Master's thesis

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

Ane Johnsgaard

Evaluation of Asset Performance

A study of Required Function, Maintenance and Operational History

Master's thesis in Engineering and ICT
Supervisor: Per Schjølberg
Co-supervisor: Jon Martin Fordal
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Preface

This Master's Thesis concludes the master's degree in Engineering and ICT, with the main profile ICT & Operation Management at the Norwegian University of Science and Technology (NTNU) in Trondheim. It was written during the spring of 2021 for the subject TPK4950 (Reliability, availability, maintainability and safety, master thesis). This thesis is part of the Faculty of Engineering (IV) and the Department of Mechanical and Industrial Engineering (MTP). The thesis was written in collaboration with Hydro Aluminium and was supervised by Per Schjølberg (Associate professor, MTP) and Jon Martin Fordal (PhD Candidate, MTP) from NTNU.

Acknowledgement

While concluding this thesis, there are several that deserve to be acknowledged. Throughout this period, I have received lots of support and assistance.

I want to thank my supervisor at NTNU, Per Schjølberg, along with Hydro Aluminium, for giving me the opportunity to work on this project. Thanks to both Arnt Johnsen and Per Gullaksen for making this possible and your input during the process. Thank you to my supervisor and co-supervisor, Jon Martin Fordal, for their guidance and input.

To the employees in Hydro, I would like to thank you for answering my questions. A special thanks to Torleif Berg for checking in with me every week and helping me with what I needed. Thanks to Sondre Norhaug for answering all my questions. It is very much appreciated. Thank you to my fellow students for making these five years memorable. My family and friends deserve a thank you for all their support and motivation during these years in Trondheim. To my sister, Maiken, thank you very much for proofreading my thesis and for all your support. Thank you to my parents for all the comforting words. To Birgitte, thanks for the motivation throughout these last weeks. Lastly, thanks to Jørgen for always listening and for all your encouragement.

Ane Johnsgaard

Ane Johnsgaard
Trondheim, 10.06.2021

Abstract

This master thesis laid the foundation for evaluating the asset performance in production facilities for the purpose of continuous improvement, decreased downtime and reduced profit loss. The performance of the assets is important for the overall business performance. Through measuring and evaluating the performance of the assets, the current situation could be better described, "siloes" minimised, and better decisions made. By integrating the available data, it is possible to monitor the performance of the assets continuously. However, there is a gap between the theoretical concept of asset performance and the implementation in ageing production facilities. The data available for assessing the performance is not previously indented for this task, causing the realisation of mapping the condition and current performance of a system a complex task.

To address this, a literature search and a case study were completed. The available maintenance and operational history were analysed to evaluate the required function of a transportation line for carbon anodes at Hydro Aluminium's carbon production facility in Årdal. The transportation line consists of an overhead conveyor, a roller conveyor and an automated storage, and the lack of control of the system is expanded. The transportation line transport and store anodes between the green mill, where the anodes are moduled, and the furnaces, where the anodes are baked before aluminium production. Through this analysis, including system and data analysis, critical areas of the transportation line were identified, and the effect of failures and following maintenance actions was visualised. When evaluating the required function of the system and analysing the available data, the lack of control over the system was identified, and the need for better monitoring of the system was highlighted. Through utilising condition data from the system, the function and performance of the assets can be continuously monitored.

From this mapping of the current state of the transportation line, critical areas of the transportation line were identified. These areas influence the total performance of the transportation line, and concrete improvement measures at these areas could raise the overall performance. From implementing integrated systems to monitor the current condition of the assets continuously, steps towards improved performance and condition could be made. New technological solutions would visualise the need for improvements. Future research should include how continuous monitoring would improve the performance in the long run and look further into closing the gap between the research performed and the current condition at different facilities. By integrating the divisions of a company, the overall performance will improve.

Samandrag

Denne masteroppgåva legg eit grunnlag for å evaluere tilstanden på utstyret i eit produksjonsanlegg. Dette vert gjort for å jobbe med kontinuerlig forbetring, samt for å redusere nedetid og minimere produksjonstap etter uventa hendingar. Tilstanden på utstyret er viktig for den overordna prestasjonen til bedrifta. Gjennom å måle og vurdere tilstanden kan ein beskrive situasjonen betre, fjerne "siloar" og fatte betre avgjerder. Ved å knyte saman det dataet ein har tilgjengeleg på utstyret kan ein kontinuerleg overvake tilstanden. Vidare er det ofte identifisert eit gap mellom dei teoretiske konsepta knytte til dette emnet og det å setje det ut i live på eksisterande og aldrande fabrikkar. Dataet som er tilgjengeleg for å evaluere tilstanden er i utgangspunktet ikkje tiltenkt denne oppgåva. Som følge av dette vil det vere ei større utfordring å få kartlagt både tilstanden og ytinga på utstyret.

Både ein litteraturstudie og ei konkret problemstilling vart undersøkt for å sjå nærmare på denne utfordringa. Transportanlegget for karbonanodar ved Hydro Aluminium sin karbonfabrikk i Årdal vart valt som eit område å sjå nærmare på. Denne transportlinja består av både ei hengebane, ei rullebane og eit automatisert lager for å frakte og lagre anodar mellom massefabrikken, som formar anodane, og anodefabrikken, som bakar anodane klare for aluminiumsproduksjon. Utfordringar knytte til at ein ikkje er klar over tilstanden og dermed manglar kontroll på dette anlegget, er utbreitt. Den tilgjengelege vedlikehaldshistorikken og produksjonsdataet knytte til transportlina, vart analysert for å identifisere område av linja som er meir kritiske, samt følger av feil og påfølgande vedlikehald som må utførast. Analysen inkluderer både ein systemevaluering og analyse av det tilgjengelege dataet. Dette vart vidare knytt til evaluering av den kravde funksjonen til anlegget, som synleggjorde mangelen på kontroll av anlegget og behovet for å overvake tilstanden på systemet betre. Gjennom å bruke tilstandsdata direkte frå systemet kan både funksjonen, tilstanden og prestasjonen av utstyret bli kontinuerleg overvaka.

Frå denne kartlegginga av noverande tilstand på transportlinja er spesifikke område identifisert som meir kritiske enn andre. Dette påverkar totalintrykket av ytinga på linja, og kan truleg forbetrast med konkrete tiltak. Ved å implementere integrerte system som synleggjer tilstanden på utstyret kontinuerleg får ein visualisert problema, og tiltak kan setjast i verk tidlegare. Frå denne kartlegginga av noverande tilstand, kan ein byggje steg for steg vidare til ei auka yting og forbetra tilstanden på utstyret, samt ta i bruk nye teknologiske løysingar for å synleggjere kvar forbetringar må gjennomførast. Vidare forsking bør inkludere korleis kontinuerleg overvaking påverkar tilstanden på sikt, i tillegg til å sjå vidare på korleis gapet mellom forskinga og tilstanden rundt om i fabrikkane kan minimerast. Ved at dei ulike avdelingane i bedrifta jobbar saman, kan den overordna prestasjonen bli forbetra.

Contents

List of Abbreviations

ACM	asset condition management
AI	artificial intelligence
ALCM	asset life cycle management
AM	asset management
AMMP	asset maintenance management process
ANN	artificial neural network
AP	asset performance
APM	asset performance management
BD	big data
CM	condition monitoring
DM	data mining
DMT	Digital Maintenance Toolbox
DT	digital twin
ERP	enterprise resource planning
FIFO	First In, First Out
HSE	health, safety and environment
IoT	Internet of Things
IT	information technology
IV	Faculty of Engineering
KPI	key performance indicators
MES	manufacturing execution system
ML	machine learning
MTP	Department of Mechanical and Industrial Engineering
NLP	natural language processing
NTNU	Norwegian University of Science and Technology
OEE	overall equipment effectiveness
OT	operations technology
PAM	physical asset management
PdM	predictive maintenance
SAM	smart asset management
SCADA	supervisory control and data acquisition
SM	smart maintenance
SMDSS	smart maintenance decision support system
TDL	trusted data layer
TLP	technical language processing
VDM	value-driven maintenance

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1 Introduction

Asset performance (AP) is a relevant topic for asset-intensive companies today. With the ongoing digitalisation and the new possibilities arriving, the need to evaluate the assets' performance has arrived. Implementation of Industry 4.0 technologies has the positive benefits of *"improved productivity and asset performance, reduced inefficiencies, lower production and maintenance cost"* [1]. The Standardisation Roadmap of Predictive Maintenance for Sino-German Industry 4.0/Intelligent Manufacturing indicates that assessment and monitoring of the equipment and the assets are needed for assuring efficient production and minimising unplanned downtime, which is essential for remaining competitive [2].

A survey conducted in over seventy Swedish companies by Bokrantz, Skoogh and Ylipää, in 2016, concluded that there is considerable potential in using engineering tools and methods during operations to achieve high equipment performance. The study discovered that analysing the available data is a non-prioritised task, leading to a lack of understanding of failure occurrence and consequences. By prioritising this, there is a potential of identifying profit losses, which is required for increasing the performance and an essential part of the current digitalisation [3]. This is confirmed by Campos, Sharma, Jantunen, Baglee and Fumagalli while highlighting the need to improve decision making by basing it on the collected data. The machines' existing data or other maintenance and production systems could improve the asset management process. The problem is that the data is not taken to use [4]. Making it possible to base maintenance decisions on the available data is also elaborated by Bumblauskas, Gemmill, Igou and Anzengruber [5].

