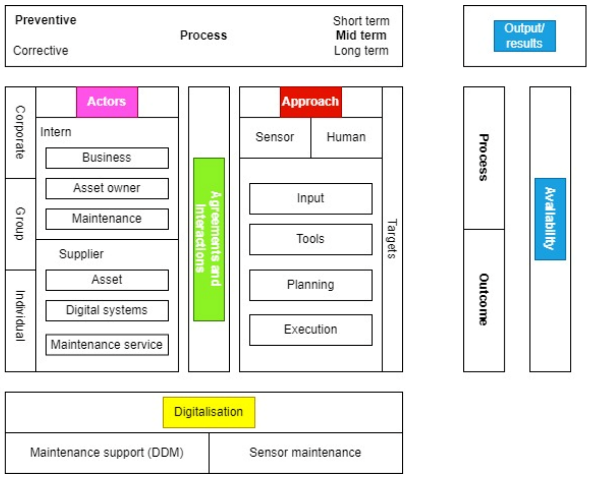
ii. Detailed problem cluster



iii. Interview questions

The colours of the sections correspond with the colours in the framework.



General:

- Please fill in the informed consent form
- What is your function?
    - What are the specific tasks that are related to this function?
- How long have you been working for this organization?

Asset:

- Which asset within your company has been affected by digitalization the most?
- What does the asset look like?
- Where is the asset located?
- How old is the asset? When was the asset built?
- What components does the asset consists of?
- What materials is the asset made of?
- Does any of the aspects mentioned above add special requirements for (the maintenance of) the asset?

Approach/Process:

Maintenance cycle

- What does the maintenance cycle look like in general?
    - What does the corrective maintenance cycle look like?
    - What does the preventive maintenance cycle look like?
    - What does the predictive maintenance cycle look like?
- How has the maintenance cycle been established?
    - Is the asset maintained as a whole, or are parts maintained separately?
    - Are there critical parts present in this asset?
        - How is this determined?

        - How is the critical status included in the maintenance cycle? Is this part maintained with a different frequency?
    - Is the maintenance of this and similar assets scheduled together, or separately?
    - Which frequency is used for the maintenance cycles?
        - How is this frequency determined?
        - Has this frequency changed due to digitalization?
    - What is the role of rules and regulations for the maintenance strategy?
        - Do these rules and regulations play a role in the frequency and maintenance activities?
- How often is the maintenance strategy revised?
    - Who is responsible for potential revisions?
    - Who is responsible for potential improvements to the maintenance strategy?
    - Which indicators are used to determine the current and potential performance of the maintenance strategy?
    - Has this been affected by digitalization?
- How is the maintenance strategy related to the overall goals and objectives of the company?
    - Has this been affected by digitalization?

Maintenance execution:

- Who is responsible for executing the maintenance activities?
    - Is done within your company, or is it outsourced? Why?
    - Is it possible to interview this party?
    - What are the tasks and responsibilities for each party?
    - What is the effect of digitalization on this process and cooperation?
- Who monitors the maintenance process?
    - How is this done?
    - What are the norms and requirements?
    - Who determines these norms and requirements?
    - Are there specific norms and requirements for the critical parts?
- Generally, there is a trade-off between reliability (and risk) and costs, what is the division for this asset according to you?
    - Does this apply for all (critical) parts?

Determining risks

- Which risks play a role for this asset?
- How are the risks determined? Which methods/techniques/tools are used?
- What is the role of digitalization to mitigate these risks?

Digitalization process asset

- What does the digitalization process look like?
    - What specific aspects have changed?
    - What is the role of digitalization on the maintenance process of the asset?
        - What are the positive effects of digitalization? Can you give an example?
        - What are the negative effects of digitalization? Can you give an example?
        - How does your company deal with these effects? Can you give an example?

Information use:

- Which information from the system are used?
  - Which tools are used to derive this information from the system?
  - Which sensors are used to derive this information from the system?
  - Where are these sensors located?
    - How is the information acquired?
    - How often is the information acquired?
    - How is the information handled?
    - Who is involved in this process?
  - How is the information used? For what purpose is the information used?
    - Which programs are used?
    - Who is using which information?
    - Is it possible to speak to these people?

Digitalization: sensors

- Which sensors are used?
- Which sensors provides which information?
- How is a continuous and reliable data stream established?
  - How are the sensors maintained?
  - Which methods are used? Redundant systems

Data quality:

- How is data quality measured?
- Who is responsible for measuring data quality?
  - Is it possible to speak to this person?
- How is data quality monitored, maintained, and improved?
- To what extent has digitalization played a role in maintaining and improving data quality? Can you give an example?

Actors and roles:

- Who is involved in the maintenance process of the asset?
  - What is the role of each person?
  - What are the tasks and responsibilities related to each role?
  - Are these tasks and responsibilities changed due to digitalization?
    - Are there additional roles and actors? Or are there less roles?
    - Are there other changes in the organizational structure?
  - Are the existing roles based on an existing concept? (ECM, AM roles, etc)
- What is your role in the maintenance process?
  - Are you the only one with this role?
  - Are there any differences between your role and the role of your colleagues?

Agreements and interactions:

- How do you communicate about maintenance within your company?
- How do you communicate about maintenance with external partners?

- What agreements and contracts are made?
    - Internally?
    - Externally?
- To what extent did digitalization have an effect on these agreements?

Data ownership:

- Who owns the data related to the asset?
- What challenges do you experience related data ownership?
- For what term are these agreements made?
- Who is responsible for making these agreements?

Output/results:

Availability

- How is availability of the asset measured?
    - Which unit is used?
    - Which indicators are used?
- Who is responsible for measuring availability?
- How often is the availability of the asset measured?
    - What happens if the availability has an unexpected value? What actions are taken?
- What is the goal value for the availability?
    - How is that value determined?
    - Who has determined this value?
- What is the effect of digitalization on the availability of the asset?

Effect digitalization:

- What are the noticeable effects of digitalization of the asset? Can you give an example?
- What are the noticeable effects of digitalization in the maintenance approach of this asset? Can you give an example?

Validation Framework:

- Are there aspects to the maintenance strategy that have been affected by digitalization that are missing in the current framework? Can you give an example?
- How can these aspects be included in the framework?
- Are all the aspects that are currently included in the framework relevant to the maintenance process?
- Do you think the framework is useful? How would you use the framework? Can you give an example?

Conclusion:

- What do you hope the outcome of the research is? What would be useful for your company?
- What is, according to you, the core of the problem related to digitalization?
- What is, according to you, the biggest advantage of digitalization?
- Do you have any questions?
- Is it possible to schedule a follow-up interview?

iv. Systematic Literature Research (SLR)

Maintenance					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Maintenance	Google Scholar	Title, keywords and abstract	6-6-2023	2010-2023	5410000
Maintenance	Google Scholar	Title, keywords and abstract	6-6-2023	2022-2023	95800
Maintenance AND Types	Google Scholar	Title, keywords and abstract	6-6-2023	2019-2023	200000
Maintenance AND classification	Google Scholar	Title, keywords and abstract	6-6-2023	2019-2023	289000
EU standard EN13306	Google Scholar	Title, keywords and abstract	6-6-2023	Any period	1580
Total	*5996380*				
Removing duplicates	*593180*				
Selected based on criteria	*35*				
Removed after complete scan	20				
Removed after complete read	5				
Total selected for review	10				

Scope: preventive maintenance					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Preventive maintenance	Google Scholar	Title, keywords and abstract	6-6-2023	2022-2023	20500
Preventive maintenance AND data	Google Scholar	Title, keywords and abstract	6-6-2023	2022-2023	16900
Total	*37400*				
Removing duplicates	*3600*				
Selected based on criteria	*12*				
Removed after complete scan	8				
Removed after complete read	2				
Total selected for review	2				

State of the art methods					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Maintenance strategies	Google Scholar	Title, keywords	7-6-2023	2022-2023	16800
Total	*16800*				
Removing duplicates					
Selected based on criteria	*12*				
Removed after complete scan	5				
Removed after complete read	3				
Total selected for review	4				

Research gap: current literature					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Maintenance digital assets	Google Scholar	Title, keywords and abstract	7-6-2023	Any period	431000
Maintenance digital assets	Google Scholar	Title, keywords and abstract	7-6-2023	2022-2023	17200
maintenance strategies implementation of a new system	Google Scholar	Title, keywords and abstract	7-6-2023	Any period	5150000
maintenance strategies implementation of a new system	Google Scholar	Title, keywords and abstract	7-6-2023	2022-2023	16600
E-maintenance	Google Scholar	Title, keywords and abstract	7-6-2023	Any period	15600
E-maintenance	Google Scholar	Title, keywords and abstract	7-6-2023	2022-2023	1280
What maintenance strategies can be used for IT systems?	Consensus	Title, keywords and abstract	7-6-2023	Any period	
Maintenance software	Google Scholar	Title, keywords and abstract	7-6-2023	Any period	4270000
Maintenance software	Google Scholar	Title, keywords and abstract	7-6-2023	2022-2023	76400
Total	*9978080*				
Removing duplicates	*222960*				
Selected based on criteria	*25*				
Removed after complete scan	12				
Removed after complete read	7				
Total selected for review	6				

Knowledge management					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Knowledge management	Google Scholar	Title, keywords and abstract	24-8-2023	2022-2023	57300
NPI AND Maintenance	Google Scholar	Title, keywords and abstract	24-8-2023	Any period	21600
new product introduction maintenance	Google Scholar	Title, keywords and abstract	24-8-2023	Any period	8360
new product introduction AND "maintenance strategy"	Google Scholar	Title, keywords and abstract	24-8-2023	Any period	96
Total	*87356*				
Removing duplicates	*78996*				
Selected based on criteria	*21*				
Removed after complete scan	13				
Removed after complete read	5				
Total selected for review	3				

Digitalisation transition					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Digitalisation transition	Google Scholar	Title, keywords and abstract	28-8-2023	Any period	5200000
Digitization	Google Scholar	Title, keywords and abstract	28-8-2023	Any period	1370000
Digitization digitalisation	Google Scholar	Title, keywords and abstract	28-8-2023	Any period	96200
Digitization factors	Google Scholar	Title, keywords and abstract	28-8-2023	Any period	529000
Digitalisation factors	Google Scholar	Title, keywords and abstract	28-8-2023	Any period	305000
Digitalisation requirements	Google Scholar	Title, keywords and abstract	28-8-2023	Any period	223000
Digitalisation criteria	Google Scholar	Title, keywords and abstract	28-8-2023	Any period	150000
Total	7873200				
Removing duplicates	5573000				
Selected based on criteria	*25*				
Removed after complete scan	*10*				
Removed after complete read	*5*				
Total selected for review	10				

Preventive maintenance IT-systems					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Preventive maintenance IT-systems	Google Scholar	Title, keywords and abstract	29-8-2023	Any period	19900
Preventive maintenance CMMS	Google Scholar	Title, keywords and abstract	29-8-2023	Any period	7720
Total	27620				
Removing duplicates	19900				
Selected based on criteria	*15*				
Removed after complete scan	*10*				
Removed after complete read	*3*				
Total selected for review	2				

CMMS					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
CMMS	Google Scholar	Title, keywords and abstract	30-8-2023	Any period	36100
Computer Maintenance Management System	Google Scholar	Title, keywords and abstract	30-8-2023	Any period	3660000
CMMS AND Maintenance	Google Scholar	Title, keywords and abstract	30-8-2023	Any period	15400
CMMS requirements	Google Scholar	Title, keywords and abstract	30-8-2023	Any period	16900
CMMS criteria	Google Scholar	Title, keywords and abstract	30-8-2023	Any period	12800
Total	*3741200*				
Removing duplicates	*3578800*				
Selected based on criteria	*10*				
Removed after complete scan	5				
Removed after complete read	2				
Total selected for review	3				

Reliability Centered Maintenance					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Reliability Centered Maintenance	Google Scholar	Title, keywords and abstract	30-8-2023	Any period	190000
CMMS AND RAMS	Google Scholar	Title, keywords and abstract	30-8-2023	Any period	2910
CMMS AND Reliability	Google Scholar	Title, keywords and abstract	30-8-2023	Any period	15900
Total	*18810*				
Removing duplicates	*171190*				
Selected based on criteria	*10*				
Removed after complete scan	5				
Removed after complete read	2				
Total selected for review	3				

Sensor Definition					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
What is a sensor	Google	Title	30-8-2023	Any period	1180000000
Sensor Definition	Google Scholar	Title, keywords and abstract	30-8-2023	Since 2019	18700
Total	*1180000000*				
Removing duplicates	*0*				
Selected based on criteria	*3*				
Removed after complete scan	2				
Removed after complete read	0				
Total selected for review	1				

Maintenance roles					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Maintenance actors	Google scholar	Title, keywords and abstract	31-8-2023	Any period	42400
Maintenance actors NOT "bad actors"	Google scholar	Title, keywords and abstract	31-8-2023	Any period	13500
"Asset management roles"	Google scholar	Title, keywords and abstract	31-8-2023	Any period	41
ISO 55000: 2014	Google scholar	Title, keywords and abstract	31-8-2023	Any period	4740
Maintenance roles NOT biological	Google scholar	Title, keywords and abstract	31-8-2023	Any period	16400
Total	*77081*				
Removing duplicates	*47181*				
Selected based on criteria	*8*				
Removed after complete scan	4				
Removed after complete read	1				
Total selected for review	3				

Agreements maintenance					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Standard maintenance agreements	Google scholar	Title, keywords and abstract	1-9-2023	Any period	17000
Standard maintenance communication	Google scholar	Title, keywords and abstract	1-9-2023	Any period	56100
Standard maintenance contracts	Google scholar	Title, keywords and abstract	1-9-2023	Any period	18800
Total	*91900*				
Removing duplicates	*20300*				
Selected based on criteria	*5*				
Removed after complete scan	1				
Removed after complete read	1				
Total selected for review	3				

Data ownership digital maintenance					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Data ownership digital maintenance	Google scholar	Title, keywords and abstract	1-9-2023	Any period	17100
Data ownership digital maintenance issues	Google scholar	Title, keywords and abstract	1-9-2023	Any period	17200
Data ownership digital maintenance complex	Google scholar	Title, keywords and abstract	1-9-2023	Any period	17100
Total	*51400*				
Removing duplicates	*100*				
Selected based on criteria	*2*				
Removed after complete scan	0				
Removed after complete read	0				
Total selected for review	2				

Digital maintenance					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Digital maintenance	Google scholar	Title, keywords and abstract	4-9-2023	Any period	376000
e-maintenance	Google scholar	Title, keywords and abstract	4-9-2023	Any period	3770
smarteneance	Google scholar	Title, keywords and abstract	4-9-2023	Any period	10
Digital maintenance train TMS	Google scholar	Title, keywords and abstract	4-9-2023	Any period	17500
Total	*397280*				
Removing duplicates	*354720*				
Selected based on criteria	*15*				
Removed after complete scan	2				
Removed after complete read	0				
Total selected for review	13				

Maintenance cycles					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Maintenance cycles	Google scholar	Title, keywords and abstract	4-9-2023	Any period	23000
Software development cycle	Google scholar	Title, keywords and abstract	4-9-2023	Any period	215000
Systems development life cycle	Google scholar	Title, keywords and abstract	4-9-2023	Any period	31900
SDLC AND maintenance	Google scholar	Title, keywords and abstract	4-9-2023	Any period	13800
Total	*283700*				
Removing duplicates	*146300*				
Selected based on criteria	*12*				
Removed after complete scan	5				
Removed after complete read	1				
Total selected for review	6				

New technologies maintenance					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
New technologies maintenance	Google scholar	Title, keywords and abstract	5-9-2023	Since 2019	69300
Digital maintenance developments	Google scholar	Title, keywords and abstract	5-9-2023	Since 2019	18400
Digital maintenance new technologies	Google scholar	Title, keywords and abstract	5-9-2023	Since 2019	38500
Digital maintenance evolution	Google scholar	Title, keywords and abstract	5-9-2023	Since 2019	23800
Total	*150000*				
Removing duplicates	*12400*				
Selected based on criteria	*20*				
Removed after complete scan	5				
Removed after complete read	5				
Total selected for review	10				

Risk-Based Inspection					
Search string	**Database**	**Scope**	**Date**	**Date range**	**Number of entries**
Risk-Based Inspection	Google scholar	Title, keywords and abstract	5-9-2023	Any period	2320000
RBI AND Reliability centered maintenance	Google scholar	Title, keywords and abstract	5-9-2023	Any period	6870
RBI AND FMECA	Google scholar	Title, keywords and abstract	5-9-2023	Any period	495
Total	*2327365*				
Removing duplicates	*7365*				
Selected based on criteria	*8*				
Removed after complete scan	5				
Removed after complete read	0				
Total selected for review	3				

Maintenance		
Number	Criteria	Reason to include/exclude
1.	Date of article	The article is considered too old if it is written before 2010, since maintenance has been developing as are the classification methods to categorize maintenance
2.	Keywords: preventive, corrective, maintenance.	A general explanation is provided, without a focus on a specific sector or industry. Furthermore, an explanation on the establishment and the components is provided, no specific calculations for a specific part or item. In the available information there is a distinction between preventive and corrective maintenance.
Scope: preventive maintenance		
Number	Criteria	Reason to include/exclude
1.	Keywords	A general explanation on what preventive maintenance is
State of the art methods		
Number	Criteria	Reason to include/exclude
1.	Date	The article is considered too old if it is written before 2015, since the state of the art methods have to be described.
Research gap: current literature		
Number	Criteria	Reason to include/exclude
1.	Date	The article is considered too old if it is written before 2015, since the state of the art methods have to be described.
2.	Scope	Articles have to be about the maintenance of an asset and the role of digital systems
3.	Maintenance of sensors	Articles should describe how sensors should be maintained.
Knowledge management		
Number	Criteria	Reason to include/exclude
1.	Establishment	Articles have to describe how and why Knowledge management is applied, not only provide examples

Digitalisation transition		
Number	Criteria	Reason to include/exclude
1.	Date of article	The article is considered too old if it is written before 2010, since maintenance has been developing as are the classification methods to categorize maintenance
2.	Language of the article	Other languages than Dutch, English or German cannot be understood.
	Generalizibility	General definitions that can be applied for any organization
Preventive maintenance IT-systems		
Number	Criteria	Reason to include/exclude
1.	Role of IT	Articles should explain how data plays a role in developing and executing a maintenance strategy
CMMS		
Number	Criteria	Reason to include/exclude
1.	Requirements	By investigating requirements for a CMMS, relevant distinctions between different systems can be evaluated
Reliability Centered Maintenance		
Number	Criteria	Reason to include/exclude
1.	General	The concept has to be explained, so a general description rather than applications or comparisions is required
Sensor Definition		
Number	Criteria	Reason to include/exclude
1.	General	A general description of a sensor in a maintenance application is required
Maintenance roles		
Number	Criteria	Reason to include/exclude
1.	General	A general overview of the standard roles is required (ISO 55000: 2014), because multiple companies are used in the case studies, which can be compared by using the standard roles
	People/actors	Roles for people or actors are required, not the role of maintenance. Also, the concept of bad actors (unpredicted failures) is not wanted in this case.
	Sector	The roles that are used in the infrastructure sector are wanted, because this might be different per sector.
Agreements maintenance		
Number	Criteria	Reason to include/exclude
1.	Standard contracts	The effect on the standard procedures, communication and contracts is evaluated, so a list of what standard contracts are used is required.
	Business related	Articles about the maintenance of communication or agreements between partners, relationships, hierarchical organizations is not wanted.

Data ownership digital maintenance		
Number	Criteria	Reason to include/exclude
1.	Issues	A statement about the related issues is provided
2.	Legal	No detailed descriptions about legal activities
Digital maintenance		
Number	Criteria	Reason to include/exclude
1.	Other phrasing	Article states other terms for similar concepts (e-maintenance, smartenance)
2.	New technologies	Articles provides information on new technologies that are used in digital maintenance
Maintenance cycles		
Number	Criteria	Reason to include/exclude
1.	Software	Shorter development cycle of software
2.	Related concepts	Systems development life cycle
RBI		
Number	Criteria	Reason to include/exclude
1.	Explanation and establishment	Article explains the concept and how it has been developed
2.	Related to RCM	Article explains the connection between RBI and RCM
Information overload		
Number	Criteria	Reason to include/exclude
1.	Explanation and issues	Article explains the concept and what issues play a role
2.	Related to knowledge management	Article explains the connection between information overload and knowledge management

v. Informed Consent Template

U wordt uitgenodigd om deel te nemen aan een onderzoek genaamd "Designing a framework for a maintenance strategy for digitized assets". Dit onderzoek wordt uitgevoerd door Eleanor Thelen van de TU Delft voor de master Transport, Infrastructuur en Logistiek.

Het doel van dit onderzoek is achterhalen welke factoren een rol spelen bij het onderhoudsproces van digitale systemen, en zal ongeveer 60 minuten in beslag nemen. De data zal gebruikt worden om de belangrijke factoren te identificeren en na te gaan welk effect iedere factor heeft in de praktijk. U wordt gevraagd om een beschrijving te geven van uw dagelijkse werkzaamheden en om meer uitleg te geven over de totstandkoming van een onderhoudsplanning voor digitale systemen.

Zoals bij elke online activiteit is het risico van een databreuk aanwezig. Wij doen ons best om uw antwoorden vertrouwelijk te houden. We minimaliseren de risico's door:

- Alle bestand op te slaan op een met wachtwoord-beveiligde opslag van de TU Delft. De data is alleen beschikbaar voor de onderzoeker en het team van begeleiders vanuit de TU Delft.
- Alle bestanden via één apparaat op te slaan en niet naar anderen, of andere apparaten te sturen.
- Verkregen informatie uit de interviews te anonimiseren, door geen namen, functies of afdelingen te benoemen.

Nadat het interview is afgelopen, zal u een samenvatting van het interview ontvangen. U bent vrij om hier op- of aanmerkingen op te maken. De samenvatting zal worden toegevoegd aan de MSc thesis en zal daarom publiek beschikbaar zijn.

Alle data zal tot 2 jaar worden bewaard op de TU Delft, onder verantwoordelijkheid van de W.W. Veeneman. Deze data kan gebruikt worden ter ondersteuning van een wetenschappelijke publicatie. In het geval van een publicatie, zal u anoniem blijven.

In het onderzoek willen we graag gebruik maken van anonieme quotes uit de interviews. U kunt hieronder aangeven of toestemming geeft om anonieme quotes uit uw interview te mogen gebruiken.

	JA	NEE
Ik geef toestemming om anonieme quotes te gebruiken	☐	☐

Uw deelname aan dit onderzoek is volledig vrijwillig, en u kunt zich elk moment terugtrekken zonder reden op te geven. U bent vrij om vragen niet te beantwoorden. De verkregen informatie wordt verwijderd en niet gebruikt voor het onderzoek.

Ik ga akkoord met de deelname aan het onderzoek:

Handtekening		
Naam van de deelnemer	Handtekening	Datum

Contact informatie:

Eleanor Thelen (Researcher)
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Wijnand Veeneman (TU Delft)
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You are being invited to participate in a research study titled "Designing a framework for a maintenance strategy for digitized assets". This study is being done by Eleanor Thelen from the TU Delft for the master Transport, Infrastructure and Logistics.

The purpose of this research study is to determine what the current maintenance process of digital infrastructure looks like and what issues play a role, and will take you approximately 60 minutes to complete. The information from the interview will be used to identify key factors and their relevance. We will be asking you to provide information on your daily business activities and to provide more information on how the maintenance activities for the digital systems have been established.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by

- Storing all the files on a password-protected institutional storage. The data is only accessible to the researcher and the TU Delft supervision team.
- Keeping the files on one device and not sending the files to a different device or person.
- Using the findings from the interviews anonymously, by not mentioning names, functions or departments.

Once the interview is complete, we will produce a summary, which will be send back to you for review. You are welcome to provide feedback or comments on the contents of the summary. The summary will be included in the MSc thesis and will be made publicly available.

All data will preserved for up to 2 years at TU Delft under the responsibility of W.W. Veeneman. The data may be used to support additional scientific publication, in which case you will be anonymous as well.

Your participation in this study is entirely voluntary **and you can withdraw at any time.** You are free to omit any questions. Information gathered from your interview will be removed from the research.

We would like to have the option to add anonymous quotes from the interviews. Please indicate below if you agree to be anonymously quoted:

	YES	NO
I agree to be anonymously quoted:	☐	☐

I agree to participate in the research as is described above:

Signatures		
Name of participant	Signature	Date

Contact details:

Eleanor Thelen (Researcher)
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Wijnand Veeneman (TU Delft)

vi. Interview Summaries

NS (Nederlandse Spoorwegen)

Interview 1:

De afdeling Maintenance Engineering is verantwoordelijk voor onderhoudsconcept van een materieelserie. Hij/zij bepaalt welke onderhoudstaken gedaan moet worden, en wanneer (en met welke frequentie) dit gedaan moet worden.

Bij de levering van de trein, wordt door de leverancier ook een eerste instandhoudingsconcept geleverd. Dit is het uitgangspunt voor de onderhoudscyclus en hier wordt gekeken waar mogelijke wijzigingen of optimalisering plaats kan vinden. Bij de optimalisering wordt gekeken naar kosten, veiligheid, bedrijfszekerheid, betrouwbaarheid en comfort.

Actoren:

Materieelteam: bestaande uit (onder andere) Reliability Engineer, Maintenance Engineer, Production Engineer

Maintenance Development houdt zich bezig met het optimaliseren van de onderhoudsactiviteiten door het gebruik van data. Zo willen ze fysieke inspecties vervangen voor inspecties met sensoren.

Aanpak/Proces:

Het startpunt is het onderhoudsconcept van de leverancier. Op basis van ervaring, kennis en praktijkervaringen worden hier aanpassingen aan gemaakt. Er wordt al bij de ontwerpfase van de trein meegedacht door NS over eisen omtrent onderhoud, zoals locatie inrichting en andere praktische zaken (bijvoorbeeld; zijn onderdelen makkelijk te bereiken), en er worden kritische vragen gesteld over waarom bepaalde beslissingen gemaakt zijn of over de reden van bepaalde voorstellen over onderhoudsduur en frequentie. Het voorschrift van de leverancier is onder andere gebaseerd op instructies van leveranciers van losse componenten en is bovendien erg veilig ingericht. Er is dus ruimte voor verbetering. Hier wordt samen met die leverancier naar gekeken en overlegd. Daarnaast kijkt de ME (in samenwerking met de systems engineer, reliability engineer en andere partijen) naar punten waar het voorgeschreven onderhoud niet voldoende is, of niet goed uit te voeren is, of waar ruimte ligt om termijnen aan te passen zodat het beter in de intervallen past, of zodat er kosten bespaard kunnen worden. Er wordt dan een afweging gemaakt of het zin heeft om een onderhoudstaak te vervroegen (en dus werkend materieel te vroeg te vervangen), of uit te stellen (en dus mogelijk meer risico te lopen op een storing). Het doel is wel om zo veel mogelijk rekening te houden met de bestaande onderhoudscyclus.

De huidige onderhoudscyclus bestaat voor preventief onderhoud bestaat uit drie onderdelen: DO (Dagelijks Onderhoud), KCO (Kort Cyclisch Onderhoud) en LCO (Lang Cyclisch Onderhoud).

De levenscyclus van een trein is ook in 3 onderdelen te verdelen: infaseren, garanderen en uitfaseren. Bij infaseren ligt de focus op het voorbereiden van de operatie op de nieuwe trein, kennis opdoen over hoe de trein zich zal gedragen in de praktijk, en inzichten krijgen en verwerken. Het garanderen is de stabiele fase waarin alles werkt en op elkaar is afgestemd. De levensduur wordt afgesloten met de periode van uitfaseren waarin de trein uit de operatie verdwijnt. De SNG zit momenteel tussen infaseren en garanderen, maar van die overgang is weinig verschil te merken in de werkzaamheden van de ME.

Vanuit de instandhoudingsvisie van NS Techniek is opgenomen om LCO werkzaamheden, alle onderhoudstaken met een interval groter dan 2 jaar, uit te voeren bij NSTM Haarlem in de vorm van een R-beurten regime. De focus ligt op de r-beurt (revisie beurt), ofwel clusterbeurt, waarbij alle beurten met een interval van 6 jaar in Haarlem gedaan moeten worden.

Het onderhoud aan sensoren en digitale systemen vindt plaats door middel van correctief onderhoud, omdat het faalgedrag willekeurig is en er dus geen voorspelling gemaakt kan worden in wanneer iets kapotgaat.

Afspraken:

Tussen de leverancier en NS bestaan afspraken over garantie van de trein. De eerste twee jaar zijn deze standaard en valt veel onder de garantie, mits de onderhoudsvoorschriften voldoende gevolgd zijn. Daarna zijn aanvullende (long-term) support contracten mogelijk. Dit gaat om bijvoorbeeld onderdelen en componenten, onderhoud of documentatie. Bovendien worden de aanpassingen aan het initiële voorschrift teruggekoppeld aan de leverancier. Enerzijds om de garantie te blijven houden, en anderzijds zodat de leverancier ook kan leren wat de mogelijkheden zijn.

Digitalisering:

Er zijn veel soorten data. Allereerst is er digitale informatie over welke (correctieve) acties uitgevoerd zijn en informatie over eerdere storingen. In combinatie met Reliability Engineer wordt gekeken wat de oorzaak van de storing is en waar biivoorbeeld de huidige voorschriften onvoldoende zijn, om deze storing in de toekomst te voorkomen.

Data kan helpen bij instandhoudingsresearch, door een beeld te geven van de status van de trein. De eerdere storingen, alarmen en het daaropvolgende onderhoud kunnen een beeld geven van de status. Bovendien geeft de trein veel data uit sensoriek. Deze data bestaat uit verschillende soorten data. Er is diagnosedata die gaat over de alarmen en storingen van de trein. Dit wordt naar het RTM (Real Time Monitoring) systeem gestuurd, waarna het door vlootanalisten geanalyseerd wordt. Daarnaast is er meetpunt data, dit zijn measurements voor indicatoren op bepaalde punten in de tijd. Nog niet alle data uit de trein is beschikbaar voor analyses. Een voorbeeld waar potentie in zit, zijn onderdelen die na een aantal draaiuren vervangen moeten worden. NS werkt met verlopen kilometers of dagen en er worden dus geen draaiuren geregistreerd. Voor sommige onderdelen is er wel een meter die de draaiuren bijhoudt, maar die data wordt niet naar de wal gestuurd. Er wordt wel een statusupdate naar de wal gestuurd, dus steeds wanneer de status verandert wordt die naar de wal gestuurd. Dit betreft meetpunt data (measurements) die naar de wal gestuurd worden over de status van de trein. Doordat dit een groot pakket aan data betreft, is daar nog een probleem mee dat deze niet goed omgezet wordt aan de wal-zijde zodat deze data leesbaar en bruikbaar is. Daaruit kunnen de draaiuren onttrokken worden. Echter moet dit gevalideerd worden en bovendien moet in de onderhoudstaak worden toegevoegd dat de data wordt uitgelezen. Dat vergt dus nog wat tijd.

Output/Resultaten:

Het grootste effect van digitalisering op de onderhoudsstrategie is dat het mogelijk is om digitaal inzicht te hebben in wat er is uitgevoerd en wat er dus gedaan moet worden. Echter zijn er nog veel mogelijkheden voor data gebruik en preventief (conditie gestuurd) onderhoud.

Interview 2:

De rol van de afdeling Reliability Engineering bestaat uit een aantal dingen, maar het belangrijkste is de veiligheid van de vloot. Ten tweede kijkt de RE naar de beschikbaarheid en bedrijfszekerheid van de vloot. Kan de dienstregeling zo goed mogelijk doorgaan, zonder te veel technische defecten. Daarnaast kijkt de RE naar comfort en kosten. De RE zorgt ervoor dat treinen die operationeel zijn ook veilig zijn, voor zowel de reiziger als voor het personeel. Er worden hiervoor verschillende soorten input gebruikt. De ME schrijft voor hoe een trein bij O&S (Onderhoud en Service) preventief moet worden onderhouden, zodat de performance zo hoog mogelijk blijft. Dit wordt gedaan door onderdelen preventief vervangen of systemen preventief onderhouden om te voorkomen dat onderdelen kapot gaan en de trein dus beschikbaar blijft. De RE analyseert alle defecten die tot verstoring van de dagelijkse operatie leiden. Wanneer op vlootniveau een trend wordt waargenomen, wordt onderzocht of een procesmaatregelen en/of technische wijziging nodig c.q. haalbaar is.

Actoren:

Materieelteam: Maintenance Engineer, Reliability Engineer, Production Engineering, Supply Chain Operations, Controller, Rolling Stock Software Desk en de Materieel Manager.

MBN: materieel besturing Nederland/ NedTrain – helpdesk voor de machinisten voor technische ondersteuning op afstand om de trein weer verder te helpen.

Aanpak/Proces:

De vraagstelling voor het onderzoek zit met name aan de maintenance kant: zowel bij de maintenance engineer als de mensen die bij maintenance development kijken naar instandhoudingsresearch. Het gaat dan over 2 dingen: Hoe kan je met data, sensoren en digitalisering je onderhoud optimaliseren? (op de lange termijn) Zo wil men bijvoorbeeld niet te vaak onderhoud plegen, want dat resulteert in onnodig hoge kosten. Voor deze afwegingen en overwegingen kan data ondersteunen: de status direct na onderhoud kan in kaart worden gebracht en zo kan de performance van een systeem gemonitord worden na een aantal onderhoudsmomenten. Dan kan bepaald worden na hoeveel momenten onderhoud nodig is om te voorkomen dat een onderdeel kapot gaat. Binnen NS is Maintenance Development verantwoordelijk voor het maken van dit soort beslissingen en het doen van de instandhoudingsresearch. Op de kortere termijn kan je met sensoren kijken naar de huidige status van de trein. In andere woorden staat een trein op het punt van defect gaan en moet daar misschien een mobiele monteur heen gaan? Dit speelt zich veel meer af op een individueel stelniveau om een stranding of een defect op de baan te voorkomen.