Norsk Hydro is currently on the journey towards utilising their data for continuous improvement. In Årdal, a carbon anode production facility produces aluminium for Hydro Aluminium's aluminium facilities. Carbon anodes are necessary for the production of aluminium for conducting electricity. Like many other ageing production facilities, there is a need to control the assets' performance. The product being produced has been getting the attention, and the connection between a well-functioning asset performance system and the ability to save money on maintenance and operations has been overlooked [6]. If possible, to use the available data, decisions would be made on the proper foundation and not the familiar gut feeling. A basis for asset performance evaluation could be made by analysing the transportation line's required function and the available maintenance and operation history. When gaining control over the performance of the assets, the production efficiency could increase and the profit losses reduced.

1.1 Background

How to gain control over the assets and evaluate their performance is central to this thesis. Parida concluded already in 2012 that most industries lack a proper asset management strategy [7], and it has been better understood in the following years due to the rapid digitalisation. Spüntrup and Imsland stated in 2018 that different prognosis and optimisation technologies combined with an asset management strategy is crucial to improve the performance of the assets in the process industry for the future [8]. Wang, Chen and Parlikad identified the importance of connecting asset management performance and business performance, especially for asset-intensive production companies [9]. This is confirmed by Maletic et al., stating that physical asset management has a *"statistically significant impact on operational performance"* [10].

Lukens, Naik, Saetia and Hu point towards the quality of the maintenance data being an obstacle for industrial companies when wanting to take their maintenance data to use for the new technologies and data-analytics possibilities, to increase their overall performance [11]. Therefore, it is relevant to find ways to apply the maintenance history and operational data to evaluate the performance of the assets. New analytical methods are dependent on available data, and to be able to connect the asset performance to the business performance, the asset condition must first be found. It is indicated that in addition to the new technology, the people-relied factors [12], the management process, and the reliability-engineering provides a crucial part in enlarging the performance of the assets [13]. Thus, these aspects must also be considered when finding ways to measure the performance of the equipment.

The three-round Delphi survey with 25 maintenance experts conducted by Bokrantz, Skoogh, Berlin and Stahre in 2017 identified that *"data analytics, interoperable information systems, big data management, emphasis on education and training, fact-based maintenance planning, new smart work procedures, and maintenance planning with a system perspective"*, will influence the maintenance organisations by 2030 [14]. Lundgren Skoogh and Bokrantz indicated that to keep up with the digital change, including the new technologies and the more complex systems, the maintenance department must take a vital role in this process, which will reduce risks and consequences of unplanned downtime [15]. In light of this, the combination of asset performance and maintenance is essential. Bradbury, Carpizo, Gentzel, Horah and Thibert also point to the need for looking beyond the aspect of predictive maintenance to see how the digital and analytical tools are helpful for the entire organisation [16]. Hence, asset performance evaluation based on the available data could be seen as the first step towards incorporating the digital shift, improving the overall performance towards the assets and the maintenance organisation and overall business performance.

Maintenance is an essential part of digital change and the key to eliminate risk and reduce downtime affecting production efficiency. Condition monitoring of the assets is a course made possible by digitisation, which connects the aspects of asset performance, and maintenance [2]. De la Fuente, González-Prida, Crespo, Gómez and Guillén point to asset management, performance assessment, and monitoring of systems as an essential subject in scientific literature and industrial companies. This is due to more complex equipment and production processes, technological development and the continued focus on cost reductions, high quality, sustainability and improved safety. Greater focus towards the evaluation of the assets could give a competitive advantage [17]. The different factors creating a background for the problem statement is visualised through Figure 1.

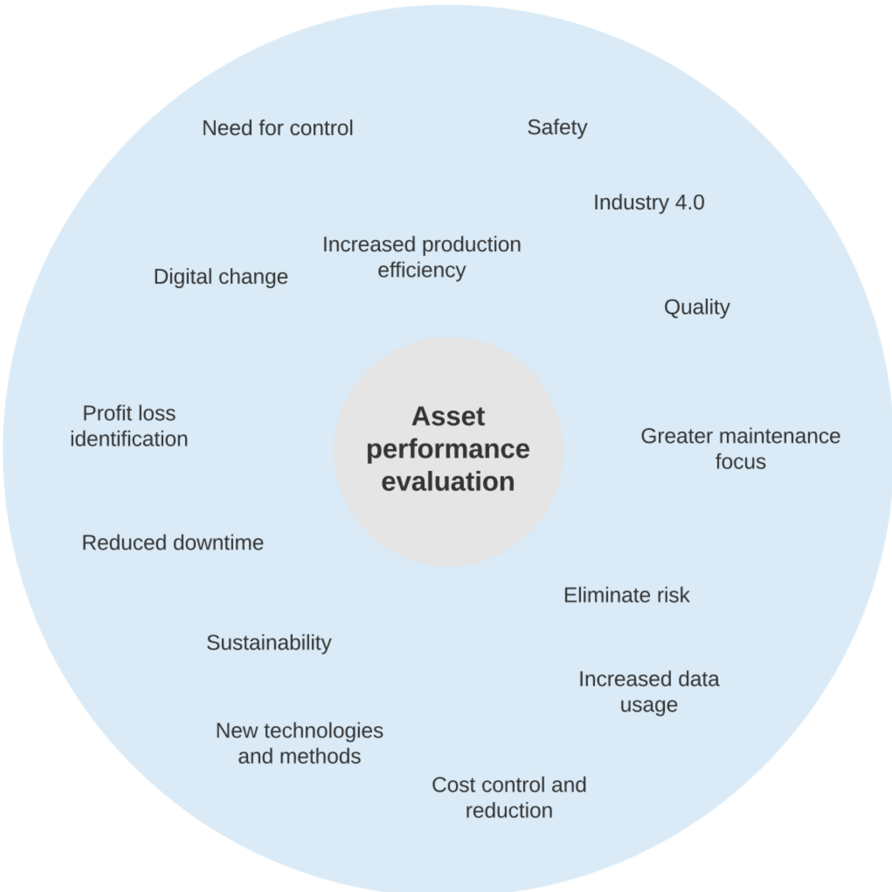

Figure 1: Background for problem statement

In light of Hydro's commitment to sustainability, related to the performance, the environment and climate, the local communities, the business integrity and the health and safety, the evaluation of the current performance is critical [18]. If a system can perform better, last longer, require fewer spare parts, and not hinder the production process, this will affect the sustainable footprint. There are several examples of accidents occurring due to the equipment and the maintenance, such as the latest incident in Norway, the fire at Equinor's facility in Hammerfest [19]. This shows the need to control the asset and the processes and make sure that maintenance actions and plans align with the current condition. The Norwegian Ministry of Local Government and Modernisation points to the need for exploiting the available data as an essential resource, the possibilities of using new technologies for utilising the available data in a better way and the potential for more value through applying and sharing data throughout the value chain [20].

The issue is how to use what the scientific literature says about asset performance and adapt it to an existing production facility with complex ageing systems and present digital solutions. Bumblauskas et al. identify a lack of scientific literature on systems where data is used for physical asset management and maintenance [5]. The Standardisation Roadmap of Predictive Maintenance for Sino-German Industry 4.0/Intelligent Manufacturing also indicates a gap between the theoretical and practical application of the new technologies introduced by the fourth industrial revolution [2]. Chin, Varbanov, Klemeš, Benjamin and Tan point to a lack of literature considering the overall life-cycle of the asset and limitations related to oversimplifying assumptions related to the lifetime and the condition of the assets [21]. The hiatus between maintenance research and industry practises is also identified by Lundgren et al. [15]. Hence, a case study utilising the maintenance and operation history and analysing the required function of a system could cut this gap while interpreting the case study results in light of the available scientific literature.

1.2 Problem statement

The purpose of this master thesis is to evaluate how monitoring of asset performance and condition is helpful for detecting areas of improvements, detecting profit loss, and improving production efficiency. The system of analysis is the transportation line between the green mill *(massefabrikken)* and the bakehouse *(brennovn)* at the carbon facility at Hydro Årdal. After being moduled, the carbon anodes produced at the facility goes through the transportation line before reaching the furnace. There is no overview of the condition and performance of the transportation line. There is no way to be aware of the transportation line's status before it causes a delay in production. Lack of insights leads to financial loss, and improvement in this area is much needed. Through analysing the current state of the transportation line and the maintenance performed, presenting improvement measures and gaining insight into the transportation line's performance, the thesis should present a possible future state where asset performance is crucial.

1.3 Research questions

The scope of this master thesis is prepared in collaboration with the supervisors, the representatives from Hydro, and the author of this thesis. From the problem statement, the research questions listed below are established to explore the problem.

- **Question 1:** How can analysis of asset performance be useful for detecting areas of improvement, detecting profit loss and improving production efficiency?
- **Question 2:** How can the transportation line of anodes from the green mill *(massefabrikken)* to the furnaces *(brennovn)* at the carbon facility at Hydro Årdal be improved with asset performance analysis?

1.4 Research objectives

The problem statement of the master thesis is divided into research objectives that correspond to the research questions. The goal is to answer the research question by performing the research objectives and the problem elaborated. Researching and presenting relevant theories regarding the topics are a crucial part of the thesis. The theory will be used as a basis for the case study presented by Hydro. Meetings and discussions with different employees in Hydro will be an essential part of the work with the case study, together with the author's earlier experience from working at the production facility. Analysis of relevant data regarding the area of study is crucial for getting an understanding of the situation. The research objectives are listed below.

- **Objective 1:** Discuss how asset performance and condition monitoring can affect productivity, efficiency and minimise profit loss
- **Objective 2:** Present the current state of the transportation line, related to production, maintenance and costs
- **Objective 3:** Analyse how the transportation line meets the required function
- **Objective 4:** Identify areas of improvement and their effect on the production, the profit losses and the asset performance
- **Objective 5:** Present the future state for getting better insight into the transportation line's performance

All objectives will be necessary for both research questions. The first objective will answer the first research question. In combination with the first objective, the second and third objective build the foundation for the fourth objective. This leads up to the fifth and final objective, which answers the second research question. The relationship between the research questions and the research objectives is shown in Figure 2.

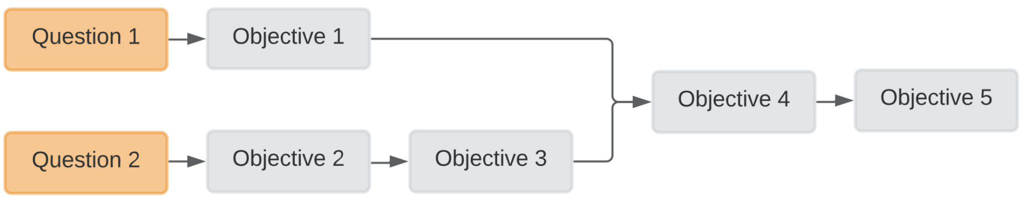

Figure 2: Relationship between research questions and research objectives

For the first objective, a literature review and presentation of the relevant theory is crucial. Questions as to what and how to measure performance and the usefulness of the results are essential. Information related to the production facility, the system for evaluation and maintenance and operations information is relevant for the second objective. To reach the third objective of the thesis, both system analysis and an analysis of relevant data of the transportation line is essential. The transportation line needs to be defined, and the architecture of the transportation line must be analysed. The relationship between required and delivered function is to be found. For the fourth objective, data analysis of the available data is necessary for gaining insight into the actual status of the transportation line. Based on the system analysis and the data analysis, the fifth objective aims to answer how to get a better insight into the transportation line.

1.5 Limitations

Some limitations could affect the result of this master thesis. The scope is limited to the research questions and research objectives presented in Section 1.3 and Section 1.4. The thesis is tied to the case study from Hydro. The results found are therefore not directly transferable to other situations and companies. The methods and relevant theory are, on the other hand, universal and is therefore useful in other situations. The problem and research objectives for this thesis revolve around capturing the transportation line's current status analysed to say something about the performance of the assets. Suggestions and possible improvements based on the current status and the theoretical background are presented. It would be beyond the scope of the thesis to investigate the details and implementation of a continuous asset performance monitoring system. The development of such a system could be based on the results highlighted by analysing the current status of the transportation line. This goes beyond the intention of this thesis.

The period for this thesis is the spring semester of 2021. The project start was set to 15.01.2021, while the delivery was set to 10.06.2021. This gave a 20 weeks long project period, and the thesis execution was limited to this period. The ongoing Covid-19 pandemic affected this master thesis largely. Due to the virus, physical communication was limited. The project meetings had to be completed digitally. The virus also made it impossible to perform company visits at the industry partner. For most of the thesis period, it was recommended to work from home.

1.6 Report structure

This master thesis consists of the sections listed below, as well as this introductory section and the appendix.

- **Section 2:** Methodology
- **Section 3:** Theoretical background
- **Section 4:** Case study introduction
- **Section 5:** Case study results and analysis
- **Section 6:** Discussion
- **Section 7:** Conclusion

Section 2 describes the methodology of the thesis. Both a literature review for gaining the theoretical background and a case study will be conducted. Section 3 presents the relevant theory and Section 4 gives an introduction to the case study. The results and analysis of the transportation line investigated are found in Section 5. The case study results are discussed in light of the theoretical background in Section 6, before the conclusion of the thesis is presented in Section 7. Lastly, the references and appendix are found. In the appendix, the extensive results from the analysis of the transportation line and the scripts for the data analysis are included. The overall report flow is shown in Figure 3.

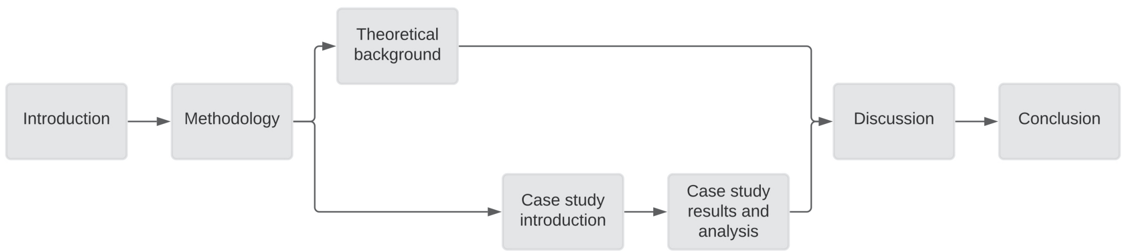

Figure 3: Structure and progress of report

2 Methodology

A literature review and a case study were completed to address the problem of this master thesis. This section answers how the research questions and research objectives were addressed and described how data was gathered, analysed, and quality assured. Both qualitative and quantitative methods were used. This triangulation of methods, where qualitative and quantitative methods are combined, strengthens the results and makes it possible for the two directions to fulfil each other. The topic of asset performance was chosen due to the increased focus on the subject from the industry partner. The case study was selected due to this particular system being a part of the production facility associated with significant consequences due to breakdowns, in addition to being an area where no previous improvement project was initiated. An overview of the research methodology is given in Figure 4. The actions were supported by information from discussions and talks with employees in Hydro and the author's background knowledge from working experience in Hydro. The theoretical background gained from the literature review is essential for interpreting the results from the following system analysis and data analysis as part of the case study. The following sections describe the different methods further.

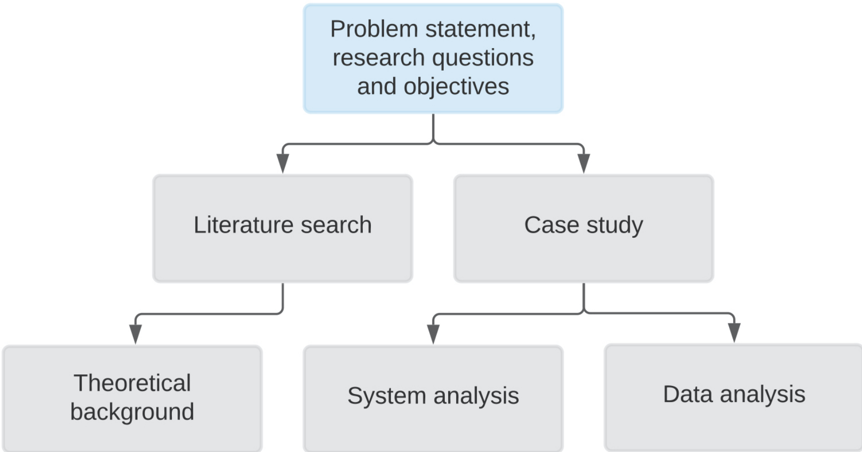

Figure 4: Overview of the research methodology

2.1 Literature search for theoretical background

A literature search was conducted to create a theoretical background of relevant aspects of the problem. This background was necessary for identifying improvements and a future state for the case study. Since performing a literature search is a qualitative method, where interpretation is based on the literature itself, it was necessary to consider credibility, transferability, and conformation. A literature review is an essential research method to keep up with the current research and works as a foundation for all types of research. The literature then serves as the background for future ideas and directions in the field [22].

The literature search was conducted through different databases for scientific literature and Oria, NTNU's collections. ScienceDirect, Google Scholar, Scopus and Web of Science have all been used to gather relevant literature. The focus was on newer literature from the last couple of years to restrict the search results and ensure that the newest information on the topics was included, as this is vital due to the industry's current rapid change and development. The chosen academic literature and research papers were required to be peer-reviewed to ensure high quality and validity.

In addition to academic literature, papers from different actors established in the industry were included to ensure that the current situation in the industry was considered. A breach between the theoretical solutions and the status around in different production facilities is identified, and the degree of digitalisation and technological development does not always correspond [2]. Therefore, it is vital to include the industry's point of view for better insight into the current situation in production facilities. These articles capture the issues, and current status in the industry and have therefore been necessary for the topics of this report. The different standards published on the topics was also an essential part of the theoretical background of this thesis.

When performing the literature search, several search words were used. These were both combined and filtered with logical operators, such as *and*, *or* and *not*. The search was narrowed to the five latest years. In addition to these searches, references and cited articles from articles that fulfilled the search criteria were searched. Search words used were among others: *asset performance, asset management, asset performance management, asset analysis, maintenance, maintenance analysis, maintenance history, smart maintenance, digital maintenance, condition monitoring, industry, process industry, profit loss* and *system analysis*.

2.2 Case study

The second part of this thesis, the case study, had the transportation line from the green mill to the bakehouse at the carbon facility at Hydro Årdal as an area of analysis. This study was performed to analyse the transportation line itself and analyse available data associated with the line. This information was supported with information about the transportation line and area from Hydro's internal systems, discussions with Hydro employees, and information gathered during the period the author worked at the facility.