1. Kan je op basis van sensoren bepalen dat een component minder vaak onderhouden/vervangen hoeft te worden

2. Kijken we al actief naar data om in te schatten of er een mobiele monteur ingezet moet worden?

Voor de eerste vraag zijn filters een goed voorbeeld. Er zijn een hoop computers aan boord van een trein. De computer hardware moet gekoeld worden. Dit gebeurt met lucht die erlangs of doorheen geblazen wordt. Omdat er standaard deeltjes zoals stof in de lucht zitten, moeten er filters geplaatst worden om te voorkomen dat deze deeltjes in de hardware terecht komen. Zo kan de hardware gekoeld worden, zonder te vervuilen. De volheid van het filter kan gemeten worden met flow en temperatuur sensoren waarvan bij bepaalde waarde kan worden bepaald dat het filter te vol is en vervangen moet worden. Er is een begin gemaakt met dit soort overwegingen, maar die zijn nog geen onderdeel van het standaard proces.

Afspraken:

De RE krijgt vanuit verschillende bronnen input over mogelijke aanpassingen aan de systemen van de trein: de data die in het dashboard (met de KPI's voor beschikbaarheid) terecht komt en input vanuit bedienend personeel. Het uitgangspunt is echter wel dat er niks veranderd wordt aan de voorschriften van de leverancier, tenzij deze input zodanig aangeeft dat een aanpassing noodzakelijk is. Er wordt vooral gekeken naar kosten en daarom worden er eerst aanpassingen (als ze al plaatsvinden) gedaan aan het proces en daarna pas aan het materieel. Dit verschilt ook tussen treinen die wel of niet in de garantiefase zitten. In het geval van garantie is de leverancier verantwoordelijk voor het maken van aanpassingen.

Vanuit het personeel vindt communicatie plaats via email, (scannen op) bedrijfsplatforms en via een overleg tussen de aspectmanager en S&O (Service en Operatie, vertegenwoordigt hier de HC en machinisten) waarin wordt gekeken welke zaken er spelen bij het bedienend personeel en welke inderdaad een rol spelen bij de meerderheid van het personeel. Voor alle aanpassingen wordt eerst gekeken of ze haalbaar zijn en wordt er een actielijst opgesteld. In de analyse voor de haalbaarheid worden aspecten als toelaatbaarheid, kosten en risico worden altijd getoetst, waarbij budget vaak de beperkende factor is.

Digitalisering:

Veiligheidsstoringen zijn lastig te voorspellen met sensoren. Het is ooit gedaan met relais en schuiftreden. Er kan dan een business rule opgesteld worden als de trede al niet meer volledig uitschuift, om te voorkomen dat de situatie optreedt dat de schuiftrede helemaal niet meer uitschuift (=veiligheidsstoring). Deze storingen zijn goed te voorspellen via sensoren en te monitoren (temperatuur, toilet). Momenteel wordt dat te weinig gedaan omdat het systeem wat daarvoor gebruikt moet worden: RTM-O (Real Time Monitoring Operation) is nog niet goed genoeg. Er zijn problemen met de business rule engine. Dit zijn regels die als het ware een rood vlaggetje creëren als er aan een bepaalde voorwaarde wel/niet wordt voldaan. Bijvoorbeeld: de tschuifrede, als een trede op een gegeven moment niet verder uitschuift dan een bepaalde waarde, komt er een rode vlag/indicatie dat er onderhoud nodig is en er kan dan geautomatiseerd een werkorder aangemaakt worden voor het nodige onderhoud. Het is belangrijk dat de business rule wel gevalideerd is zodat er niet onnodig capaciteit ingezet wordt op onderhoud wat niet nodig blijkt te zijn. Het probleem is dat de business rule engine een vertraging van weken/maanden op heeft, waardoor de rode vlag als het ware al lang in een storing is geresulteerd. - Het is niet mogelijk om dit proces met de hand te doen. - MD (Maintenance Development) heeft een dashboard gemaakt waarin de temperatuur in alle rijtuigen van de volledige VIRM vloot te zien is.

Output/Resultaten:

Beschikbaarheid wordt gemeten in TVTA: Te verklaren trein afwijkingen. NS krijgt vanuit ProRail gerapporteerd hoeveel minuten de dienstregeling per treinstel vertraging heeft opgelopen als gevolg van een technische fout van de trein, of als bedieningsfout van het personeel. Beide zijn relevant voor de RE.

In het dashboard 'materieelmonitor' worden alle KPI's van alle materieelteams gepubliceerd. Daarin is een norm voor iedere indicator vastgesteld door de materieelteams en de aspectmanagers. Deze is gebaseerd op de fase waarin het materieel zit (badkuipcurve), waarin SNG ongeveer in het midden van de dalende lijn aan het begin zit. Als laatste wordt er gekeken naar past performance, dus hoe wat de afgelopen jaren de gerealiseerde performance was en wat de ambitie voor de norm is, gebaseerd op vergelijkbare treinseries die al verder in de curve zitten. Elk jaar wordt het plan geëvalueerd en aangepast.

In het dashboard staan de volgende indicatoren

- Veiligheid: aantal veiligheidsstoringen per miljoen gereden bakkilometers
    - Deze eenheid is gekozen zodat treinseries met elkaar vergeleken kunnen worden
    - Er zijn vaste definities voor een veiligheidsstoring

- Reizigerspunctialiteit: aantal minuten vertraging dat ProRail koppelt aan technisch materieel falen of een probleem aan de interface man machine
    - Dit wordt door NS omgerekend naar de KPI: vertragingsminuten per miljoen gereden bakkilometers
    - Een opgeheven trein zorgt standaard voor 30 min.
- Comfort: o Input gaat via bedienend personeel, via de ‘mijn materieel’ app naar Maximo.

Interview 3:

De manager van het materieelteam is verantwoordelijk voor de veilige inzet van een materieeltype en voor het realiseren van de afgesproken KPI's: bedrijfszekerheid, beschikbaarheid en kosten. De trein moet veilig zijn, dus in het geval van storingen moet er altijd een check plaatsvinden om te kijken of de storing leidt tot een mogelijk veiligheidsrisico voor reizigers, personeel of omgeving. Mogelijk moeten er dan aanvullende maatregelen getroffen worden. Daarnaast moet het onderhoud kwalitatief goed, efficiënt en op tijd uitgevoerd worden, kijkend de life cycle kosten. Het is een regiefunctie met eindverantwoordelijkheid voor het hele materieelteam. Dit houdt in dat het doel centraal blijft en dat het team als geheel de taken uitvoert en taken niet tussen wal en schip vallen. Ook houdt de materieel manager nauw contact met de typehouder over veranderingen aan de trein en de daarbij horende effecten rondom toelatingswetgeving.

Actoren:

Materieelteam. Er zijn een hoop functionarissen in het materieelteam wat aan de ene kant zorgt dat een hoop taken uitgevoerd kunnen worden, maar het zorgt wel dat het overzicht van taken en verantwoordelijkheden soms lastig zichtbaar blijft.

NO (Netwerk Ontwikkeling en Strategie) is de asset owner en die bepalen ook de behoefte aan treinen vanuit NS en maken op dat gebied de strategische keuzes.

Monteur in Leidschendam met een eigen kwaliteitsafdeling binnen het productiebedrijf die de kwaliteitscontroles uitvoert.

De ME stelt vast of het voorgeschreven onderhoud resulteert in het gewenste resultaat. De RE kijkt naar wat een trein doet in de operatie en er wordt bijgehouden of de trein tijdens de inzet last had van (technisch) falen. Dit wordt uitgedrukt in TVTA: te verklaren trein afwijkingen.

Afspraken:

Er wordt nauw samengewerkt met de leverancier omdat er belangrijke regelgeving bestaat over de toelating van treinen op het (Nederlandse) spoor. Treinen worden formeel toegelaten op basis van een uitgebreid typebeproevingstraject. Daarin heeft de leverancier primair de verantwoordelijkheid om aan te tonen dan een trein aan alle Europese en nationale eisen voldoet en daarmee wordt de treinbouwer oorspronkelijk de typehouder. Dit is het geval totdat de garantie afloopt, zodat bij grote veranderingen aan het begin van het traject de treinbouwer verantwoordelijk is voor onderbouwing voor veranderingen aan het design en ook de nieuwe toelatingstesten moet regelen. Dit moet allemaal geborgd en geformaliseerd worden samen met de typehouder. Er mag dus niks veranderd worden aan de trein zonder dat de typehouder hiervan op de hoogte is.

Tussen de monteur en materieelmanager is er regelmatig contact over in hoeverre het voorgeschreven onderhoud mogelijk is om uit te voeren met de juiste kwaliteit. Echter lijkt er nog veel verbetermogelijkheid te zijn tussen de ME en de monteur, omdat er onderhoud voorgeschreven kan worden wat niet uitvoerbaar is. Wanneer de ME met de monteur het voorgeschreven onderhoud langsgaat, kan dit onduidelijkheden uit de lucht halen. Het is persoonsafhankelijk hoe goed deze communicatie is, wat niet zou moeten. Iedere combinatie van monteur en ME zou even goede communicatie moeten hebben. De monteur kan via een klankbordgroep bij de support afdeling van de onderhoudslocatie wanneer er twijfel of vragen ontstaan over het voorgeschreven onderhoud. Eventueel wordt dan een RE/ME/SE ingeschakeld om hierbij te helpen. Er zijn standaard afspraken die bestaan uit een reden waarom de treinen gereserveerd zijn en het bijbehorende volume. Dit zijn afspraken tussen de materieelmanager en de afdeling dienstregeling.

Aanpak/Proces:

De real-time analyse bestaat op dit moment voor het grootste deel uit operationele warnings. Deze worden aangeduid met een letter, afhankelijk van de aard en de ernst van de storing en zorgen ervoor dat er gerichter een monteur op een storing afgestuurd kan worden.

De inspectiefrequentie is 15 dagen voor SNG en die is bepaald door wat de leverancier heeft voorgeschreven. De leverancier stelt dat dit 30 dagen moet zijn, maar doordat de SNG vaak te maken heeft met externe factoren die veel invloed hebben op de performance van de trein is besloten dit elke 15 dagen te doen. Dit is besloten door de Maintenance Engineer. Elke 3,5-4 maanden gaat de SNG naar het onderhoudsbedrijf voor een geplande preventieve onderhoudsbeurt. Hiervoor vindt ook een vooropname plaats en vindt dus een inspectie plaats voor het functioneren en uitstraling van de trein. Dit is visueel en op data gebaseerd. Het is daarbij belangrijk dat alarmen voor onderhoud wat ten tijde van het alarm niet direct onderhouden hoefde te worden, nu wel meegenomen wordt.

NS is niet in staat om toestandsafhankelijk onderhoud uit te voeren, omdat de hele bedrijfsvoering draait op de planmatige aanpak die momenteel gebruikt wordt, waarin treinen met een afgesproken frequentie naar de onderhoudslocatie gebracht worden. Bijvoorbeeld: je kan deuren beter onderhouden aan de hand van hoeveel zijn open en dicht zijn gegaan. Die data kan je uitlezen uit de trein. Dat betekent dat je meer moet voorbereiden tijdens de operatie en dat je om moet kunnen gaan met een afwijkende werkorderstroom per trein. We willen liever dat we zeker weten dat we alle deuren moeten controleren, want daar kan je capaciteit op plannen, dan dat er meer voorbereiding plaatsvindt en losse verschillende onderdelen (specifieke deuren en schuiftrede) worden onderhouden. Daar mist NS flexibiliteit en visie op delen in de organisatie. Het vergt namelijk aanpassingen op meerdere vlakken: andere manier van werkorders omschrijven en inschieten etc.

Er is veel meer mogelijk met een moderne trein dan wat er momenteel mee gedaan wordt. De vraag daarover is: waarom doen we dat niet? Willen/kunnen/andere reden. Er is een mismatch tussen wat er mogelijk is in de trein en wat er mogelijk is vanuit het onderhoudsbedrijf. Het managen van de mismatch moet ervoor zorgen dat je de slag kan maken naar een ander level van detail: gemiddeld worden alle deuren nog steeds gecontroleerd, in plaats van altijd alle deuren controleren. Dit hangt ook samen met capaciteit, vaardigheden en bevoegdheden van het onderhoudspersoneel, waardoor niet iedereen alles mag onderhouden. Dit zorgt voor minder flexibiliteit. Er zijn weinig zichtbare stappen in de organisatie richting conditie afhankelijk onderhoud. Visie moet een integraal gedragen beeld zijn, waarbij begrip moet zijn voor de impact die een keuze aan de ene kant, aan de kant heeft. Nu is er soms te zien dat men onvoldoende op de hoogte is van de impact van een beslissing. De vraag is dus: wat vraagt de slag naar toestandsafhankelijk onderhoud van een bedrijf die net de slag heeft gemaakt naar voorspelbaar onderhoud.

De reden voor deze mismatch is dat er niet voldoende een gemeenschappelijk doel bekend is, waarin de andere aanpak een centrale rol speelt. Hierbij is van groot belang dat de belangen worden bekeken over de hele keten. Er is een digitale trein die een hoop kan en dat wordt hard geroepen. Echter zijn de effecten van het gebruik van deze mogelijkheid over de hele keten onvoldoende bekend, om in te schatten of het gebruik van alle mogelijkheden digitale trein ook baat heeft.

Het is beter om kleine effectieve veranderingen tot uitvoering te brengen dan steeds maar grote ambities te roepen die vaak niet echt haalbaar zijn. SNG en SLT vormen een belangrijk deel van de vloot, maar zijn zeker nog te overzien. Veranderingen binnen deze vloten doorvoeren is dus te overzien, maar kan wel voor echte resultaten zorgen.

Predicatief onderhoud lijkt in dit geval dus niet ‘zomaar’ de volgende stap in dezelfde richting na preventief onderhoud. Het vraagt een andere aanpak, ondanks de aanname dat het een lineair proces is.

Bij een kwaliteitscontrole worden er steekproeven uitgevoerd en de gevonden storingen worden gerelateerd aan veiligheid, bedrijfszekerheid, comfort. De aanpak is met name gebaseerd op de manier die nodig is voor hardware en gebeurt dus niet dynamisch.

De RE doet een maandelijkse analyse naar welke verstoringen het meeste effect hadden op de dienstregeling. Er wordt gekeken naar welke systemen zorgen voor de meeste vertraging. De bevindingen worden teruggekoppeld naar de ME om aanpassingen aan de voorschriften in het onderhoud te maken. Er zit potentie om in dit proces meer gebruik te maken van data, maar dan moet daar wel aandacht aan gegeven worden. De voorbeelden zijn meestal erg basaal, maar hebben een groot effect: wanneer de ruitenwisservloeistof niet wordt bijgevuld, lijkt dat erg klein, maar kan dat ervoor zorgen dat de ruiten op een gegeven moment zo vies zijn dat de machinist niet met de trein gaat rijden.

Digitalisering:

Er is veel meer data aanwezig in de trein, maar die wordt niet ontsloten. Alleen wanneer er een laptop op de trein aangesloten wordt. Er zit een filter op welke data uitgelezen wordt voor de real-time analyse. De slag waar we nu voor staan is de analyse van de condities terwijl een storing optrad. Voorbeelden hiervan zijn weersomstandigheden, temperatuur, locatie op het spoor, zodat er links gelegd kunnen worden. Deze verbanden worden nog relatief weinig gebaseerd op de real-time data. Het wordt voornamelijk gedaan met data die direct uit de trein wordt uitgelezen (met een laptop aan de trein). Met andere woorden, nu worden alleen alarmen real-time doorgegeven en moet de analyse gedaan worden op basis van data die direct uit de trein gehaald moet worden en er ligt potentie in het feit dat er meer data direct real-time uit de trein gehaald kan worden, waardoor de analyse sneller gedaan kan worden.

Er wordt veel energie gestoken in het opzetten en ontwikkelen van tooling om analyses en inzichten vanuit de data te creëren. Er wordt dan minder gefocust op de betrouwbaarheid en hoeveelheid van data. Het hoeft niet 100% perfect te zijn om wel stappen mee te kunnen maken.

Output/Resultaten:

Er wordt gekeken naar punctualiteit en beschikbaarheid. Er is standaard een deel van de vloot wat geen onderdeel is van de dienst omdat het bij het onderhoudsbedrijf is, of er wordt een modificatie op uitgevoerd. Er is een afgesproken norm voor de toegestane onttrekking en er wordt steeds gekeken of de realiteit afwijkt van de norm.

Beschikbaarheid = Bruto park-onttrekking, waarbij er op de onttrekking gestuurd kan worden door bijvoorbeeld onderhoud uit te stellen, mits de veiligheid niet in het geding komt = vrijgave buiten tolerantie.

Punctualiteit: hoe ver wordt er afgeweken van de dienstregeling? Daar komen veel aspecten bij kijken: betrouwbare trein, betrouwbare infra en voldoende en juiste mensen op de juiste tijd en locatie.

Het grootste merkbare effect van digitalisering op de onderhoudscyclus is dat men kan vertrouwen op de zelftesten in de trein die door de machinist worden uitgevoerd bij het starten van de trein. Zo kan de trein sneller veilig starten. Vroeger gebeurde dit met dagelijkse controles en die zijn nu dus niet meer nodig. Nu wordt de trein slechts elke 15 dagen helemaal naar binnen gebracht voor onder andere inspecties. Dit maakt het mogelijk dat er gerichtere vervolgacties plaats kunnen vinden.