Using a case study as a research method was necessary to include the complexity of the chosen case, including planning, management, analysis, and writing. The key to case studies is to understand the case analysed, and therefore it was essential to keep in mind that a case study is unique, and therefore generalisations are hardly found. Through the case study, better insight into a topic may be found [23]. Case studies are often used when questions as *"how"* and *"why"* needs to be answered, as the case was in this situation. The type of research data used varies between the different studies, but it is essential to see the analysed data in context to understand the case overall. The research method allows gathering lots of data for gaining a thorough insight into the case chosen [24].

2.2.1 System analysis

To understand the system for examination, the transportation line, a model of the system had to be established. Visualisation of the transportation line was crucial for realising the connections between this system and the rest of the facility and the different components in the transportation line. A model or a visualisation of the transportation line makes it easier to answer the questions about the system. System block diagrams help to understand the role of the different assets [25].

The International Standard ISO 15288:2015 defines system engineering as an *"interdisciplinary approach governing the total technical and managerial effort required to transform a set of stakeholder needs, expectations, and constraint into a solution and to support that solution throughout its life"* [26], and the concept is relevant when studying a complex system for evaluation of its performance. In line with this standard, it is necessary to identify assumptions, perform system analysis, review the results and use this with the recorded results as a basis for recommendations [26]. When preparing for the system analysis, it was essential to identify and define problems, questions, stakeholders, scope, objectives, methods, strategy and plan for the system analysis [26]. The needed data for the analysis could then be collected.

The standard NORSOK Z-008 *(Risk-based maintenance and consequence classification)* perform consequence classification in line with ten steps. This includes investigating the technical information and input from other analysis, which is used to identify the system's main function and sub-functions. Redundancy and consequences are then assigned both for the main and sub-functions. The final steps include mapping the system's function to the equipment executing this function [27]. The same steps were necessary when analysing the system of this case study.

An architectural framework of the system would establish *"a common practice for creating, interpreting, analysing and using architecture descriptions"* [28]. For visualising the architecture of the system, a combination of different diagrams was taken to use. An analysis of the required function of the system was also a part of the system analysis. Different parameters were then analysed using a table utilised in Hydro. The table is developed to understand the function of the different systems better when working with improvement measures.

To understand the relationship between the system's functional architecture and physical architecture, both the functions and components of the system had to be identified. When analysing the function, it was essential to identify the functions provided by the system, while the physical architecture should answer how the system can perform those functions [29].

The data used for the system analysis was descriptions of the transportation line and the components from Hydro's internal systems. The technical hierarchy from Hydro's enterprise resource planning (ERP) system, *SAP PM*, was used to identify the different components in the transportation line. These technical hierarchies are shown in Appendix A. The data analysis supported the system analysis and architecture definition, bringing crucial information for the required function analysis. By understanding the transportation line, creating diagrams of the systems, analysing the functional and physical architecture, and analysing the required function of the transportation line compared to the given performance, the system analysis was completed.

2.2.2 Data analysis

The process of data analysis started with deciding on what to analyse and how to perform the analysis. In light of the problem statement and the case study, the question of what was already explored. All the available data had to be analysed to support the system analysis. The data had to be collected and cleaned before the visualisation of the data in combination with the system analysis could be interpreted in light of the theoretical background. By analysing the available data related to the transportation line, decisions could be made on relevant information, instead of the typical gut-feeling [25].

The data used for the data analysis was obtained from *SAP PM* [30], where maintenance records of all the maintenance orders completed on the transportation line were recorded for over the last twenty years. Information such as cost of the repairs, duration of the repairs, description of problem, priority, and cause related to each functional location is found. The data was collected from the system in excel sheets. First, the technical locations of the different components in the transportation line had to be obtained, and through different searches in the system, the wanted data and needed information were acquired. Secondly, the data then had to be cleaned and systematised. The focus of the analysis was limited to the last ten years. This was performed through short scripts written in the programming language *Python* [31], where the data analytics library *pandas* [32] and the mathematical library *NumPy* [33] was crucial. For visualisation of the data, the visualisation library in *Python*, *Matplotlib* [34] was used. The scripts for the data visualisation are found in Appendix C, and further details about the analysis and the results of the analysis are found in Section 5 and Appendix E. Additional data for support and to identify production losses was also obtained and analysed in the same way. Downtime and stop registrations was extracted from Hydro's manufacturing execution system (MES) system, *APICS*. Records of production setbacks were located from an excel sheet used for recording this. Introductory, the plan was also to include data from the supervisory control and data acquisition (SCADA) systems for measuring the performance, but the appropriate data was not available. The details about the data analysis are further described in Section 5.3.

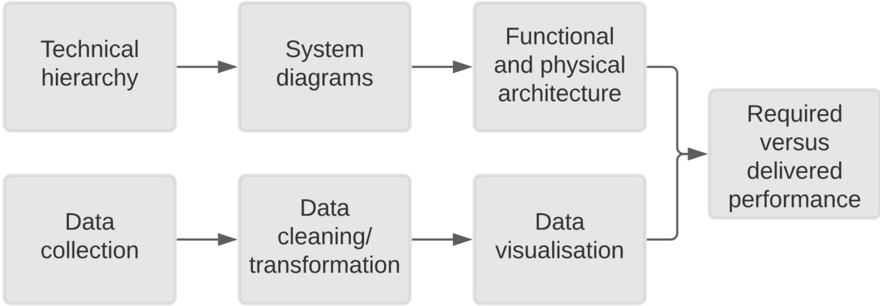

Figure 5: Overview of the system and data analysis

To summarise the methodology of this paper, both a literature search and a case study was performed. The case study was completed through several steps, visualised in Figure 5. An understanding of the transportation line was established by analysing the technical hierarchies, building system diagrams, analysing the functional and physical architecture, and finally looking further into the required performance and function of the transportation line. The data was then captured, cleaned, transformed, and visualised to map the transportation line's current situation and make it possible to identify problem areas and possible improvements in light of the literature search. The literature search and review results are presented in the next section before the case study, and its results are elaborated.

3 Theoretical background and previous research

As described by Wang, the asset performance (AP) will in asset-intensive production companies directly determine the performance of the business [9]. It is therefore essential to have a clear overview of the performance of the assets. A literature search was conducted to gain a theoretical background and an understanding of the relevant concepts, theories, and methods. This theoretical background is needed for combining different theories and as a basis for interpreting the results of the case study. Definitions of the important terms are included, as well as previous research and possible solutions. This chapter presents the concept of AP, looks closer to digital development and its contribution to AP and connects the concepts of AP and maintenance.

3.1 Asset management and asset performance

Asset management and AP are essential for the future. Through the theoretical model presented by Lima, McMahon and Costa, the link between asset management and business performance is elaborated. Knowledge of how investments in assets could lead to better business performance caused by the increased asset performance is the reason for the increased focus on asset management in the industry. The direct link between overall company performance to investment is essential for companies needing reasons behind their investments. If the right information is presented for decision-making, linking the goals of the company to the potentially increased asset performance, a better decision could be made [35]. In the following sections, asset management and asset performance will be further defined before the connection between them are drawn.

3.1.1 Asset management

Asset management (AM) is from the International Standard ISO 55000:2014 defined as the *"coordinated activity of an organisation to realise value from assets"* and includes the task of finding the right balance of *"cost, risks, opportunities and performance benefits"* [36]. An **asset** is defined as *"an item, thing or entity that has potential or actual value to an organisation"* [36]. The benefits of AM include, among others, improved financial performance, informed decision making, risk managing, and improved sustainability, efficiency, and effectiveness. The fundamentals of the concept are value, alignment, leadership, and assurance. An asset management system is described to include a context of the organisation, leadership, planning, support, operation, performance evaluation and improvement. The standard defines that *"the organisation should evaluate the performance of its assets, its asset management and its asset management system"* [36].

Data management, data transformation, monitoring, analysis and continuous evaluation of asset data is presented as necessary for AM. By monitoring the performance of the assets, improvement measures will be directly identified. Relevant activities for obtaining asset information is data management, condition monitoring (CM), systems engineering, value management and availability, reliability and maintenance support [36]. The goal of AM is described as *"to enable an organisation to realise value from its assets as it pursues its organisational objectives"* [25]. While working for an asset management strategy, the risk of getting communication issues between the different divisions in a company, such as operations and maintenance or between maintenance and management, is reduced. To understand the condition and the value of the assets in an organisation, all the different elements of the organisations must work together [25]. The process and elements of an asset management system are described in Figure 6, where plans, policies, objectives, implementation and the assets themselves lead to the performance evaluation, which identifies AM as the foundation for further asset performance.

A study published in 2020 examines how the physical asset management (PAM) practises influence operational performance through analysing survey data from 138 organisations. The core practises of PAM was identified to be strategy and planning, risk management, life-cycle delivery, asset information and asset review. A conceptual framework linking PAM and operational performance was developed. The study shows that the PAM practices have a *"statistically significant impact"* on operational performance and that companies benefit from focusing on asset management. It is also shown that AM affects the company's sustainability positively, both in the short and the long term, due to both the performance and the operations becoming more sustainable [10]. By focusing on the assets, more value could be extracted throughout the lifetime. These findings link AM with asset performance, leading up to the definition of AP in the next section.

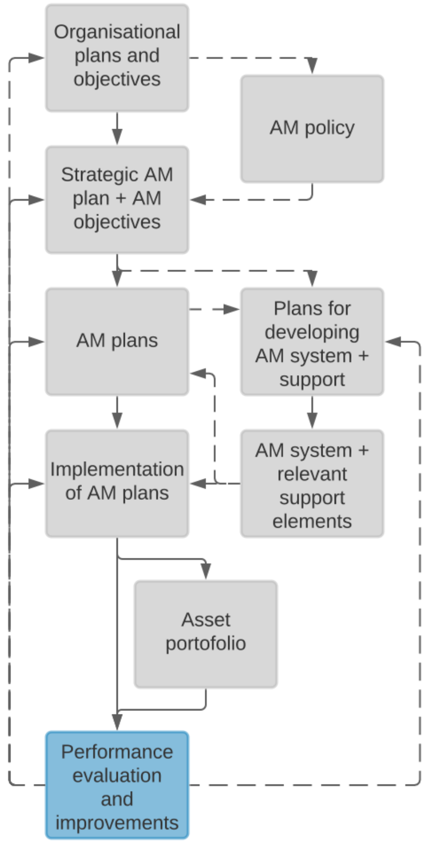

Figure 6: Key elements of an asset management system

Source: Adapted from [36]

3.1.2 Asset performance

ISO 55000 defines **performance** as *"measurable results"*, and in the context of AM, performance is related to *"assets in their ability to fulfil requirements or objectives"* [36]. In the International Standard ISO 55001:2014, the performance evaluation is further described. It states that an organisation must determine what and when to monitor and measure, which methods to use and when to analyse and evaluate the results from the performance evaluation. The standard also elaborates on establishing criteria for the required processes and gaining control over the process in line with these criteria. By gaining control over the process and monitoring the assets, both corrective and preventive actions related to failures in asset performance could be performed to work for continuous improvement related to both sustainability and effectiveness [37]. As a result of this, AP is a central part of an improvement process, and the details related to how to incorporate it into the organisations must be solved.

Parida confirms that *"performance needs to be measured for managing technical asset throughout its entire life cycle"* [7]. Assessment of asset performance is crucial for a company's economic and business aspects, and more companies utilise measurement of their asset performance in their business objectives and strategies. The article reflects on several issues related to asset performance. It is a complex issue with several factors, and there is a lack of integration between *"stakeholders and their changing requirement in strategic performance assessment"* [7]. How to assess the performance of the assets is also an essential aspect of the issue. Operation and maintenance cost are noteworthy in asset-intensive industries, making it more important to keep track of investments on assets to reach business requirements [7].

In the International Standard ISO 55002:2018, AP is set as an objective for AM. It is crucial to monitor the assets that could affect the value of the organisation. Both the technical, operational and financial aspects are important when evaluating performance. The decision-making methods, given criteria, risks, and opportunities are vital when deciding upon what, when and how to monitor assets. Performance monitoring could be used to identify patterns, provide needed information for decision-making, setting performance metrics, and require the needed information about the accurate status of the assets. When working towards an AP activity, it is important to identify failures and failure modes of the assets, provide sufficient information, look into detectability, research the historical evidence, and investigate cots, benefits, time horizon, and risks [38]. Thus, the AP process should start with the available historical data to map out the details needed for measuring the actual asset performance.

3.1.3 Asset performance maturity

Deacher, Das, Dunn and Sniderman describe an **asset performance management (APM)** program that goes beyond maintenance. It makes it possible to integrate several other business aspects, making it feasible to *"optimise operations and safety, and drive financial results"* [6]. A program as described would integrate the data across the companies. Both information technology (IT) and operations technology (OT) would bring critical information to the table, making it possible to draw complex decisions. Today, many asset-heavy companies cannot see the connection between having an excellent program for asset performance and savings in both maintenance and operations. The program developed has six steps of maturity, described in Figure 7. As progressing through the maturity steps, more data could be integrated into the system, enabling several functions. The report presents several examples of how sharing information between several divisions and actors in the organisation would help get better insight into the current situation, and hence, make it possible to work toward the exact directions when no longer having opposite goals. An integrated asset performance management system makes it possible to see how small changes would have severe effects and deliver holistic views of both reliability and safety [6]. The maturity steps of AP is in line with the digital development, as described throughout Section 3.3. Combining the different departments of a company, such as operations and maintenance, motivate AP as a step towards the future.

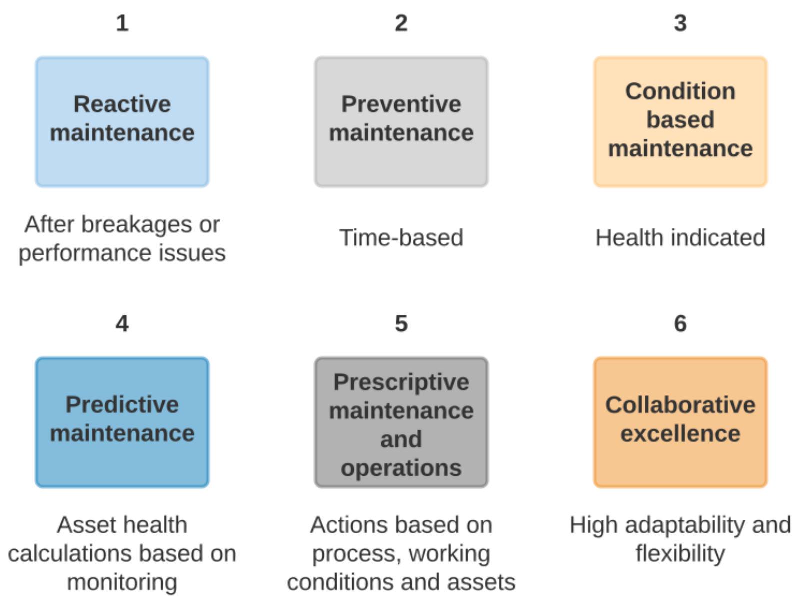

Figure 7: Asset performance management maturity steps

Source: Adapted from [6]

3.1.4 The link between asset management and asset performance

The European Standard EN 16646:2014 defines **physical asset management** as *"the optimal life cycle management of physical assets to sustainably achieve the stated business objectives"* and focuses on the value the assets provide, not the asset itself [39]. **Physical asset** is defined as *"item that has potential or actual value to an organisation"*, by the European Standard EN 13306:2017 [40]. By evaluating the performance of the assets, the standard points to the risks of *"silo"* behaviour, lack of holistic picture, making the wrong decisions, and uncertainty in decision-making could be avoided [39].

While delivering a framework for how value-based asset management could be implemented, Roda, Parlikad, Macchi and Garetti state that because of the central role AM has while developing strategies, the value of a companies assets must be measured to be used as a basis for decisions. The article describes value as involving *"balancing costs, risks, opportunities and benefits arising from the way assets are specified, procedures, deployed, used, maintained and disposed"* [41], which exemplifies how vital it is to understand the value of the assets, making it possible to make informed decisions based on the correct information. In ISO 55000, it is outlined that asset creating value for the companies is a crucial element of AM [36]. By implementing an asset management strategy, while also making sure that the communications between the organisations in the company, the value should be obtained from the assets [42]. Volkova and Kornienko describe the importance of developing asset management strategies for different units of a company to make it possible to monitor both the different units, in addition to the entire company. It is vital to make sure that the company's diversity is shined to light, instead of drowning in unified indicators [43]. To make sure that the value of each asset is taken into account when making decisions, the division of asset monitoring throughout the company is therefore essential.

Schuman and Brent presented back in 2005 an **asset life cycle management (ALCM)** model directed towards assets of the process industry. The important factors for the different stages of the life cycle of the assets are included. The goal was to optimise the value extracted from the assets in a process plant during the entire life cycle. Recommendations based on this model was to integrate asset management early on when planning new facilities. Both maintenance and operational factors should be addressed. From the model, several performance measures from the utilisation stage of the assets are mentioned. For human reliability, the model points to continuous improvement of culture and root cause failure analysis. Monitoring of the process and the assets is mentioned to improve the process reliability. Optimisations strategies and making use of history is important for equipment reliability. These measures are important to improve the overall asset performance [44]. The digital development from 2005 until today is powerful, but the same ideas presented back then are also crucial today. Process and asset monitoring and historical analysis are seen as the solution to many of the challenges faced in the process industry today. How the digital development affect the possibilities are elaborated in Section 3.3.

Wan suggest that reliability could be maximised in power grids through asset performance management. The ongoing digitalisation makes it possible to overcome "silos" in organisations to ensure that analysis of the available data is performed. Among other business drivers, the ageing assets worldwide increase the need for decisions concerning both operation and maintenance. In a case study in an electrical company, the neglect of asset inspections and maintenance and the lack of asset condition data were replaced with an asset performance system where all the condition monitoring data was utilised. This lead to a 50% reduction in asset failures. An asset model where all asset data is included and knowledge about the operations, the equipment, the data solution needs, and the industrial communication make it possible to perform better decisions regarding asset management, improving the overall performance of the assets [45]. Rødseth, Strandhagen and Schjølberg also identify the challenges regarding "silos" where poor collaboration between the organisations in a company leads a sub-optimised production. By integrating both maintenance and operation departments, the collaboration and coordination between the departments should be improved and lead to a better understanding of how the departments work together [46]. To integrate the company's divisions, extract the value of the assets, make decisions on a better foundation and monitor the assets, the concepts of AM and AP are linked. The following section will review how the condition of the assets and the AP are connected to be capable of fulfilling the ideas mentioned.