Een belangrijk ander aspect is dat software zorgt voor een idee dat er steeds meer mogelijk is en daarvoor ook steeds nieuwe dingen (tools, programma's, etc.) ontwikkeld worden. Er wordt veel gewijzigd in de software, juist omdat de software het mogelijk maakt om wijzigingen aan te brengen. Dit zorgt voor extra risico's omdat het onzeker is of het werkt zoals verwacht. Het is beter als er gewerkt wordt met een bepaalde versie zodat goed gekeken kan worden of het werkt, en als het werkt is het goed en moet ermee gewerkt blijven worden. Te veel iteraties geeft onduidelijkheid en onzekerheid.

Interview 5

De afdeling Maintenance Engineering is voor de hele vloot van NS verantwoordelijk voor de instandhoudingsconcepten van de trein. Er wordt voorgeschreven wat, gezien de randvoorwaardes (bijvoorbeeld inzet, levensduur, veiligheid en kosten), het instandshoudingsconcept zou moeten zijn. Dit is een dynamisch concept, waar samen met de ketenpartners steeds wordt gereflecteerd over de huidige status en performance van de trein. Er wordt steeds gekeken naar mogelijkheden waar dit concept geoptimaliseerd kan worden. Wanneer er een revisie aanstaande is, wanneer moet deze plaatsvinden en welke onderhoudsactiviteiten moeten er dan uitgevoerd worden. Hierbij spelen de 4M een belangrijke rol: Mensen, Middelen, Materialen en Methodes. Alle beslissingen van de maintenance engineer zijn gebonden aan wetgeving waaraan voldaan moet worden om gebruik te mogen maken van het Nederlandse spoornetwerk. De focus ligt met name op aantoonbaarheid, of onderbouwing van de genomen beslissingen.

Per vloottype, of treinserie is er (minstens) een maintenance engineer die een plek heeft in het materieelteam. De manager van de afdeling Maintenance Engineering is verantwoordelijk voor alle Maintenance Engineers.

Actoren:

Leverancier: levert trein en eerste instandhoudingsconcept

Materieelteam: bestaat uit onder andere: MM, ME, PE, SCM, RE

Materieel manager: leider van het materieelteam. Het materieel team is de beheerder van de asset, dus is de MM de Asset Manager.

Maintenance Engineer: kijkt waar aanpassingen aan instandhoudingsconcept mogelijk zijn en geeft aan SE de opdracht om de effecten te analyseren. Na deze terugkoppeling wordt gekeken of de aanpassing mogelijk is.

Productie Engineer: vertaalt de adviezen van de ME naar productieconcepten, ofwel onderhoudstaken.

Supply Chain Manager: zorgt ervoor dat de juiste materialen aanwezig zijn voor de instandhouding

Reliability Engineer: analyseert het effect van het onderhoud in de praktijk en koppelt terug waar er verbeteringen mogelijk zijn.

Systems Engineer: doet namens ME onderzoek naar de effecten van de voorgestelde aanpassingen aan het instandhoudingsconcept. De SE is geen onderdeel van het materieelteam.

Maintenance development: onder andere een team van data analisten die de ME ondersteunen bij het vinden van data om instandhoudingsvoorstellen te onderbouwen

Proces:

Bij de levering van de trein wordt door de leverancier van de trein het eerste instandhoudingsconcept meegeleverd. Dit concept wordt vervolgens door de ME verder uitgebouwd en geoptimaliseerd. Hiervoor worden verzoeken voor mogelijke verbeteringen uitgezet naar de afdeling Systems Engineer, om te onderzoeken wat de effecten zijn van voorgestelde aanpassingen aan het instandhoudingsconcept. De ME is uiteindelijk verantwoordelijk, en kan dus het advies van de SE (of andere specialisten) aannemen of laten liggen. In principe wordt dit advies vaak wel overgenomen. Alle leden van het materieelteam voeren constant het PDAC proces uit en maken daarbij gebruik van bijvoorbeeld de SE voor advies.

Momenteel is het onderhoud allemaal gepland (na verstreken tijd of kilometers) en nog niet volledig ingeregeld aan de hand van de actuele behoefte. Wanneer de trein binnen is wordt het voorgeschreven onderhoud uitgevoerd, ongeacht of het volledig of deels versleten is.

Er vinden als het ware experimenten plaats bij een aantal treinstellen waarbij wordt gemeten wat de kritieke waarde van een onderdeel is (volheid tank), op het punt dat het onderhouden moet worden. Deze waarde vormt de basis voor een onderhoudsregel en wordt middels de PDAC cyclus gemonitord en eventueel bijgesteld.

Er is ook een keten met menselijke input voor de maintenance engineer. Het bedienend personeel heeft een lijntje met de RE, waarin door de machinisten wordt teruggekoppeld of bepaalde systemen werken of niet en waar er verbeteringen mogelijk zijn. De ME heeft direct contact met de monteur, die kan terugkoppelen dat er (systematisch) ander onderhoud nodig is dan de ME voorschrijft. Het materieelteam zit 1-2 dagen in de week in het onderhoudsbedrijf, zodat deze communicatielijn kort blijft.

Ieder materieelteam werkt met een materieelmonitor, een dashboard wat inzicht geeft in de status van het materieel. Hierin wordt gekeken naar trend en wordt gekeken of in materieel bijna een storing zal ontstaan door slijtage van het materiaal. De ME en RE kijken vervolgens naar een plan om de oorzaak te achterhalen en het onderhoud erop aan te passen.

Er wordt gekeken naar de VBKK indicatoren: veiligheid, bedrijfszekerheid, kwaliteit en kosten.
Veiligheid: het aantal veiligheidsstoringen per maand. Dit moeten er 0 zijn, dus voor elke veiligheidsstoornis die optreedt wordt door het materieelteam een analyse gemaakt om te achterhalen wat de oorzaak hiervan was (bijvoorbeeld: monteur heeft zijn werk slecht uitgevoerd, of voorgeschreven onderhoud is niet correct). Na de analyse is er een oorzaak en een actiehouder.
Bedrijfszekerheid: aantal vertragingen. De RE maakt analyses gebaseerd op een norm die door het materieelteam is vastgesteld en kijkt naar de trends die te zien zijn. Er wordt op basis van de trends gekeken of er aanpassingen aan de strategie nodig zijn. Bijvoorbeeld, de laagspanning laat een trend zien. De SCE geeft bijvoorbeeld aan dat dit onderdeel vaak uitverkocht is, of dat er een slechte lading binnen is gekomen. De oplossing is dan dat dit teruggekoppeld wordt naar de leverancier, er een ander onderdeel uit een andere lading gebruikt wordt, zodat het probleem is opgelost.
Kwaliteit: er gaan keurders langs in de onderhoudslocaties om te controleren of onderhoud correct uitgevoerd wordt. Ook over deze rapportages worden trendanalyses uitgevoerd.
Kosten: onderdeelverbruik, slechte performance, uren van monteurs resulteren allemaal samen in een bedrag wat de treinserie kost.

Correctief onderhoud: er wordt 'gewacht' totdat onderdelen falen. Dit gebeurt alleen bij systemen waarbij van tevoren is vastgesteld dit niet resulteert in een onveilige situatie. Preventief onderhoud wordt gedaan aan de hand van onderhoudsregels: wanneer een bepaalde status (aantal draaiuren of kilometers) wordt bereikt, moet er onderhoud plaatsvinden.

Omdat IT systemen een random faalcomponent hebben, past dit slecht binnen de huidige onderhoudsaanpak. Voor de onderhoudsaanpak worden de voorschriften vanuit de leverancier gevolgd. Bovendien zijn dit soort systemen snel verouderd. Een voorbeeld is het OBIS systeem (beeldschermen in de trein). Uit de trends is gebleken dat dit ongeveer naar 5-6 faalt. In plaats van instandhouding, wordt het hele systeem vervangen. Dit is goedkoper, makkelijker en er is inmiddels een nieuwere versie op de markt. Treinen hebben een lange levensduur van ongeveer 30 jaar. Het loont om te kijken naar maatregelen die deze tijd significant kunnen verlengen, maar dit is meestal voor systemen zoals OBIS niet het geval, omdat de ontwikkelingscyclus erg kort is en er dus snel betere producten beschikbaar zijn, waarmee de oude systemen vervangen kunnen worden.

Bevindingen over mogelijke verlengingen van systemen worden teruggekoppeld naar het aanbestedingsproces via de RAMS/LCC engineer, die als het ware de voorganger van de ME is. Bevindingen uit ouder materiaal worden meegenomen in de aanbesteding voor nieuwe treinen.

De triggers voor de ME is een combinatie van verschillende input: terugkoppeling van de monteur, input vanuit het materieelteam: via RE vanuit de machinist, via RE vanuit trends enzovoorts. Hierin moet een prioriteit bepaald worden middels een kosten baten analyse, waarin storingen die nauw samenhangen met wetgeving en veiligheid, of verbeteringen die grote kostenverminderingen als resultaat hebben bovenaan staan. Hierbij is een belangrijke uitdaging dat de vloot waarvoor de ME werkt uniek in Nederland is en dat een hoop opmerkingen die als input binnenkomen nog nooit ervaren zijn en dat daar wel de juiste conclusie uit getrokken moet worden.

Digitalisatie

Maintenance engineer moet het probleem analyseren en bepalen welke data nodig is om het probleem op te kunnen lossen, of in kaart te brengen. Voorbeeld is de bioreactor in de (toilet van de) VIRM. Hierbij is actuele data nodig over hoe vol deze tank is, zodat de trein niet onnodig naar binnen gehaald hoeft te worden, maar de tank ook niet zal overstromen. De maintenance engineer kan achterhalen wat het kritieke volheidsniveau van de tank is, zodat de trein op het juiste moment binnengehaald kan worden. Hiervoor zou het slijtageproces real-time gemonitord moeten worden zodat er een seintje kan komen wanneer de trein naar binnen moet worden gebracht voor onderhoud. Condition-based maintenance is nog geen onderdeel van de normale gang van zaken in de onderhoudscyclus.

Met de huidige technologie is het mogelijk dat ieder systeem zichzelf controleert. Echter is dat niet altijd beter, want digitale systemen hebben een random faalcomponent. Zo is het dus niet zeker of ze misschien een vals-positieve of vals-negatieve indicatie geven. De oplossing is meestal om dit soort systemen dan redundant (dubbel) in te bouwen, maar dat lost in feite de kern van het probleem niet op en kan ervoor zorgen dat er steeds maar systemen bij blijven komen.

De uitdaging van de ME is om de vertaalslag te maken tussen een (hypothetische) storing en de data die ervoor nodig is om deze storing in de toekomst te voorspellen én waar deze data vandaan gehaald kan worden.

Voor de mogelijkheid van data analyse moest de ME zelf naar de trein om de input vanuit de keten te kunnen vertalen naar storingen en mogelijke aanpassingen aan het instandhoudingsconcept. Door digitalisatie is dit minder nodig en kunnen een hoop zaken vanaf een afstand uit de trein worden gelezen en kan de ME daarop een root-cause analyse maken. Met deze analyse kunnen de ME en de SE een voorstel voor een aanpassing aan het instandhoudingsconcept maken. Bovendien kan de data gebruikt worden om als het ware een formule op te stellen, waarin de input wordt meegenomen zodat er een voorspelling voor het volgende moment van falen gemaakt kan worden. Deze formule wordt iteratief gecorrigeerd afhankelijk van hoe de trein in de praktijk opereert, mits het geen veiligheidsrisico veroorzaakt. De ME kan ook naar de trein gaan en er een laptop op aansluiten om vanuit de brondata te bepalen wat kritieke waardes voor bepaalde storingen zouden kunnen zijn (voorbeeld biobak VIRM). Dit hele proces heet instandhoudingsresearch.

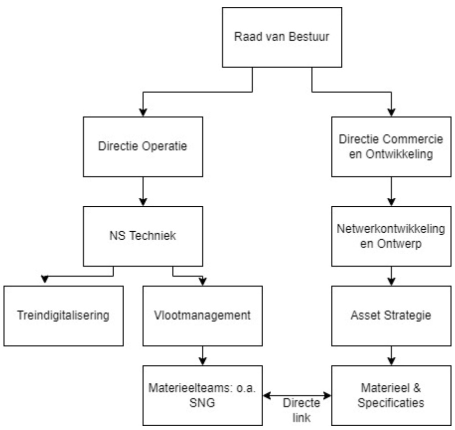
Beschikbaarheid:

Het grootste effect van digitalisering op onderhoud. Hoe beter het instandhoudingsconcept is, hoe beter de performance van de trein is. Digitalisering is een verdiepingsslag hierin, omdat de informatie die de ME nodig heeft om tot het ultieme instandhoudingsconcept te komen beter wordt. De digitale signalen zijn in grote hoeveelheid en bijna altijd aanwezig. De kwaliteit van de input die de ME kan gebruiken voor voorgestelde aanpassingen wordt groter en dus wordt je concept beter en dus wordt je performance beter.

Interview 6:

Bij de afdeling Asset Strategie ligt de focus met name op het dossier CCS (Command, Control and Signalling) waarvan ETCS een van de onderdelen is. Daarmee is de LA onderdeel van het ERTMS programmateam dat zich bezighoudt met digitalisering en de impact daarvan. Dit gebeurt op nationaal en Europees niveau (ERTU) Bovendien wordt er gekeken naar een modulaire opbouw van het ETCS systeem, om ervoor te zorgen dat er onderdelen makkelijker toegevoegd en weggehaald kunnen worden uit het hele systeem en zodat er makkelijker onderhoud gepleegd kan worden.

Actoren:



In de keten:

Netwerk en Ontwerp: NO: dienstregeling van de toekomst, kijkend van 6 weken tot 25 jaar (korte en lange termijn)

Lead Architect: Kwaliteit van het materieel en welke eisen stellen we aan toekomstig materieel.

Assetregie: vlootmanager; wat gaan we doen in de toekomst en wat zijn de geplande wijzigingen. Deze vloot manager is er voor iedere treinserie die heeft een directe link met het materieelteam.

Aanpak:

Wat is precies de definitie van onderhoud: het in stand houden van de huidige functionaliteiten. Wat kan de trein vandaag en moet hij morgen nog steeds kunnen. Dit is een logisch perspectief als je kijkt naar de afgelopen 175 jaar waar de trein een mechanische machine is die uit elkaar geschroefd kan worden en die in de basis weinig verandert. Echter wordt een trein steeds digitaler en gaan sommige systemen dus ook niet meer zo lang mee als vroeger en moet het steeds vaker vervangen worden. Bovendien gaat het voor digitale systemen niet alleen meer over het onderhouden van de systemen, maar ook over het toevoegen van functionaliteiten. De vraag is of het toevoegen van functionaliteiten nog steeds onderhoud genoemd kan worden. Bovendien is het toevoegen van functionaliteiten vaak geen keuze, omdat het standaard in een nieuwere versie inbegrepen is.

Er is een mismatch ontstaat tussen de levensduur van IT (3-5 jaar) en OT (6-10 jaar). Er wordt gekeken naar het effect op de kosten, onttrekking (uit de operatie halen voor onderhoud) en de toevoeging van structurele momenten om functionaliteiten toe te voegen. Ook wordt er gekeken naar de aanschaffase, er wordt gekeken naar wat de trein allemaal moet kunnen, gebaseerd op bewezen beleid. Daarbovenop wordt er gekeken naar future oriented design. Dit gaat over techniek die al bekend maar die nu nog niet volwassen is. Echter wordt verwacht dat de techniek voldoende ontwikkeld is zodra de trein geleverd wordt, dus moet daar nu al rekening mee gehouden worden. Daarbovenop is nog een niveau voor toekomstige ontwikkelingen waar minder zekerheid over is. Hierover worden afspraken gemaakt met leverancier over hoe deze technologie middels projecten toegevoegd kan worden. Zo kunnen systemen modulair ontwikkeld en onderhouden worden, zodat er in delen gewerkt kan worden en de trein dus niet volledig uit elkaar gehaald hoeft te worden bij een eventuele aanpassing. Dit vergt een nieuwe mindset en andere contractmethodiek.

Voor grote hardware onderdelen is NS goed in het oprekken van de levensduur van een onderdeel en kan onderhoud dus worden uitgesteld. Bij IT is steeds meer te zien dat het voorschrift van de leverancier gevolgd wordt en dat deze afspraken en samenwerkingen toewerken naar SLA's, waarin de leverancier bijdraagt aan het onderhoud en updates mee laat contracteren.

Bij VIRM moet ETCS worden ingebouwd, waarbij er ook een update aan de diagnosecomputer nodig was. Een bijkomende probleem was dat treinen met en zonder deze update niet meer aan elkaar gekoppeld konden worden, wat voor grote moeilijkheden kan zorgen in de dienstregeling. Deze update is daarom snel (in 2 weken) met een mobiel team uitgevoerd, waarbij het onderhoud naar de trein toe gebracht is. Andere medewerkers hebben meer beeld over de algemene visie over hoe het onderhoud er in de toekomst uit zal komen te zien.

Er wordt heel bewust rekening gehouden met de menselijke input van een systeem bij de aanbesteding van een nieuw systeem/nieuwere versie van een systeem, of het opstellen van specificaties (human factorschap bediening en gebruik). Incorrect specificeren zorgt namelijk voor grote fouten. Vanuit onderhoud worden de ervaringen van de maintenance engineers meegenomen.