3.1.5 The connection between the condition of the assets and the asset performance

As Wilson describes, it is vital to find the connection between the condition and the performance of the assets. The assets is described as an *"integrated package"* because of the connection between the different assets. All the assets in an area or organisation influence each other highly, and together they deliver a production facility's overall performance. However, it is essential to identify the connections between the overall system and every part it consists of. To identify failure modes and how the performance is affected, the system must either be evaluated from the top-down point of view, from facility, system, sub-system until asset, or from failure to cause [47]. An understanding of the system function and components must be established to identify how the condition affects the asset performance.

Downtime in a production facility has several consequences, such as loss of production, recoverable and not, financial loss, loss of goodwill from customers and the need for spare capacity [25]. Rødseth, Schjølberg, Kirknes and Bernhardsen present the *"hidden factory"* to identify profit loss and waste in production. Profit loss is defined as the total turnover loss and extra costs [48]. To prevent unscheduled downtime, Diaz-Elsayed, Hernandez, Rajamani and Weiss present a framework for **asset condition management (ACM)**, which will improve the assets by delivering real-time condition monitoring, diagnostics of the assets and predictions for the future, since a manufacturing company depends on high system performance for meeting the production demand. The framework has three cores, as presented in Figure 8. The idea is that the useful rest lifetime of the assets and the different production systems should be increased and the sustainable impact of less waste and reduced resources. The framework has six levels, or capability levels as they are called: *"limited failure indicators, diagnostics, asset monitoring, prognostics, comprehensive ACM and self-adaptive ACM"* [49]. The goal is to gain control over the condition and performance of the asset, not to reach the highest level. A lower capability level could be sufficient as it depends on the given situation [49]. This framework connects asset condition, asset performance and asset management into one strategy, where the available data is used to hinder unscheduled downtime, waste and profit loss.

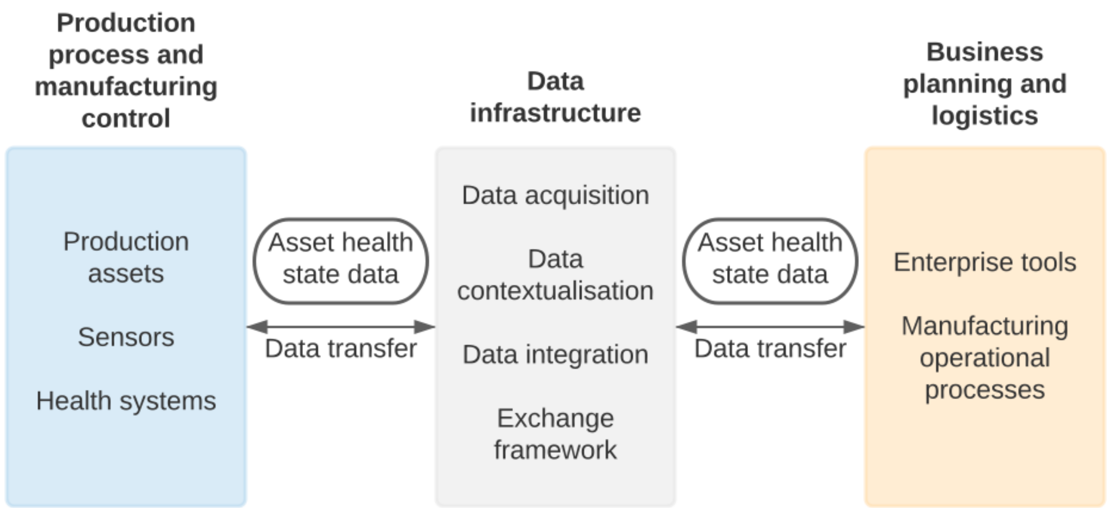

Figure 8: An overview of the architecture for the ACM framework

Source: Adapted from [49]

In the study by Scarpellini, Testa, Magoni and Riva, it is shown that the performance model developed can assess the reliability of different components. It is pointed out that different digital asset management methods are crucial to assess the status and health of the assets. Data analytical methods are therefore seen as the foundation for asset management and asset maintenance strategies. Healthy equipment is needed to prevent process downtime, and by monitoring the asset, it is easier to make sure that the equipment stays healthy. Statistical data, sensor data, environmental data, and operational data were taken to use in the study's model. The study confirmed that the operational parameters had a significant impact on the health of the assets, and a model monitoring the assets as proposed is shown crucial for an asset management solution [50]. This shows the importance of utilising the available data to monitor the assets for continuous performance evaluation, which will affect the maintenance of the assets. The following section will therefore look closer into the connection between exactly AP and maintenance before the effects of the digital development to AP is elaborated in Section 3.3.

3.2 Asset performance and maintenance

The relationship between asset management, asset performance and maintenance needs to be further investigated. EN 16646 focuses on the relationships between maintenance and events through the life cycle of the assets. There are relationships between maintenance and operations, maintenance and modernisation, maintenance and disposal, maintenance and physical asset management supports, and maintenance and management of assets. From managing assets, maintenance gets information about physical asset management and maintenance organisations structure, objectives, policies, strategies, methods, procedures, and control systems. The asset management process gains information about life cycle cost, the impact of maintenance strategies and activities from the maintenance process [39]. This shows that maintenance decisions affect the entire life cycle of the assets and the current performance and status of the assets throughout the life cycle. Hence, the bond between maintenance and asset performance is very significant. In the following sections, maintenance management, maintenance processes and required function will be described in light of asset performance.

3.2.1 Maintenance management

The European Standard EN 13306:2017 defines **maintenance** as *"the combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function"* [40]. Divisions of maintenance are **corrective maintenance**, defined as *"maintenance carried out after fault recognition and intended to restore an item into a state in which it can perform a required function"* [40], **preventive maintenance**, defined as *"maintenance carried out intended to assess and/or to mitigate degradation and reduce the probability of failure of an item"* [40] and improvements. Corrective maintenance is again divided into planned and unplanned, while preventive maintenance is split into predetermined and condition-based [40]. The different maintenance performed will affect the current status of the assets, and therefore, the maintenance management and the process around the maintenance decisions and actions are essential for the performance of the assets.

Chin et al. present the state-of-the-art maintenance management for chemical process industries for asset maintenance optimisation. This sector mainly depends on the performance and condition of the assets due to the complex systems and need for stable production. There is a need for performing the correct maintenance at the right time. The importance of maintenance in the industry has risen and is often a large portion of the overall budget [21]. This show how influential the maintenance actions are toward the performance of the asset, and hence, the maintenance management must be in order.

The maintenance management process visualised in Figure 9 shows the different aspects of the maintenance process. The work process, the results and the available resources are all covered [27]. The technical condition is highly relevant for the asset performance, and from Figure 9, the following actions of reporting, analysis and improvements are thereby strongly linked. The actions leading up to the technical conditions, including goals and requirements, maintenance programme, planning and executing of the maintenance, are also necessary when assessing the asset performance. Every decision leading up to the current technical condition will affect the status and performance, thus exemplifying how strong the relationship between maintenance and asset performance is.

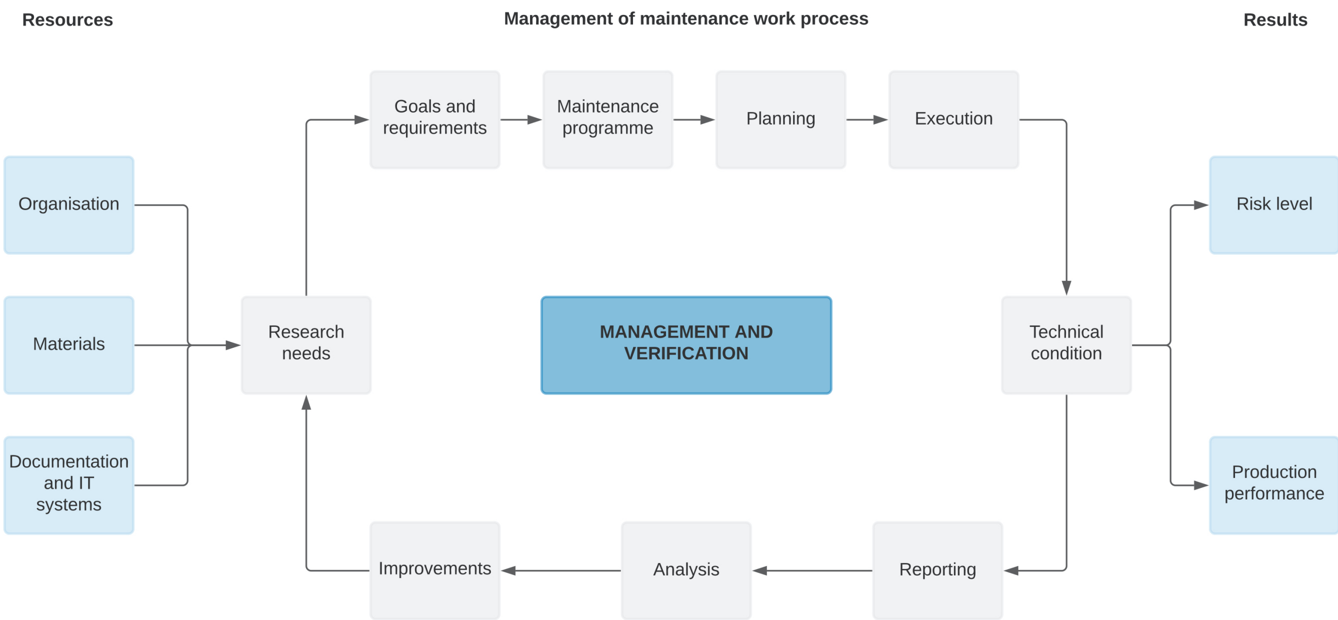

Figure 9: Maintenance management process

Source: Adapted from [27]

Okoh, Schjølberg and Wilson show how maintenance influences all different life-cycle phases of the assets, from product development to decommissioning. This shows that maintenance is a crucial part of asset life and, therefore, both the assets' performance and the management of the assets. To extract the value of the assets, maintenance needs to be performed to make sure that the assets can provide value. Through presenting the **asset maintenance management process (AMMP)**, maintenance and asset management are integrated. Maintenance management could be improved through the asset management system, ensuring maintenance also contributes to better asset performance. Through poor or lack of maintenance, companies have experienced losses from production downtime and harm to both the assets, humans and the environment. When connecting asset management with maintenance management, the asset's value through the entire life-cycle could be optimised [51]. Through an asset management strategy, where the asset performance is measured, the value of the maintenance actions is visualised.

As argued by Marais and Saleh, the value of maintenance is often overlooked when trying to minimise the cost of maintenance performed while increasing reliability. The article concludes that every maintenance strategy should include an aspect of the value of maintenance [52], which is also described in Haarman's concept of **value-driven maintenance (VDM)**. The idea is that through the four value drivers of maintenance: *asset utilisation, resource allocation, cost control* and *health, safety and environment (HSE)*, maintenance could bring significant value [53, 54]. These value drivers are visualised in Figure 10. The purpose is to find the ideal balance between the four value drivers. This is important when looking further into maintenance processes in the following section since every maintenance action's value during the process affects both the overall value and performance of each asset.

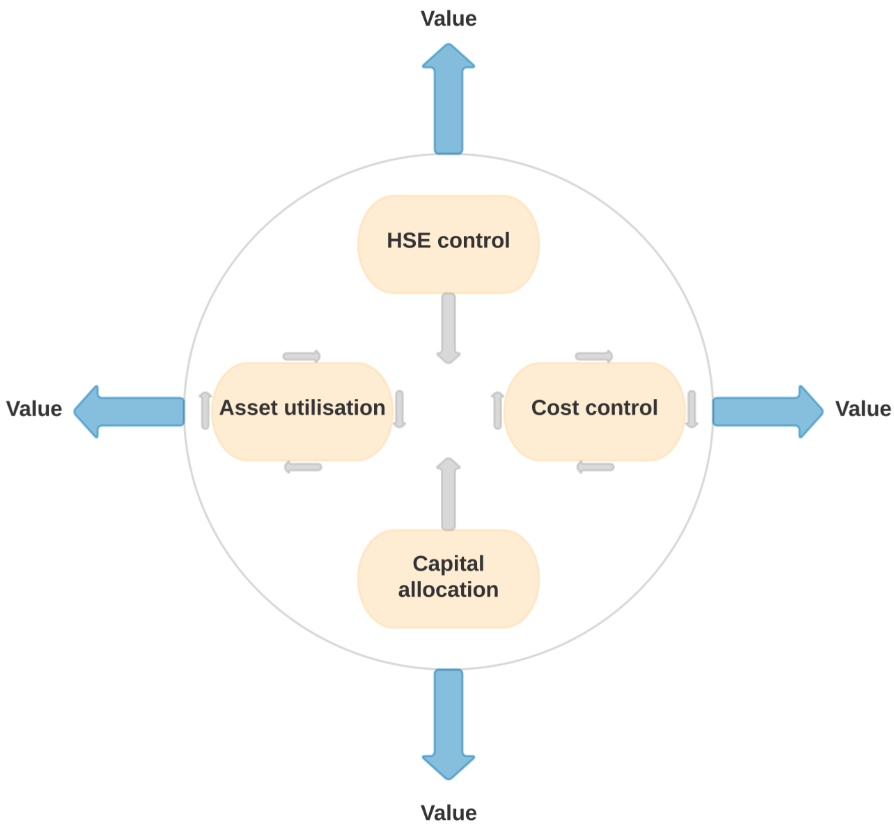

Figure 10: Value drivers in maintenance

Source: Adapted from [54]

3.2.2 Maintenance processes

The European Standard EN 17007:2017 gives an overview of **maintenance processes** and the associated indicators for these processes. When managing maintenance, key activities are related to establishing policies, strategies and development actions, budgets, overseeing actions, communicating crucial information, and defining areas of improvement. The core elements of the maintenance process are visualised in Figure 11. Characterisation of undesirable events is also necessary for evaluating the performance of assets. To do so, EN 17007 states key activities in this process to determine the primary cause and effect of this cause and prioritise maintenance actions based on the cause and its effects. When it comes to the process of managing data, which is a crucial part of evaluating the performance of the assets and defining areas for improvement, the standard defines the purpose of this process to *"collect, analyse, store and transmit all data needed to document and improve the maintenance process"* [55]. The key activities are related to storing the data, evaluating the reliability and maintainability of the items by assessing the state of the items, drawing up a list of necessary items, evaluate and analyse the available data, compare maintenance practices, monitor methods and technologies, and finally provide access to performance and monitoring indicators [55].

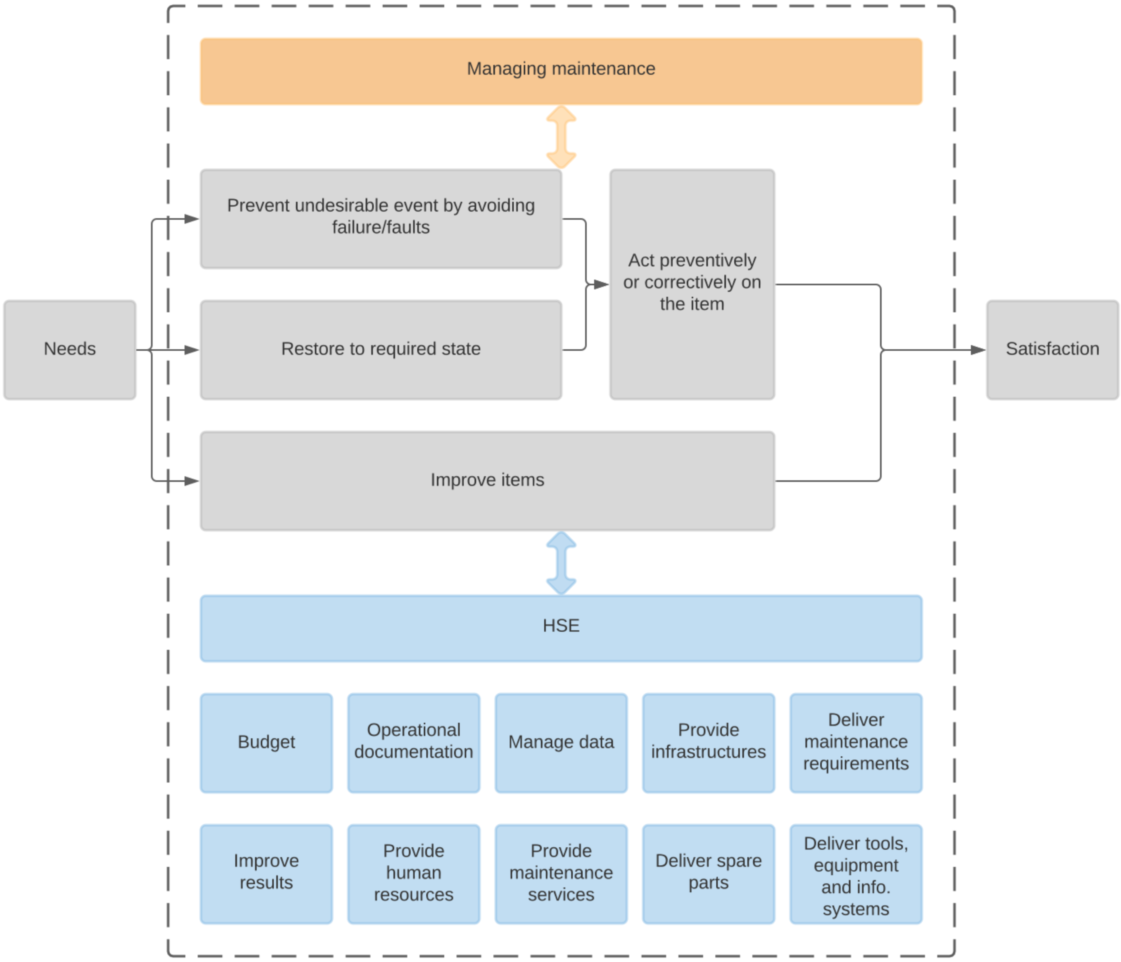

Figure 11: Core elements of the maintenance process

Source: Adapted from [55]

Figure 11 visualise how several aspects affect the maintenance process. From the needs identified, failures must be prevented or restored, while items are improved to prevent further failures. When performing these actions input from the maintenance actions and all the factors visualised in *blue* are important to keep in mind. Maintenance requirements, tools, equipment, spare parts, infrastructure, data, maintenance services, human resources, documentation, budget, health, environment and safety all affect the maintenance process and the results of the maintenance actions [55]. Keeping in mind the strong bond between maintenance management and asset performance, all of these factors will also influence the status of the assets. If implementing asset performance monitoring, the maintenance process will also be affected.