Er is een referentiekader met alle standaardspecificaties en hoe belangrijk deze specificaties zijn. Deze kan worden aangevuld. Het toevoegen van het domein IT en welke functionaliteiten daarbij horen is de grootste aanpassing geweest. Voor onderhoud specifiek, gaat het dan met name over de vraag welke informatie de trein moet kunnen sturen, zodat de trein gemonitord kan worden. Het is dan standaard vastgelegd dat data uitgelezen moet kunnen worden er is meegenomen welke data uitgelezen moet kunnen worden. Er wordt vaak een afweging gemaakt tussen kosten/tijd en of een data aspect door een leverancier geleverd kan worden.

Afspraken

In de onderhoudsvisie is de vertaalslag vanuit de algemene visie van het bedrijf niet specifiek bekend. Er zijn voorbeelden zoals duurzaamheid waarbij in de specificaties van de trein aspecten meegenomen worden. Voorbeelden zijn gebruik maken van groene stroom, maximale recyclebaarheid etc.

Digitalisering

Mogelijk wordt de nieuwe aanbestedingsaanpak om een extra trein van een bepaald model aan te schaffen zodat het mogelijk wordt technologie ondertussen door te ontwikkelen en uit te proberen op deze extra trein. Wanneer alles dan goed werkt, kan het met terugwerkende kracht op de rest van de trein toegepast worden.

Het proces om systemen modulair te ontwikkelen zodat ze ook modulair onderhouden kunnen worden, begint bij het definiëren van de modules samen met de leverancier. Vervolgens wordt er gekeken naar de criteria voor betrouwbaarheid en onderhoudbaarheid. Bovendien wordt er gekeken naar de toelatingseisen en wordt er gekeken hoe deze getoetst kunnen worden. Dit wordt gedaan met andere Europese partijen.

De aanpak van het onderhoud van IT systemen verschilt qua aanpak niet enorm van de huidige aanpak. Er wordt een matrix met faalvormen en de bijbehorende risico's gemaakt. Er wordt gekeken naar de minimale betrouwbaarheid van een component en deze aanpak wordt ook gedaan voor niet-IT componenten. Dit gaat helemaal terug naar de vraag naar de leverancier, waarbij dus gevraagd wordt om componenten die deze minimale betrouwbaarheid moeten kunnen leveren. Bovendien moet het passen in de treinarchitectuur, waarbij er een verschil is tussen nieuwe treinen en treinen die al uitgerold zijn. Er kan gekozen worden voor redundantie, betrouwbare componenten, procesafhandeling kan versterkt worden. Er wordt gekeken hoe men om moet gaan met nieuwe faalvormen. Hier kan een reliability engineer meer over vertellen.

Output/resultaten

Betrouwbaarheid op componentniveau wordt uitgedrukt in de kans dat het uit kan vallen. Dit kan doorberekend worden naar treinniveau door ook te kijken naar de effecten binnen een hele trein bij het falen van een component.

Onderhoudbaarheid is een van de factoren die bij de aanbesteding van belang is. In het voortraject wordt hiervoor een inschatting gemaakt gebaseerd op expertise en als het materieel eenmaal beschikbaar is en daadwerkelijk onderhouden moet worden, wordt er gemeten wat de onderhoudbaarheid is door bijvoorbeeld te meten hoeveel tijd een klus kost en hoe makkelijk dit te doen is. Het effect van datagedreven onderhoud op deze factor is nog niet te zeggen. Echter is de verwachting dat dit weinig effect heeft omdat DDM gaat over het uitstellen van onderhoud en de tijd waarop onderhoud gedaan moet worden en onderhoudbaarheid gaat over hoe makkelijk onderhoud uitgevoerd kan worden.

Port of Rotterdam

Interview 1

De verantwoordelijkheden van de afdeling asset management zijn dashboarding, data analyses uitvoeren, predictive maintenance, monitoring en cyber security. De RPA-12 valt onder de afdeling fleet, die verantwoordelijk is voor de vaartuigen die eigendom zijn van het havenbedrijf. Dit zijn patrouillevaartuigen en calamiteitenvaartuigen.

Actoren:

Asset Manager, Asset Owner, Reliability engineer, Maintenance engineer en D&IT: Data en IT afdeling

Service Provider: DHMR (Divisie Haven Meester) gebruiker van de vaartuigen en doet vast klein onderhoud en inspecties en vaste leveranciers van onderdelen voor groot onderhoud. TD (Technische Dienst) is bij correctief onderhoud het eerste aanspreekpunt.

Afspraken:

Havenbedrijf Rotterdam heeft een afspraak met Divisie Havenmeester (DHMR): 24/7 moet er minstens 5 vaartuigen beschikbaar zijn. Dit is de service level agreement. DHMR leasen de vaartuigen en varen met de vaartuigen. Zij doen ook de dagelijkse onderhoudstaken. De communicatie tussen DHMR vindt op een hoge frequentie plaats, dus is communicatie makkelijk en snel.

Wanneer een reparatie niet door de Technische Dienst uitgevoerd kan worden, zijn er standaard partijen die de reparaties uitvoeren.

Havenbedrijf Rotterdam is in alle gevallen eigenaar van de data die uit de vaartuigen gehaald wordt. Dat is zo omdat het uitlezen van de vaartuigen door het Havenbedrijf zelf is opgezet, door de D&IT afdeling in samenwerking met de assetmanager. De data komt binnen in de eigen cloud van het Havenbedrijf en wordt ook door hen beheerd en gecontroleerd.

Aanpak/Proces:

Elke 3 maanden worden de vaartuigen naar binnen gehaald voor een reguliere onderhoudsbeurt. Dit resulteert in 4 onderhoudsmomenten, waarvan 2 een kortere, zogenaamde pitstop. In de pitstop wordt alleen de olie ververst. Deze onderhoudsfrequentie is bepaald aan de hand van storingsanalyses en onderhoudsanalyses en de afgesproken SLA's. De leverancier van componenten en onderdelen geeft aan na hoeveel draaiuren bepaald onderhoud uitgevoerd moet worden.

Na een analyse van het Havenbedrijf is besloten dat de onderhoudsfrequentie omlaag kon. Dit resulteerde in 2 grote onderhoudsmomenten, in plaats van 4. Deze onderhoudsfrequentie kon bij gebrek aan data en de daarbij horende mogelijkheid om de data uit te lezen niet met een onderbouwing worden aangepast, dus gebeurde dat ook niet.

Momenteel kan de data wel worden uitgelezen en wordt er gewerkt met VDMXL (Value driven maintenance), hieruit bleek dat er ruimte was om met de frequentie te experimenteren. Daarnaast is er een reliability engineer in dienst. De reliability engineer houdt zich constant bezig met het verbeteren van het onderhoudsproces. De uitkomsten van de experimenten met de onderhoudsintervallen worden getoetst door de risicomatrices met elkaar te vergelijken. De inzichten van de reliability engineer worden gecombineerd met ervaringen van de rest van het asset management team om vast te stellen of de onderhoudsfrequentie wel of niet aangepast dient te worden. Over een langere periode (ongeveer een jaar) wordt vervolgens gekeken wat het effect van de aanpassing is op het aantal storingen en de beschikbaarheid.

VDMXL is opgesteld door mainnovation, en houdt in dat de economische waarde van beslissingen wordt gemaximaliseerd. Bij alle beslissingen wordt een kostenplaatje gemaakt. Het is vergelijkbaar met het idee van risk-based maintenance waarin risico's worden geminimaliseerd. Hierin worden alleen de risico's in kosten uitgedrukt. Risico's worden bepaald door een risicomatrix, op basis van het FMECA principe. Bij het Havenbedrijf is imago een belangrijke factor die meegenomen moet worden.

Op dit moment is de rol van digitalisering nog niet heel zichtbaar geweest in de voorspelling van zo'n matrix, maar er is een voorbeeld waarin het zeker duidelijk werd dat data in specifieke gevallen al kan helpen bij de vermindering van storingsrisico's. Bij een aantal vaartuigen bleek uit de data dat filters minder snel verstopt zouden raken als er meer gas gegeven zou worden. Zo is dus het risico op een storing (verstopte filters) verminderd door middel van een inzicht uit de data. Voor in de toekomst wordt er gedacht dat potentie ligt in het meten van trillingen en temperatuur om te voorspellen waar storingen zullen optreden.

Bij correctief onderhoud wordt eerst gekeken of de Technische Dienst (TD) het vaartuig kan repareren. Zij hebben een 24/7 piketdienst om in te spelen op plotselinge storingen. Via het HCC (Haven Coördinatie Centrum) wordt degene met piketdienst opgepiept. Als de TD het niet op kan lossen, wordt er een vervangend voertuig ingezet en wordt een externe partij (leverancier van het onderdeel) ingeschakeld voor de reparatie van het onderdeel.

Digitalisering:

80% van de vloot is al gedigitaliseerd en daarvan kan data worden uitgelezen. Bij de overige 20% is dit nog niet het geval, omdat de hardware van de vaartuigen verouderd is. Er zitten eigenlijk al 10 jaar sensoren op de vaartuigen, maar worden pas de laatste 1-2 jaar uitgelezen op afstand.

Het is nog niet zo dat de data het onderhoudsmoment gaat bepalen. Dan is het pas data-driven maintenance en houd je je dus niet meer aan vaste onderhoudsmomenten. Een van de uitdagingen die voor dit punt genoemd wordt, is dat dit ook flexibiliteit vanuit de onderaannemers vraagt. Het is immers pas op een later moment en niet met een vast interval duidelijk wanneer zij het onderhoud uit moeten voeren. Dus een hogere flexibiliteit is nodig, of al het onderhoud moet door het Havenbedrijf zelf worden uitgevoerd, zodat dit op ieder moment mogelijk is. Momenteel kan tot op een zekere hoogte voorspeld worden wanneer onderhoud moet plaatsvinden en daardoor kan de afspraak met de onderaannemer dus wel gemaakt worden, of een item besteld worden zodat het op voorraad ligt.

De reden dat het havenbedrijf nog niet kan werken met datagedreven onderhoud is dat er te weinig data wordt uitgelezen. Bovendien moeten ze dan bepalen welke indicatoren bepalend zijn voor de onderhoudscyclus als randvoorwaarden. Voor de vaartuigen zelf moet worden bepaald wat de grenswaarden voor alle indicatoren is om een vaartuig uit de dienst te halen voor onderhoud.

De data wordt nu meer gebruikt voor root cause analyses om te achterhalen wat precies de storingen veroorzaakt, en om de vloot met elkaar te kunnen vergelijken. Deze data wordt gebruikt om per vaartuig een vaarprofiel op te stellen. Dat vaarprofiel wordt gebruikt bij de aanschaf van nieuwe vaartuigen. Ze kunnen als cases gebruikt worden om te checken of potentiële nieuwe modellen geschikt zijn voor de doeleinden.

Wanneer er verschillen optreden in de data, dus tussen het dashboard en het vaartuig gaat de asset manager naar het vaartuig om te achterhalen waar dit verschil vandaan komt. Dit gebeurt in samenwerking met de afdeling D&IT, afhankelijk van de kant waar de storing zit. Na een kalibratie wordt er vanuit gegaan dat de sensors juiste data geven.

De belangrijkste vereisten voor een succesvolle transitie naar meer digitalisering zijn als volgt. Allereerst validatie, klopt de data die er te zien is in het dashboard en kan men de data kwaliteit garanderen. De juiste tools moeten worden gebruikt op de juiste manier en men moet gebruik maken van dezelfde tools zodat er geen verschillen kunnen optreden en zodat resultaten vergeleken en gecombineerd kunnen worden. Als laatste moeten de mensen de juiste kennis en skills hebben, en moeten verantwoordelijkheden goed verdeeld worden.

Data kwaliteit wordt momenteel gemonitord door de asset manager en de afdeling van D&IT. Er wordt alleen gekeken naar verschillen tussen het dashboard en het vaartuig. Na kalibratie wordt er aangenomen dat de waardes kloppen. Het is pas een probleem als er een storing optreedt die niet voorspeld kon worden door het dashboard. De sensor kan stuk zijn, maar dat is dus wel zichtbaar in het dashboard. Er zijn geen kritische sensoren, dus er hoeft niks redundant ingebouwd te worden.

Output/Resultaten:

Beschikbaarheid is lastig in kaart te brengen, want er is geen gradatie in beschikbaarheid, terwijl die er in de praktijk wel is. Een vaartuig kan technisch beschikbaar zijn, dus bijvoorbeeld het vaartuig werkt, maar de blusinstallatie is defect. Dit vaartuig kan dan wel ingezet worden voor inspecties, maar kan geen brand blussen. In principe is dit vaartuig niet volledig beschikbaar, maar ook niet volledig onbeschikbaar. Bovendien kan er vervangend materiaal ingezet worden waardoor de SLA wel gehaald wordt en de afspraak dus nagekomen wordt, maar dat dekt dus niet de volledige beschikbaarheid van de vloot. Dit zorgt er dus ook voor dat de huidige waardes voor de SLA niet volledig kloppen. Hier kan digitalisering een rol spelen om dit volledig in kaart te brengen.

Het doel voor de toekomst is hier om te gaan werken met verschillende levels, of conditiescores (door bijvoorbeeld kleuren of letters) om aan te geven wat er stuk is en in hoeverre een vaartuig volledig beschikbaar is. Het grootste effect is dat er mogelijkheid is voor voorspellend onderhoud in de toekomst. Voor nu is het effect vooral dat de monteur gerichter gestuurd kan worden. Ook kan digitalisatie een rol spelen bij het maken van de SLA's omdat het duidelijker in kaart is gebracht wat er daadwerkelijk geleverd kan worden.

Visie voor toekomst in het algemeen is gebruik te gaan maken van algoritmes en Artifical Intelligence systeem waarin alle systemen en alle input is meegenomen. Dit vormt dan een model wat zelf kan bedenken wanneer er onderhoud nodig en mogelijk (!) is, rekening houdend met alle randvoorwaarden en restricties. De uitdaging is dan vooral om alle juiste inputwaardes voor dit model te genereren en te garanderen dat deze waardes kloppen.

Interview 2

Bij Asset Management wordt er gekeken naar de strategische kant van asset management, waarbij kosten prestaties en risico's worden afgewogen. In dit geval is ligt de verantwoordelijkheid over de hele asset base van het havenbedrijf, dit bestaat uit 23 soorten asset, verdeeld over 4 afdelingen: vaartuigen, vessel traffic management systems, natte infra en droge infra.

1. Strategisch: Richten – asset owner

2. Tactisch: Inrichten – asset manager

3. Operationeel Verrichten – service provider

De werkzaamheden van de asset owner gaan met name over hoe het asset management proces ingericht is, welke ondersteunende systemen daarbij nodig zijn en hoe het beleid van het havenbedrijf wordt vertaald naar asset management.

Actoren

Divisie Havenmeester Rotterdam (DHMR)

Veiligheidsregio Rijnmond (VRR)

Afspraken

De havenmeester en de veiligheidsregio Rijnmond hebben een convenant gesloten met afspraken over o.a. de eisen waar de assets aan moeten voldoen die met name te maken hebben met de beschikbaarheid van de assets.

De subjectieve aspecten die effect hebben op of een vaartuig wel of niet beschikbaar beschouwd mag worden, worden objectief gemaakt in SLA's tussen het havenbedrijf en de havenmeester. Deze afspraken zijn grotendeels vastgelegd en kunnen steeds scherper vastgesteld worden.

Aanpak/proces

De vertaling van de visie en doelstellingen van het havenbedrijf naar concrete stappen voor enerzijds het asset management proces en anderzijds de assets, worden vastgelegd in een strategisch asset management plan (SAMP). Het havenbedrijf wil bijvoorbeeld de duurzaamste haven zijn. Wat betekent dat precies en hoe moet dat eruit zien in de praktijk? Deze stappen komen voort, en zijn gebaseerd op de ISO normen die ook gebruikt worden voor de certificering.

De ondernemingsstrategie van het havenbedrijf bestaat uit de volgende visie:

Wij zijn toonaangevende, veilige, efficiënte en duurzame haven waar onze klanten succesvol kunnen ondernemen.

Door de volgende 3 speerpunten:

- Slimme partner in logistieke ketens
- Versneller van de verduurzaming van de haven
- Ondernemende en slagvaardige organisatie.

Deze worden vertaald door te kijken naar de impact, randvoorwaarden en de maatregelen die daarbij horen. Dit staat beschreven in het strategisch asset management plan (SAMP).

Het Asset Management proces draait om de afweging van kosten, prestaties en risico's. Hierbij staan de prestaties voorop, want de assets zijn er voor een reden. De functies van de assets komen voort uit de doelstellingen en afspraken van een organisatie. Zo moeten de patrouillevaartuigen binnen een bepaalde tijd bij een calamiteit aanwezig kunnen zijn, dus moet het een gemotoriseerd voertuig zijn. Dit heeft effect op het ontwerp en het instandhoudingsconcept van het vaartuig. In de praktijk betekent dit voor de RPA dat er 24/7 5 vaartuigen beschikbaar moeten zijn.

De afspraken over de beschikbaarheid van de assets moeten meegenomen worden in een risicoanalyse waarin gekeken wordt naar de faalvormen die voor kunnen komen waardoor de prestaties niet geleverd kunnen worden en hoe deze faalvormen gemitigeerd kunnen worden. Er wordt gebruik gemaakt van een bedrijfswaarde/risicomatrix. Hierin staat voor verschillende aspecten (financieel, imago, mens, milieu en core business) beschreven wat het risico is wanneer een bepaalde gebeurtenis optreedt op een bepaalde schaal. Deze risicomatrix is meegenomen in het SAMP.

Het idee van de matrix is om maatregelen te bedenken die of het effect van de gebeurtenis verminderen of die de kans van optreden verkleinen. Deze set aan maatregelen kunnen eigenlijk gezien worden als de basis van de onderhoudsconcepten. De rol van de asset managers is dan om te kijken hoe deze concepten er in de praktijk uitzien en wat de ideale/optimale onderhoudsfrequentie is om deze concepten uit te voeren zodat de risico's ook echt zo klein mogelijk gehouden worden.

Menselijke input wordt eigenlijk bij alle assets meegenomen omdat data door mensen nog geïnterpreteerd dient te worden. Dit vergt kennis en ervaring om de juiste conclusies uit de data te kunnen trekken.

Binnen het Havenbedrijf zijn er afdelingen en teams bezig met de uitdagingen die rondom data spelen. Bovendien wordt er gekeken waar de potentie ligt om gebruik te maken van predictive maintenance en hoe deze potentie gebruikt en ingericht kan worden. Dit wordt onder andere gedaan door te kijken wat de duurste assets zijn en om bij deze assets na te gaan wat de dominante faalvorm is. Deze wil je dan verbeteren op de aspecten: financieel, imago, mens, milieu en core business.

Het havenbedrijf werkt met de VDMXL (value driven maintenance) aanpak. Het gaat daarin om het creëren van waarde. Dat kan door de prestaties van de assets te verhogen (asset utilization), of door de kosten te verlagen (cost control). Reliability Engineering draait om de risicoanalyse: wat zijn de faalvormen en de risico's. Via de een risicomatrix wordt aan een bepaalde risico een bepaald bedrag verbonden, waardoor alles uit te drukken is in kosten. De specifieke waardes worden niet gepubliceerd in deze samenvatting.

Digitalisering

Sensoren en data worden ingezet op punten waar weinig grip of zicht is op de gang van zaken. Een voorbeeld waar data gebruikt is en er een effect op het onderhoud te zien was, zijn de roetfilters van bepaalde vaartuigen. Deze raakten vol en door de inzet van sensoren kon een verband gelegd worden tussen de volheid van het filter en het geven van gas en konden volle filters als het ware schoongebrand worden waardoor onderhoud/vervanging aan de filters niet meer zo frequent nodig was.

Een ander voorbeeld is te zijn bij de kadermuren. Hier zitten stalen wanden in waar gaten in kunnen ontstaan. Door middel van data is er in kaart gebracht waar en hoe een stalen damwand degradeert, en dus ook waar punten ontstaat waar de slijtage zodanig is dat er een onveilige situatie kan ontstaan. Door middel van anodes wordt de slijtage door corrosie voorkomen. De muren werden geïnspecteerd door een duiker die visueel inspecteert of er gaten in de muren zitten. Naast het feit dat dit veel geld kost, is het erg veel werk voor de duiker omdat er kilometers aan muur zijn, die tot 24 meter diep kunnen gaan. Door het gebruik van data is nu bekend wat overal de dikte van de muur is en de degradatietrend is bekend, wat in modellen is meegenomen.

Door de plaatsing van anodes zouden de muren nu niet meer moeten corroderen, maar ook dat moet getoetst worden. Dit gebeurt door de anodes te wegen en te kijken of dit overeenkomt met het model.

De grootste uitdagingen voor predictive maintenance rondom data zijn: kennis over wat er gemeten moet worden, hoe de connectiviteit georganiseerd moet worden, waar de data opgeslagen moet worden, welke sensoren nodig zijn voor welke informatie, met wie de data gedeeld moet worden, hoe de data vertaald kan worden naar informatie.

Het grootste effect van data is dat het de mogelijkheid biedt om met wereldwijde partijen te communiceren over de logistieke stromen in de haven en dingen als *Just in time sailing* toe te kunnen passen. Hierbij is het van belang om afspraken te maken over actualiteit, uniformiteit, definitie gebruik, locaties (global location numbers), uitwisselbaarheid en adoptie.

Het havenbedrijf is bezig met het opstellen van voorwaarden waar data aan moet voldoen, om de juiste data kwaliteit te garanderen. Het is nog niet helemaal wat de voorgang is van deze randvoorwaarden. Momenteel lijkt de vulgraad van een data sheet als enige indicator gebruikt te worden. Hier zijn data stewards binnen de organisatie mee bezig.

Resultaten/output

Er zijn een hoop aspecten die een rol spelen bij de beschikbaarheid van de vaartuigen. De voornaamste afspraak is dat er altijd 5 vaartuigen beschikbaar zijn. Echter spelen aspecten zoals bijvoorbeeld inzet van vervangend materieel en beschikbaar personeel om te varen een rol bij de berekening van beschikbaarheid. Een afgeleide van de afspraak is dat ieder vaartuig 92% van de tijd beschikbaar moet zijn. Ook hier is een grijs gebied over wat er mag falen om een vaartuig nog steeds de status beschikbaar te geven. Daar wordt over gebrainstormd tussen het havenbedrijf en de havenmeester.

De ROI wordt voor een investering in sensoren of digitalisering wel bepaald. Een voorbeeld is de kadermuur waar ooit een kostenplaatje van de kosten van een herinvestering is vergeleken met de investeringen voor de digitale sensoren. Voor projecten met hoge investeringskosten blijkt dat digitalisering vaak grote effecten kan hebben voor een (relatief) kleine investering ten opzichte van de herinvesteringswaarde.

Voor het Havenbedrijf zelf is het lastig om specifiek iets te kunnen zeggen over de ROI van de digitale systemen, omdat ze een in hun visie hebben staan dat ze een slimme partner willen zijn. Dit resulteert in veel samenwerking, en dus ook data delen met partners, om de logistiek in de haven te optimaliseren. Er zijn dus afdelingen vanuit het havenbedrijf bezig met het data gebruik over het hele bedrijf, en niet slechts voor specifieke business cases. Er is dus een bedrijfsbrede sensorstrategie. Er een platform waar alle data gestructureerd binnenkomt, er is een afdeling die zich bezighoudt met digitaliseringsinitiatieven op het gebied van connectiviteit en data governance is ingericht. Met andere woorden de data infrastructuur is op orde om ermee aan de slag te kunnen. Dit is opgezet door een proces van vallen en opstaan.

Interview 3:

Bij Asset Management wordt er gekeken naar Reliability binnen de afdeling Fleet. De fleet bestaat uit vaartuigen, veiligheidsmiddelen en bedrijfsmiddelen. Er wordt onder andere gekeken naar de PO (preventie onderhoud) plannen gaan over het effect van bepaald onderhoud op de soort en de frequentie van storingen. Er worden analyses gemaakt over onderhoud en er wordt gekeken wat het effect op de betrouwbaarheid is en of dit binnen acceptabele risico's en kosten valt. Bovendien wordt er gekeken wat de rol van techniek hierin kan zijn.

Actoren

Een vaartuig wordt bij een scheepswerf als geheel geleverd. Er is een programma van eisen vanuit alle betrokken partijen en de scheepswerf heeft contact met leveranciers om onderdelen voor het vaartuig te leveren om aan de eisen te kunnen voldoen.

De haven van Rotterdam is de asset owner van de vaartuigen. De asset manager binnen het havenbedrijf is verantwoordelijk voor het beheren en het beschikbaar stellen van de vaartuigen.

De havenmeester (DHMR) is de gebruiker van de vaartuigen en is verantwoordelijk voor het eerstelijns onderhoud. Dit zijn taken zoals het smeren van onderdelen, de motorolie en het brandstofpeil inspecteren en waar nodig bijvullen, het schoonmaken en houden van het vaartuig en het melden van defecten.

De Technische dienst wordt ingeschakeld zodra een defect is gemeld door een van de partijen. Er gaat dan iemand naar het vaartuig om het defect te inspecteren en om in te schatten of het door de Technische Dienst onderhouden kan worden, of dat de leverancier van het specifieke onderdeel ingeschakeld moet worden.

De afdeling Data & IT van de haven de Rotterdam zorgt voor veilige connecties en ze zorgen dat de signalen vanuit de sensoren in de vaartuigen naar de wal gehaald kunnen worden.

Afspraken

Tussen het havenbedrijf en DHMR bestaat de afspraak dat er altijd minimaal 5 vaartuigen beschikbaar moeten zijn.

Wanneer de garantie voorbij is (na 1-2 jaar) wordt bij defecten contact opgenomen met de leverancier van de originele onderdelen om deze repareren of te vervangen. Soms is er sprake van een groter contract. Zo zijn alle motoren van dezelfde leverancier en wordt deze dus bij een defect aan de motor standaard benaderd.

Aanpak

Een storing wordt gemeld door de bemanning van het vaartuig (DHMR) in een app (ServiceNow), deze melding wordt omgezet naar SAP en wordt wekelijks geëxporteerd naar PowerBi door de Reliability Engineer.

Voor preventief onderhoud komt ieder vaartuig 2 keer per jaar naar binnen voor een grote onderhoudsbeurt en 1 of 2 keer per jaar binnen voor een pitstop. Dit is afhankelijk van de gemaakte draaiuren. Voorheen kwamen de vaartuigen 4 keer per jaar binnen voor onderhoud, maar dat is door experimenten en ondersteuning van data gereduceerd naar 2 onderhoudsmomenten. Dit experiment was gedaan omdat het aantal storingen al een lange periode laag was, dus er leek potentie in te zitten en dit bleek inderdaad gereduceerd te kunnen worden. Echter zijn de onderhoudsmomenten wel langer omdat er meer onderhoudstaken zijn toegevoegd.

Aan de sensoren zelf vindt nauwelijks onderhoud plaats, omdat het eigenlijk niet mogelijk is. Het is zodanig ingericht dat er een continue output uit de sensor komt. Wanneer dit stopt, is er een probleem en werkt de sensor niet. De informatie uit de sensoren wordt gevalideerd door de output te vergelijken met de analoge meters aan boord van het vaartuig.

Momenteel zijn er nog weinig sensoren aan boord waarvan de data voor onderhoud gebruikt wordt. De Reliability Engineer is bezig met APM (Asset Perfomance management) en Predictive Maintenance en er zijn al voorbeelden uit de praktijk. Er komen meldingen binnen wanneer er water in het schip loopt en wanneer het brandalarm afgaat. Het doel is om dit uit te breiden om niet alleen meldingen te zien, maar een continue statustoestand in kaart te kunnen brengen en trends te kunnen ontdekken. Er wordt nu gekeken naar motor gegevens en hoe deze omgezet kunnen worden naar een dashboard. Er wordt dan gekken naar het brandstof- smeerolie- en koelwaterpeil en naar de snelheid van een vaartuig.

Digitalisatie

De keuze voor extra sensoren op een vaartuig wordt afgestemd met de Asset manager. Er wordt een kosten-baten analyse gemaakt en er wordt gekeken wat het potentiële effect op de betrouwbaarheid en beschikbaarheid van het vaartuig is. Er wordt bijvoorbeeld nu naar trilling sensoren gekeken, want die hebben veel effect op kritische (relevantie voor werking) en dure onderdelen, en op de veiligheid van het vaartuig.

Sensoren worden geplaats om te kijken of het voorgeschreven onderhoud juist en zinvol is en om na te gaan wat de optimale frequentie van het onderhoud zou moeten zijn. Bovendien wordt er nagedacht over welke informatie nodig, hoe het gevisualiseerd moet worden en hoe trends ontdekt kunnen worden. Het is dan zeer waarschijnlijk dat de data niet wekelijks, maar met een hogere frequentie geanalyseerd wordt.

Het grootste effect van digitalisering is dat men niet altijd meer naar een vaartuig toe hoeft te gaan om de status te beoordelen. Dit scheelt tijd en uitstoot. Bovendien kan het vaartuig vanuit een veilige (kantoor)omgeving geanalyseerd worden en komt daardoor niemand in gevaar, of spelen externe factoren (geluid, weer, lucht, trillingen) geen rol. In de praktijk zijn er nog weinig effecten te zien omdat er te weinig data is, behalve het aantal onderhoudsmomenten. De uitdaging ligt met name in de digitale infrastructuur en het aanleggen en beveiligen ervan.

Beschikbaarheid

Beschikbaarheid is nauw verbonden met betrouwbaarheid. Met betrouwbaarheid wordt bedoeld: stilstandverliezen, ofwel ongeplande stilstand van het vaartuig. Sensoren en data zorgen ervoor ongeplande stilstand voorkomen kan worden, waardoor de betrouwbaarheid en de beschikbaarheid omhoog gaat.

ProRail

Interview 1:

Actoren

Elk gebied heeft specialisten, omdat er per gebied unieke assets zijn. Er is ook landelijk beleid wat per gebied vertaald wordt. Zo wordt het beleid en regelgeving centraal opgesteld en vertaald naar de losse 9 gebieden. Centraal in Utrecht zijn er systeemspecialisten die kennis en expertise hebben op een bepaald gebied om het landelijke beleid op te stellen. Door vakspecialisten wordt dit regionaal uitgevoerd.

Er zijn externe bedrijven betrokken bij het onderhoudsproces van de tunnel. In de gemaakte afspraken staan de prestatie-eisen waar de tunnel (en de andere assets in het gebied) aan moet blijven voldoen.

Afspraken

Omdat deze onderhoudsaannemers sneller baat bij een snelle digitalisatietransitie hebben, want ze zijn commerciële bedrijven, wordt er van hun kant veel in digitalisatie geïnvesteerd. Het tempo van ProRail ligt op dit gebied een stuk lager. Toch moeten de beide partijen samen een overeenkomst sluiten. Het gebruik van data kan soms onderdeel zijn van de PGO (prestatie gestuurd onderhoud). Echter is het doel wel om alle data eigendom te maken van ProRail, waarbij onderhoudsaannemers inzicht mogen hebben zodat ze het onderhoud uit kunnen voeren en kunnen optimaliseren.

Aanpak

Er is een splitsing gemaakt in de onderdelen van de brug: civiel technische onderdelen, zoals beton en staal en de installaties, en IT systemen. Onderdeel van de Civiele Techniek en installaties zijn: energiesystemen, zoals de hoogspanningskabels, railsystemen, zoals de wissels en treinbeveiligingssystemen, die o.a. de luchtkwaliteit en het zicht in een tunnel meten.

Deze splitsing is gemaakt is omdat de verschillende soorten systemen ander faalgedrag vertonen. IT systemen worden sneller obsolete en moeten dus anders onderhouden worden. Ze kunnen bijvoorbeeld eerder vervangen worden voor een nieuw systeem, waar civiel technische onderdelen veel langer slechts gerepareerd hoeven te worden.

Digitalisatie

Digitalisering kan helpen in het beter voorspellen van storingen omdat er inzicht is in de status van een onderdeel en analyses van het faalgedrag gemaakt kunnen worden. Daarnaast biedt het de mogelijkheid tot benchmarking. Bovendien kan onderhoud efficiënter uitgevoerd worden en kan de veiligheid en snelheid van het onderhoud omhoog.

Interview 2:

Functie:

Bij de projectmanager ligt de focus ligt op het monitoren van beweegbare bruggen en tunnels in Nederland. 20 tunnels die wel beheerd en gemonitord worden, maar nog geen data onttrekking en analyse. Zodra de storing voorbij is wordt de data weggegooid. De overkapping in Barendrecht heeft een vernieuwd besturingssysteem en is daarom geschikt om gemonitord en op afstand uitgelezen te worden. Dit wordt gedaan sinds mei 2023.

De rol van de Rail systems Engineer bestaat uit: het coördineren van data gedreven werk binnen Civiele Techniek & Utilities, waarin wordt nagegaan welke vragen en aspecten een rol spelen in de digitaliseringstransitie, als coördinator datagedreven werken . Verder wordt er gekeken met andere partijen gekeken wat men van elkaar kan leren op het gebied van datagedreven onderhoud aan tunnels en bruggen, zodat in de toekomst onderhoud beter voorspeld kan worden en de status van de objecten gemonitord kan worden.

Actoren

Onderhoudsaannemer: Volkerrail

Prorail: er is sprake van een matrix met op de ene as de 9 geografische regio's met o.a. een regiobeheerder en vakspecialisten en op de andere as o.a. de verschillende soorten techniek, of assets zoals: o.a. ERTMS, treinbeveiliging, CT&U (Civiele Techniek en Utility) en Spoor en wissels en Geotechniek

Binnen Prorail is er een losse afdeling (ICT en automatisering) die naar de digitale aspecten van de assets kijkt en er ook een afdeling die specifiek kijkt naar het civiele onderdeel, zoals de materialen en manier waaruit de asset is opgebouwd.

Aanpak

De onderhoudscyclus bestaat momenteel uit 2 routes. De eerste is voor de lange termijn en bestaat voornamelijk uit preventief onderhoud. Er wordt gekeken voor alle onderdelen wat de levensduur is en wanneer ze vervangen moeten worden. Dit is met name gebaseerd op de instructies van de fabrikant. De 2e route wordt ook wel PGO (prestatie gestuurd onderhoud) genoemd waarin de onderhoudsaannemer verantwoordelijk is voor het halen van gestelde prestaties en daar ook zelf het onderhoud voor moet inrichten. Dit is vastgesteld in contracten per regio en het hangt dus van de regio af welke assets onderdeel zijn en hoe het onderhoud en de planning ervan eruit ziet.

Ook hier is er enigszins sprake van een splitsing tussen Civiele Techniek en ICT. In principe wordt dit op dezelfde manier gepland, maar is de levensduur van ICT vaak korter.

Een inspecteur van ProRail inspecteert alle assets en iedere 5 jaar wordt door een externe partij bepaald welk (groot) onderhoud nodig is. Vakspecialisten van ProRail worden ingeschakeld om onderzoek te doen om de onderhoudsstrategie en planning vast te stellen. Met andere woorden: hoe snel bepaald onderhoud moet plaatsvinden, wie het uit moet voeren (of het onderdeel is van PGO) en of het met ander onderhoud gecombineerd kan worden.

Er kan sprake zijn van meldingen, storingen, kritische storingen en alarmen. Deze geven aan hoe belangrijk een storing is en hoe snel het opgelost moet worden. Dit is onderdeel van de zaken waarvoor de PGO aannemer ingeschakeld wordt. Het bepalen van de mate van kritiek is gebaseerd op voorschriften (of er sprake is van failsafe, redundantie etc.) en risicoanalyses, zoals FMECA.

Het onderhoud wordt gecontroleerd door een inspecteur, vakspecialist of externe partij. Vanuit de dagelijkse operatie wordt door de inspecteur het werk van de onderhoudsaannemer gecontroleerd. Dit vind ongeveer 1x per week plaats (afhankelijk van agenda van de inspecteur en de andere assets in de regio).

Digitalisatie

De huidige sensoren geven momenteel alleen storingen en alarmen aan (bijv te hoge temperatuur) maar er wordt nog niet gekeken naar trends van de temperatuur over de tijd. Bovendien wordt ook alleen informatie over storing bewaard en wordt de rest weggegooid. Het doel voor de toekomst is om relevante data op te slaan om trends over de tijd te kunnen maken. Zo kan het de inspecteur ondersteunen door de oorzaak van storingen makkelijker te achterhalen en gerichter onderhoud toe te passen.

De aanpak voor nu is niet om nieuwe sensoren plaatsen, maar juist te kijken naar wat er momenteel uit de systemen uitgelezen kan worden en wat de informatiebehoefte is. Dat wordt eerst alleen voor de ventilatoren gedaan omdat dit de grootste kostenpost is. Er wordt alleen gekeken naar aanschafkosten, niet vanuit het kritische punt. Daarna wordt dit uitgebreid voor meer systemen om uiteindelijk een generieke aanpak te maken voor alle tunnels in Nederland, waarin dezelfde data wordt uitgelezen en geanalyseerd waardoor tunnels met elkaar vergeleken kunnen worden. Het uiteindelijke doel is om inzicht in het functioneren en de status van de asset te hebben en ongeplande storingen voorkomen.

Data kwaliteit speelt nog geen significante rol. Er wordt wel rekening gehouden met de bestaande standaarden voor o.a. cybersecurity. Zo moet worden gewaarborgd dat data slechts in één richting uitgelezen kan worden en dat er dus alleen data uit kan en niks in gestuurd kan worden. Dit wordt momenteel gedaan door te garanderen dat apparatuur die geïnstalleerd wordt voldoet aan de bestaande eisen omtrent cybersecurity. Daarnaast speelt data eigenaarschap een belangrijke rol en moet ervoor worden gezorgd dat data eigendom van ProRail is en blijft.

Onderhoud aan sensoren speelt nog geen rol. Maar meestal is het integraal onderdeel van apparatuur en worden sensoren dus vervangen zodra het systeem vervangen wordt.

Bij Prorail wordt de invulling van het strategisch plan op het gebied van onderhoud in dit geval uit de praktijk gehaald. Het lange termijn plan wordt momenteel geschreven en de invulling voor de onderhoudsactiviteiten komt vanuit de praktijk, waar dit bij andere bedrijven vaak andersom gebeurt.

Afspraken

De contracten met onderhoudsaannemers zijn standaard 5 jaar via een aanbesteding.

Het effect digitalisering op de afspraken is dat ProRail meer inspraak wil over het beheer en eigenaarschap van data over storingen en problemen. Dat ligt nu vaak alleen bij de onderhoudsaannemer. Bovendien wordt er gekeken of het zinvol is om speciale objecten (zoals bruggen en tunnels) buiten de contracten halen.

Het effect van digitalisatie op PGO zou ook kunnen veranderen. Digitaal functioneren en falen anders, dus PGO krijgt dan misschien een andere vorm. Contracten staan van meer in het teken van het verlenen van een storingsdienst en garantie van paraatheid, in plaats van alleen het uitvoeren van onderhoud aan de voorkant.

Er vindt communicatie plaats met partijen, zoals Rijkswaterstaat. Alle partijen zijn nog beetje aan het verkennen wat de mogelijkheden en behoeftes zijn. Belangrijk is ook het COB (centrum ondergronds bouwen) waarin kennis gedeeld wordt met verschillende partijen.

Output

Beschikbaarheid wordt met veel verschillende indicatoren gemeten, maar het uitgangspunt is het percentage van de tijd waarin er door ongepland onderhoud geen treinen door de tunnel kunnen reizen. Hierin wordt onderscheid gemaakt tussen HK1 en 2: hinderklasse 1 en 2, die de mate van hinder aangeven.

In een afspraak met ministerie staan de prestatie eisen die geleverd moeten worden. Via prestaties.prorail.nl worden indicatoren per thema uiteengezet: reizigersvervoer, goederen vervoer, infra, veiligheid en milieu en duurzaamheid.

Rijkswaterstaat

Interview 1:

Er is onder andere (met collega's) een pilot opgesteld waarin digitalisering, met de focus op sensoring en big data, een grote rol speelt. Momenteel wordt er door (..) gefocust op de 6 stormvloedkeringen. De Kreekraksluizen zijn onderdeel van de pilot, wat betekent dat (..) kennis heeft van hoe de transitie naar het gebruik van meer digitale systemen tot stand is gekomen.

Actoren:

Er wordt gebruik gemaakt van de asset managementstructuur waarin drie asset management rollen zijn opgenomen: Asset Manager, Asset Owner en Serviceprovider. De invulling van deze rollen voor deze specifieke asset worden hieronder beschreven.

Asset Owner: Ministerie van infrastructuur en waterstaat

Asset Manager: Rijkswaterstaat

Service Provider, onderhoudsaannemer: Scaldis

Andere partijen:

WVL: Rijkswaterstaat Water, Verkeer en Leefomgeving: maken met de beleids DG's (als afgevaardigde van het Ministerie van I&W als asset owner) afspraken over prestaties

PPO: programma's projecten en onderhoud

Afspraken:

Er wordt gebruik gemaakt van zogenaamde pins, ofwel prestatie indicatoren. Dit zijn servicelevel afspraken tussen het Ministerie van Infrastructuur en Waterstaat en Rijkswaterstaat. Deze afspraak is als volgt: 0.8 % geplande downtime en 0.2 % ongeplande downtime. De wijze waarop deze getallen vast zijn gesteld, moet worden uitgevraagd bij de verantwoordelijke persoon bij WVL: Rijkswaterstaat Water, Verkeer en Leefomgeving.

Vast onderhoud en inspecties worden uitgevoerd door Scaldis, waarbij een contract loopt tussen de 5-10 jaar (7 jaar en 2x een jaar verlenging). Dit wordt continu gedaan, omdat het vaste onderhoud geborgd moet worden. Variabel onderhoud, zoals renovaties wordt uitgevoerd door middel van een aanbesteding vanuit Rijkswaterstaat.

De data die uitgelezen wordt uit de asset is eigendom van RWS, ondanks dat, in dit geval Scaldis, de inspecties doet en de data gebruikt en aanvult. Analyses en resultaten worden ingevoerd in de systemen van Rijkswaterstaat. Het is niet duidelijk of data die leveranciers zelf uit hun productanalyses halen eigendom van Rijkswaterstaat kan worden, als het in hun constructies opgenomen is.

Aanpak/Proces:

Rijkswaterstaat werkt met het concept van RCM (reliability centered maintenance). Hierbij wordt onderhoud gepland aan de hand van de potentiële faalkans en het daarbij horende risico. Echter wordt dit proces niet volledig zuiver uitgevoerd. Het doel is om zoveel mogelijk gebruik te maken van preventief onderhoud. Hierbij wordt gekeken de pins, ofwel prestatie indicatoren. In dit geval is dat 0.8 % geplande downtime en 0.2 % ongeplande downtime (van 24/7, 365 dagen). Om dit te wordt er gebruik gemaakt van availability modellen, waarin op basis van statistische analyses wordt bepaald welke onderhoudstaken in de toekomst uitgevoerd moeten worden. In deze aanpak ligt veel ruimte voor verbetering, omdat een model per definitie een vereenvoudiging is en fouten kan bevatten, waardoor de resultaten niet één op één met de realiteit overeenkomen. Bovendien is het model initieel gebaseerd op expert judgement, dus de ervaring en kennis van experts die zich bezighouden met het onderhoud van vergelijkbare constructies. Er ligt veel potentie in de verbetering van de modellen als de input van de modellen gebaseerd is op data uit de sensoren, in plaats van ervaringen van experts.

Het uitgangspunt is om zoveel mogelijk onderhoud preventief uit te voeren, gebaseerd op de modellen. Echter speelt politiek en de toegewezen budgetten een grote rol, omdat onderhoud wat vooruit gepland is (met een bepaald budget in acht genomen) misschien niet meer kan doorgaan, omdat het budget toch niet toereikend blijkt te zijn. Dit kan ook andersom gelden wanneer de modellen (gebaseerd op statistiek) een storing voorspellen die in de realiteit niet optreedt, waardoor (grootschalig) onderhoud niet nodig is en er dus budget overblijft. Concluderend is het telkens een afweging tussen budget en risico: bij te weinig budget moet er gewerkt worden met een groter risico, of moeten de prioriteiten heroverwogen worden.

Onderhoud aan de Kreekraksluis wordt gegroepeerd per componenten of subsystemen en wordt per asset los bekeken. Verder bestaat onderhoud uit vast en variabel onderhoud. Vast onderhoud bestaat uit dagelijkse (preventieve) taken die ervoor zorgen dat de asset zijn geplande levensduur zal halen. Voorbeelden hiervan zijn smeren van onderdelen en inspecteren van de onderdelen. Dit wordt gedaan door de onderhoudsaannemer en het is zijn verantwoordelijkheid om dit zo efficiënt en goed mogelijk te groeperen in werkorder. Zij houden zich ook aan de afgesproken pins. Grotere renovaties worden door Rijkswaterstaat via een aanbesteding geregeld. De planning hiervan wordt door RWS gedaan, waarin het doel is om dit risico gestuurd te doen. Gepland onderhoud wordt dus zo veel mogelijk slim gegroepeerd, mits de risico's (als gevolg van uitstellen) dat toelaten. Dit gebeurt momenteel impliciet en is dus eerder gebaseerd op kennis en inzichten op basis van ervaring, dan op kwantitatieve data.

Risico's worden berekend met het programma RCMcost. In dit systeem worden op een gestandaardiseerde wijze voor de verschillende componenten de faalkans ingevoerd. Deze input is gebaseerd op de specificaties vanuit de leverancier en op ervaringen van experts. Aan de hand van inspecties worden de inputwaardes verder onderbouwd en gefalsificeerd.

Vervolgens gaat daar een Monte Carlo simulatie overheen, om een x aantal keer de levensloop van de asset te simuleren. Het model berekent vervolgens wanneer systeem falen als gevolg van component falen optreedt. Dit model vormt de basis van de onderhoudsaanpak en dit wordt voor alle beweegbare asset van Rijkswaterstaat gedaan. De diepgang, of het detailniveau voor dit model verschilt wel per asset. Het doel is om dit te uniformiseren.

De moeilijkheid bij het invullen van het model is dat veel assets al erg oud zijn en dat er weinig informatie is over de faalkans van de componenten in de huidige status, en eerdere renovaties en onderhoud is slecht gedocumenteerd en beheerd. Bovendien zijn de inputwaardes vanuit de leverancier gebaseerd op generiek gebruik en zie je dat de onderdelen en componenten in de assets toch vaak onder unieke omstandigheden moeten opereren. Ook hier ligt ruimte voor verbetering door data gebruik.

Er ligt potentieel nog ruimte voor verbetering door de data over componenten op te vragen vanuit de leverancier, als de leverancier zelf ook door middel van datamonitoring meer kennis heeft over het verloop van bijvoorbeeld de slijtage van de component.

De inspectiefrequentie vindt plaats op basis van vaste intervallen: 1x per 5-6 jaar een grote instandhoudingsinspectie, waarbij de totale systeemstaat wordt geëvalueerd. 1x per jaar een toestandsinspectie alle componenten los worden bekeken en de status wordt vastgesteld. Een alternatief op deze aanpak is risk-based inspectie waarin de inspectiefrequentie naar mate de levensduur oploopt, verandert. De inspectiestrategie is onderdeel van de nieuwe vorm van asset management waar Rijkswaterstaat naartoe aan het werken is. Ze streven daarmee naar een gestandaardiseerde hogere flexibiliteit.

Wanneer er vaker dan verwacht correctief onderhoud uitgevoerd moet worden, heeft dat te maken met incidentenmanagement. Dit is voor deze asset onderdeel van het vaste onderhoudscontract. De onderhoudsaannemer doet de storingsanalyse en root cause analyse, wanneer er trends te zien zijn in de storingen. Dat is contractueel vastgelegd, maar het blijkt in de praktijk lastig om kwalitatief, tijdig en goede root cause analyses te krijgen vanuit de onderhoudsaannemer.

Digitalisering:

De sensoren die nu op de sluis aanwezig zijn lezen onder andere energieopname en SCADA-data uit. SCADA-data staat voor: *supervisory control and data acquisition.* Dat is onderdeel van bijna alle complexe technische systemen wat zorgt voor aansturing en data logging. Dat verzamelt real-time alle data, maar er moet wel geregeld worden dat de data wordt uitgelezen en geanalyseerd wordt. Momenteel is er veel meer relevante data beschikbaar vanuit de SCADA-systemen dan er effectief gebruikt wordt. De grootste uitdaging op dit punt zijn kennis en capaciteit. Rijkswaterstaat en de onderhoudsaannemers zijn gewend om dit soort data uit te lezen, wat erop wijst dat je mensen nodig hebt met een andere technische achtergrond. Hierbij is het van beland dat men zowel data-gerelateerde kennis als mechanische kennis van het functionele systeem heeft, om de belangrijke verbindingen tussen te twee te kunnen maken.

Aan het begin zijn er redelijk lukraak energiesensoren geplaatst, die vervolgens een grote hoeveelheid data konden genereren. Een data analist van het bedrijf die de sensoren had geplaatst zag daarin allerlei patronen, maar daar werden door gebrek aan kennis van het functionele systeem de verkeerde conclusies aan gehangen. Je moet dus een plan maken voor welke grootheden je wil meten om bepaalde storingen te voorspellen.

Beschikbaarheid:

Uren functionele downtime: tijd dat de sluis daadwerkelijk voor de scheepvaart gestremd is. Er zijn ontwikkelingen binnen Rijkswaterstaat, om te kijken naar een andere indicator: vaartuig verliesuren. Wanneer de sluis functioneel gestremd is en er is geen scheepvaart wat door de sluis moet, is dat niet erg. De indicator vaartuig verliesuren zou hier wel rekening mee houden en dekt dus de technische functionele downtime i.c.m. scheepvaartaanbod in één pin. Er zijn een aantal punten die hier belangrijk zijn. Allereerst, de belangrijkste afspraak is dat de sluis in totaal 1% van de totale tijd niet beschikbaar mag zijn. Voor deze pin is het niet relevant of er wel of geen aanbod is. Bovendien is het momenteel al lastig om voor de (eenvoudigere) indicator functionele downtime een goede risicoanalyse uit te voeren en de onderhoudsprogrammering daarop aan te laten sluiten. Het gebruik van een complexere indicator om de beschikbaarheid in uit te drukken, vereist nog meer input en inzichten die beperkt beschikbaar zijn. Zo moet bijvoorbeeld de variabele ‘scheepvaartaanbod’ inzichtelijk gemaakt worden.

Vaartuigverliesuren wordt momenteel wel gebruikt aan de beleidskant van Rijkswaterstaat omdat dit wel relevant is voor BV Nederland. Voor het onderhoud moet het doel zijn om eerst de functionele downtime op orde te hebben en de data-analyse daarvoor te regelen, voordat er verdergegaan kan worden en een nieuwe indicator gebruikt kan worden. Daarvoor is het belangrijk om duidelijk te hebben wanneer de eerste indicator goed genoeg in beeld is, zodat je ook de stap kan zetten naar de tweede indicator. De belangrijkste factoren zijn: valide en betrouwbaar model, het model is beheerd en wordt regelmatig en goed gecontroleerd en verbeterd waar nodig, en onderhoud wordt goed uitgevoerd en geïnspecteerd. Bovendien moet de data voor het scheepsvaartaanbod goed en betrouwbaar in kaart zijn gebracht en moeten de systemen die alle data bevatten aan elkaar gekoppeld zijn om een compleet beeld te maken.

Voor dat laatste punt geldt nog een extra uitdaging: uitvoering en controle gebeurt nu door dezelfde partij, wat ervoor kan zorgen dat men misschien niet snel aangeeft dat hun eigen werk slecht is uitgevoerd. Binnen Rijkswaterstaat wordt ernaar gekeken om de inspectiestrategie aan te passen, zodat dit soort grijze gebieden vermeden kunnen worden. Eigenlijk zou je willen dat de inspectie en het onderhoud twee losse activiteiten zijn die door verschillende partijen uitgevoerd worden.

Effecten:

Digitalisering heeft sowieso een positief effect op de beschikbaarheid van een asset, echter moet de capaciteit en kwaliteit aanwezig zijn binnen het bedrijf om hier mee om te kunnen gaan. Mensen moeten voldoende en juist opgeleid zijn. Digitaliseren zal helpen bij het onderhoud, asset management en beslissingen over het asset management te verbeteren. Digitalisering verhoogt de beschikbaarheid doordat het inzicht biedt in de werkelijke levensduur van componenten, waardoor hierop gestuurd kan worden. Bovendien kan het inzichten geven in dingen die je niet wist, wat positief en negatief kan zijn. Uiteindelijk zorgt het voor een hogere beschikbaarheid, omdat het er uiteindelijk voor gaat zorgen dat je kan acteren voordat falen op zal treden. Echter zal dit zijn op de lange termijn zijn, en niet direct na implementatie.

Interview 2

Het programma DGAM (data gedreven asset management) is een programma binnen het organisatieonderdeel PPO wat zich bezighoudt met het vakgebied van smart maintenance en data gedreven asset management. De programmadoelstelling van datagedreven assetmanagement is: als programma zorgen we dat de betrokken onderdelen van RWS, samen met de markt structureel kan werken met datagedreven assetmanagement.

Actoren

Asset Owner: Ministerie van Infrastructuur en Waterstaat

Asset Manager: Rijkswaterstaat

Service Provider: de markt (dit wordt per asset via een aanbesteding geregeld)

Aanpak

Er was 2017 t/m 2021 een programma, genaamd vitale assets, met als doelstelling beter inzicht te krijgen in de toestand van de assets is en om na te streven dat assets 'gezond' blijven, door correct en op het juiste moment onderhoud uit te voeren. Dit kan potentieel ook levensduur verlengend zijn. Dit programma richtten zich vooral op smart en condition-based maintenance en was meer operationeel van aard. Het programma is in 2022 veranderd naar het programma datagedreven assetmanagement, die zich ook richt op de tactische assetmanagement laag. RWS verbetert het assetmanagement om ook in de toekomst de netwerken kwantitatief en kwalitatief hoogwaardig te kunnen blijven beheren en onderhouden. RWS wil dit vakkundig en voorspelbaar doen met een centrale inrichting en sturing. Datagedreven assetmanagement helpt in deze opgave.

Méér datagedreven werken betekent in het assetmanagement gebruik maken van nieuwe IV-technieken (Denk aan de inzet van inwin-, verwerking-, analyse- en presentatietechnieken voor data uit en over de infrastructuur zoals sensoring, digitale 3D-modellen, data-analyses, algoritmes e.d.) en nieuwe databronnen (Denk aan gegevens uit SCADA-systemen, gegevens van aanvullende sensoren, gebruiksinformatie e.d.) waarmee sturing mogelijk is met een scherper zicht op prestaties, gebruik en conditie. Hiermee krijgen RWS en marktpartijen in de assetmanagement-keten de beschikking over nu nog niet beschikbare en meer actuele data over prestaties, gebruik en conditie van de assets. Data die gebruikt kunnen worden om de goede keuzes te maken in de verschillende stappen van het assetmanagementproces. Zo beschikken de managers en medewerkers in het assetmanagement over extra gereedschappen in hun werk, zowel voor de operationele, de tactische als de strategische assetmanagementprocessen.

Momenteel wordt ervaring op gedaan met datagedreven assetmanagement op zes "beweegbare" objecten binnen Nederland. Dit zijn sluizen, gemalen, beweegbare bruggen en tunnel.
De doelstelling van het programma is zorgen dat de betrokken onderdelen van RWS, samen met de markt, over twee jaar in staat zijn gesteld structureel datagedreven werken in het assetmanagement van natte kunstwerken, beweegbare bruggen en tunnels toe te passen, waarbij de toegevoegde waarde die datagedreven assetmanagement biedt kan worden gerealiseerd. De belangrijkste klantwaarde van het realiseren van deze doelstelling is ongeplande verstoringen (verrassingen) voor de gebruikers en opdrachtgevers verminderen door het creëren van extra sturingsmogelijkheden op prestaties, risico's en kosten van de natte kunstwerken, beweegbare bruggen en tunnels in de rijksinfrastructuur.

Uit audits van de afgelopen jaren is als resultaat gekomen dat de huidige aanpak van RWS voor assetmanagement minder professioneel is dan gedacht werd. Hiervoor is een verbetertraject gestart (AM2.0).

De ontwikkeling en verbetering van het assetmanagement programma 2.0 verloopt parallel aan de ontwikkeling van het datagedreven assetmanagement programma wat goed bij elkaar dient aan te sluiten. De uitdaging zit bijvoorbeeld bij de duur van de beide programma's. Deze zijn verschillend. Het doel is wel om de ontwikkelingen en resultaten uit het DGAM programma te laten integreren in het AM2.0 programma.
Het AM2.0 richt zich als eerst vooral op het strategische en tactische assetmanagement niveau. Het DGAM programma richt zich voornamelijk op het operationele en tactische assetmanagement niveau.

Implementatie Kreekraksluizen

De Kreekraksluizen is één van de zes assets waarbij gebruik ervaringen worden opgedaan met meer data gedreven werken/assetmanagement. Daarbij wordt gebruik gemaakt met van data uit de sluizen. Dit is data en het besturingssysteem van de sluis én additionele sensoren.

Het huidige onderhoudsregime richt zich met name op correctief en preventief onderhoud. De risico's worden berekend door een FMECA/ORA, op basis van failuremode, effect, criticaliteit en redundantie. Op basis van de uitkomst wordt besloten of welke beheersmaatregelen nodig zijn en of een onderdeel preventief of correctief wordt onderhouden en dit wordt altijd ondersteund door schouwen en inspecties.

Voor DGAM wordt in de basis ook de FMECA gebruikt, aangevuld met expert judgement, om te bepalen welke onderdelen in aanmerking komen voor het toestandsafhankelijk onderhouden en monitoren op basis van (sensor) data. Criticaliteit, MTTR en restlevensduur worden in deze afweging ook meegenomen. Hierin wordt ook een kosten-baten afweging gemaakt.

Afspraken

Binnen Rijkswaterstaat zijn er regionale organisaties en deze organisaties hebben de assets in deze regio onder hun hoede als asset manager. Daarnaast zijn er binnen Rijkwaterstaat nog een aantal landelijke diensten, zoals Programma's Projecten en Onderhoud (PPO). Dit is de link tussen de regio's als assetmanager (klant) en de markt als serviceprovider. Dit gaat met name over de invulling van de contracten (afspraken over o.a. kwaliteit van onderhoud) en het houden van technische gesprekken (o.a. technisch advies en omgevingsadvies) bij bijvoorbeeld storingen.

Digitalisering

De bottom-up aanpak die in het verleden gebruikt is, is een technologie push: er werden sensoren en technologie geïmplementeerd. Analyse van deze data gaf dan nieuwe inzichten. Er werd later wat er precies nuttig en relevant was (de baten). In de huidige aanpak (meer top down) werkt vanuit een informatiebehoefte: er word gekeken welke aspecten men zou willen monitoren en welke informatie relevant zou zijn. Vanuit die behoefte worden eventueel extra sensoren geplaatst. Primair is de informatiebron het besturingssysteem van een object. Hierin is al een grote hoeveel data beschikbaar. Er wordt ook gekeken welke data al beschikbaar is en wat de kwaliteit van deze data is. Daarnaast wordt op basis van o.a. de criticaliteit gekeken in welke onderdelen de meeste potentie zit voor datagebruik. Alle componenten worden tot het kleine niveau uit elkaar gehaald en alle potentiële faalvormen en effecten worden bekeken. Daarna wordt gekeken welke sensoren kunnen helpen om deze faalvormen te beheersen. Alle stappen worden door een multidisciplinair team vanuit RWS en de service provider gezet, eventueel aangevuld met externe partijen zoals leveranciers (OEM).

Nadat de juiste data voor het juiste doeleinde vergaard is, wordt de data gevisualiseerd in een dashboard. Er wordt ook een EWS toegevoegd, een Early Warning Systeem. Dit geeft aan wanneer een bepaald drempelwaarde overschreden wordt en er dus actie ondernomen moet worden. De drempelwaarde wordt bepaald op basis van beschikbare historische data, kennis en beoordelingen van experts en soms moet er eerst een storing optreden om te zien bij welke waarde een onderdeel faalt gaat.

Voorbeelden van sensoren in de Kreekraksluizen: bediening en sturing d.m.v. van een SCADA systeem, waaruit data ontsloten kan worden. Hiervan is een selectie gemaakt voor kritieke onderdelen. Verder zitten er nog specifieke sensoren in die geen onderdeel zijn van de bediening en besturing. Deze meten op energie, zoals stroomsterkte, spanning, weerstand, onbalans, etc. Voorbeelden van huidig conditie gestuurd onderhoud zijn: tijdig vervangen van vervuilde hydrauliek filters of het niet meer functioneren van een vetsmeringsysteem.

Output/Resultaten

In het assetmanagement wordt er meer gestuurd op risico, dan op prestatie. Er zijn afspraken gemaakt waarin de prestaties centraal staan (KPI's), maar die staan niet centraal in de sturing. De meting van bijvoorbeeld beschikbaarheid is daarom minder relevant voor het assetmanagement in de praktijk.

Voor beschikbaarheid wordt er ook gekeken naar passeertijden. De Kreekraksluizen bestaan uit twee sluiskolken en is daarom beschikbaar wanneer er slechts één open is om schepen te laten passeren. Echter worden de passeertijden dan langer omdat het drukker is. Daarom een de passeertijd een relevante KPI voor de beschikbaarheidsmeting van de asset.

Er zijn 6 assets waar datagedreven assetmanagement wordt toegepast. Door o.a. een community of practice worden lessen en verbeteren binnen het project aan elkaar doorgegeven, zodat collega's van elkaar kunnen leren. Dit vindt een keer per 3 maanden plaats. Er worden er van de 6 assets ervaringen uitgewisseld. Relevante externe partijen kunnen hier ook bij aanwezig zijn. Daarnaast wordt er documentatie opgesteld per kwartaal met implementaties en wat het opgeleverd heeft en worden de lessons learned opgehaald.

Interview 3:

De verantwoordelijkheden gaan met name over de vraag hoe data het systeem onttrokken kan worden en hoe het gebruikt kan worden, en hoe de beheerder daarin ondersteund kan worden. Het gaat met name om IA (industriële automatisering) systemen voor datagedreven asset management (DGAM). Het gaat om de werkzaamheden om de data in een dashboard zichtbaar te krijgen zodat een data analist of expert de analyses kan uitvoeren. IA systemen worden gebruikt voor het ondersteunen en zorgen voor goed onderhoud, beheer en operatie van objecten.

Actoren

- Rijkswaterstaat
- CIV: Centrale Informatievoorziening
- Projectteam DGAM
- Externe partijen: EnergyQ
- Onderhoudsaannemers

Afspraken

Er is een landelijke overeenkomst tussen RWS en de belangrijkste onderhoudsaannemers om na te denken over een landelijke aanpak voor datagedreven assetmanagement. De pilots waar de Kreekraksluizen een onderdeel van zijn, zijn bedoeld als startpunt voor dit landelijke beleid. De pilots zijn divers en de aannemers hebben diverse kennis en expertises. De pilots kunnen zo dus voor een beleid zorgen die past bij de diverse assets die RWS heeft en stimuleert kennis deling bij de onderhoudsaannemers zodat objecten beter onderhouden kunnen worden. Omdat er gewerkt wordt naar een landelijk beleid is er een afdeling (CIV) binnen RWS die beslist welke apparatuur er op de assets geplaatst wordt. Zeeland heeft veel sluizen en grote sluizen, dus ze lopen voorop voor het landelijke beleid.

Aanpak

De focus naar het gebruik van data in de onderhoudsaanpak ligt momenteel voornamelijk in het gebruik van de beschikbare SCADA data. Daarnaast zijn er wat energiesensoren geplaatst door een externe partij, EnergyQ. De SCADA is wel zichtbaar, maar wordt nog niet voor onderhoudstaken geanalyseerd.

Het projectteam DGAM bepaalt welke data uitlezen moet worden en waar de informatiebehoefte ligt. Het startpunt voor het bepalen van de informatiebehoefte ligt bij de onderdelen die het meest frequent falen, of waar de storingen het grootste effect hebben. Bovendien wordt er eerst gekeken naar welke inzichten verkregen worden met de sensoren die momenteel aanwezig zijn op de sluizen.

Een voorbeeld voor het inschatten of sensoren wel of niet gebruikt moeten worden ligt bij de haalkabels. Hier was de inschatting dat het risico en het daarbij horende effect te groot was als de kabels falen, dat de inspectie toch door een externe partij uitgevoerd blijft worden, in plaats van een sensor. Mocht de sensor verkeerd geplaatst zijn, of verkeerde informatie geven zouden de gevolgen erg groot zijn. Externe verantwoordelijkheden of risico delen spelen geen duidelijke rol in deze overweging. RWS is altijd verantwoordelijk in het geval van een defect want zichtbaarheid en imago zijn belangrijk.

Het feit dat RWS een overheidsinstantie is heeft voor- en nadelen. Aan de ene kant kan het beslissingsproces lang duren en is het plaatsen van bijvoorbeeld een sensor of IT systeem niet snel geregeld, omdat er veel afdelingen en mensen bij betrokken zijn. Aan de andere kant is het mogelijk om dit soort systemen snel aan te sluiten op het grote landelijke netwerk wat al aanwezig is, juist omdat het een grote landelijke organisatie is. Dit maakt uitdagingen omtrent cybersecurity makkelijker op te heffen omdat er al bij de bouw is nagedacht over beveiligingen rondom beveiliging, vanuit een landelijk beleid.

Om in te schatten welke sensor is nodig en wanneer die sensor rendabel is, wordt gekeken naar welke storingen vaak voorkomt en wat de effecten zijn. Er wordt gekeken of er kosten of tijd bespaard kan worden wanneer er een sensor geplaatst wordt. Hierbij is het belangrijk om ook te kijken naar de onderhoudsaannemer en of het plaatsen van een sensor voordelig is voor die partij.

Digitalisering

De grootste les die tot nu toe uit de pilot is gekomen is dat er veel meer data beschikbaar is dan wat er nuttig gebruikt wordt. Nadat alle beschikbare data en sensoren bekeken en de nodige data onttrokken wordt, is volgende stap om extra sensoren te plaatsen en meer, of de missende inzichten te creëren om zo voorspellingen te maken voor het onderhoud.

Andere effecten van digitalisering die merkbaar zijn is dat onderhoudsaannemers gerichter mensen naar storingen kunnen sturen omdat er sneller duidelijk is wat er kapot is. Bovendien komen er inzichten in welk preventief onderhoud precies nodig is, dus dat kan ook gerichter gestuurd worden. Zo zijn er minder mensen nodig en kunnen mensen met de juiste kennis en apparatuur op pad gestuurd worden. Bovendien is merkbaar dat mensen andere kennis nodig hebben. Onderhoud vindt steeds meer plaats aan de hand van data die via een computer inzichtelijk is, dus is het gebruik van een computer en kennis over IT dus steeds vaker noodzakelijk.

Data kwaliteit wordt nog niet gemeten aan de hand van vastgestelde eisen. Het gaat voornamelijk over de hoeveelheid, aanwezigheid en leesbaarheid van de huidige data. Bovendien heeft het bedienen van de asset prioriteit over het digitaliseren van de asset. Dit kan ervoor zorgen dat data dus niet volledig kan zijn, maar dat betekent niet direct dat het niet bruikbaar is. Data wordt wel met terugwerkende kracht geverifieerd na een storing door de te kijken of de data overeenkomt met wat er werkelijk is gebeurd. Daarnaast wordt deze data geanalyseerd om te kijken of deze storing in de toekomt voorkomen kan worden. Voor cybersecurity is er een complete set aan eisen en regelgeving, die strak worden nageleefd. Het doel is om alle data uit de asset eigendom van RWS te maken en via het netwerk van RWS te laten lopen.

Output/resultaten

Grootste effect van digitalisering is een betere bewustwording van de status van de objecten. Daarnaast maakt data het mogelijk om objecten sneller en beter te analyseren. Dit is voornamelijk van toepassing op assets die op afstand bestuurd worden en waarbij het dus lastig is om bijvoorbeeld afwijkende geluiden of bewegingen op te merken door de bestuurder. Een sensor zou dit wel kunnen, en kan early warnings geven.