Rødseth, Wilson and Schjølberg propose a step by step solution for developing an asset management strategy to *"ensure a right balance between plant capacity and maintenance activities during the life cycle of an asset"* [56]. This balance is vital for the assets in a company and hinders unexpected breakdowns. This strategy will make sure that the value of the assets is kept throughout the entire life cycle. The process consists of four steps: mapping the maintenance process and the relationship between operating and maintaining the assets, developing relevant key performance indicators (KPI) and guidelines for decision support, and developing a digital twin for smart analytics. The idea is that the digital twin (DT) will give an asset performance management plan where the available data is analysed with both analytical techniques and domain knowledge [56]. An asset management strategy will include the current maintenance management and maintenance processes for handling the assets and evaluate and monitor the performance they deliver. The following section will look further into the required function of the systems, which has to be fulfilled for accomplishing the needed asset performance.

3.2.3 Required function

Required function is defined as *"function or combination of functions of an item that is considered necessary to provide a given service"* [27]. The required function of the systems could be directly attached to the maintenance process described in Section 3.2.2. Therefore, it is required that the processes the system's function is trying to fulfil are carefully described, making it possible to link the process requirements to the system requirements, establishing the required function. Ageing equipment especially requires continuous improvement, where the operational and maintenance history is evaluated, and the current condition of the system is assessed [27]. Therefore, the required function is important to keep in mind when evaluating the required function and the asset performance.

The technical hierarchy, describing the form and organisation of the systems and giving every item identification, is an essential part of maintenance management. In this way, the history of the technical objects is linked to the actual asset, making it possible to evaluate the performance [27]. Therefore, this hierarchy is functional when assessing a system, making it possible to establish the components, their relationship, and the historic maintenance aspect of each component. When looking further into the requirements of a system, this structure will also be helpful. For evaluating asset performance, the connection between the equipment is essential.

When performing the consequence classification process, it is important to access the technical hierarchy and the operational data. This will provide the basis for identifying the system's main functions and the sub-functions. The process of classifying the functional architecture includes investigating the technical information, gaining input from other relevant analyses, identifying the main functions and the further sub-functions, assigning redundancy and consequences to both the main functions and then sub functions and finally map the equipment to the function gaining the results. The consequence classification is then based on the system's functions in the context of available reliability calculations. The result of this classification is helpful for the different aspects of maintenance management, such as the spare part analysis, prioritising, reliability analysis, risk management, KPIs, consequences related to HSE and productions and redundancy analysis [27]. In light of asset performance analysis, it is essential to identify the main and sub-functions of the assets. The possible redundancy and the consequences of failures are an essential part of identifying asset performance. The maintenance management, the maintenance processes and the required function of the system are therefore needed for evaluating the performance. How new digital tools affect this process is elaborated in the next section.

3.3 Digital development for asset performance evaluation

The current digital development affects the industry, the companies, and the idea of asset performance. New possibilities for detecting the performance of the assets arise with the new digitalised tools. For example, Bumblauskas et al. point out the challenging issue of using data to make maintenance decisions. A **smart maintenance decision support system (SMDSS)** is presented, where big data analytics is used to prioritise equipment maintenance. This will improve the asset life cycles. Due to faster processing, better storage capacity and improved analytical tools, this is possible [5]. Kumar and Galar point to the development of the Internet of Things (IoT) and big data (BD) as important for better maintenance decisions. Using the data to build degradation models makes it possible to optimise the decisions made [57].

New technologies make it possible to achieve higher performance in the industry. Excellent knowledge in data analytics is needed to reach the full potential of these technologies. Many companies do not realise that the same goal could be reached with less complex methods. Management processes and reliability engineering is significant for better performance. It is important to determine which assets are critical, start with reliability from the ground up, solve problems from the root, define clear roles and utilise the available knowledge [13]. New tools being developed due to the digitalisation of the industry would affect several asset management functions and increase efficiency and reduce costs [58]. Several examples of artificial platforms, such as the system developed by Sen, Fashokun, Bhaumik, Card and Lodhi, were developed to integrate and systematise data from different systems. Available data was put together and analysed for optimising asset management. The platform led to the operational and maintenance department working together to detect problems and figuring out solutions that would lower life cycle costs [59].

Rødseth, Schjølberg and Marhaug developed the maintenance model **Deep digital maintenance** in 2017. The model follows the principle of the Deming cycle with the phases plan, do, check and act, and consists of three parts, the AI module, the PLI module and the planning module. The combination of the new technologies can hinder unwanted events, enable root-cause analysis and improve maintenance planning due to the merge of maintenance and production planning. This exemplifies how the integration of new technologies into the maintenance process is possible in this digital world [60]. Asset performance as part of the maintenance process will therefore also be advantageous for this development. The following sections will describe different aspects of digital development in the context of asset performance. Industry 4.0, smart maintenance, predictive maintenance and condition monitoring are all critical for making it possible to continuously measure the performance of the assets and fulfilling the need of being in control over the assets in a company.

3.3.1 Industry 4.0 and its contribution to asset performance

Industry 4.0 is defined as the *"integration of information and communication technology in industrial production"* [61]. The Industrie 4.0 Maturity Index points to there being new challenges related to digital transformation. There is a huge potential but a lot to keep track of. Typical failures are associated with a lack of foundation in the company, focusing too much on one technology and working with solutions that are impossible to scale. The four areas of resources, information systems, organisational structure, and culture are highlighted as important fields of focus. The published Industrie 4.0 Maturity Index presents the Industry 4.0 development presented in Figure 12. The third step of visibility is related to determining what is happening, while the fourth wants to understand what is happening. The fifth step is predicting what will happen to be prepared, while the final step is when self-optimising is implemented. For this development to be possible, the companies must also transform their organisation and their culture. The key is an agile approach to the changes, supplemented with continuous adaption [61]. In light of asset performance, these steps are all relevant. As with Industry 4.0, the need for visualising and being transparent of the current status of the assets is important before predicting future status. By lifting the current development of Industry 4.0, the possibilities for AP developments are also expanded.

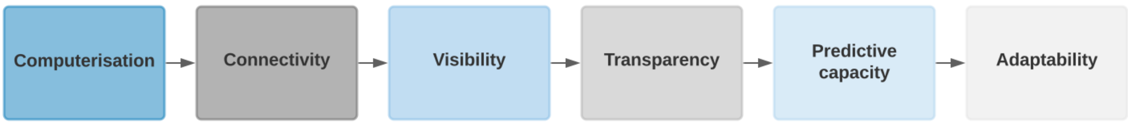

Figure 12: Industry 4.0 development

Source: Adapted from [61]

The German Standardisation Roadmap for Industrie 4.0 presents the current status of Industry 4.0. They present the Reference Architecture Model Industrie 4.0 (RAMI 4.0) to speak a common language and suitable data structures for data exchanging. The reference architecture model is presented in Figure 13. Digital development is happening step-by-step and integrates the different aspect of the company. Therefore, it is also important that the standardised models includes all of these views. The new technologies make it possible to analyse data and monitor the assets and the production processes, and this model includes the necessary sections [62]. The six cores of RAMI 4.0 are all needed for evaluating the performance of the assets. The business process combined with the function definitions and access to the necessary data connecting the physical system with the digital data could give insight into the performance of the assets if analysed. By utilising this reference architecture, issues related to making continuous asset performance evaluation could be solved.

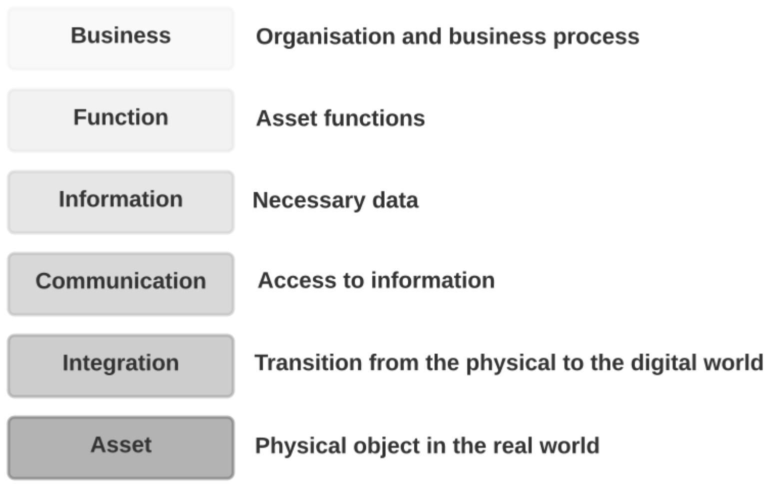

Figure 13: Reference architecture model Industrie 4.0

Source: [62]

3.3.2 Smart maintenance in an asset performance perspective

The concept of **smart maintenance (SM)** is by Bokrantz, Skoogh, Berlin, Wuest, and Stahre defined as *"an organisational design for managing the maintenance of manufacturing plants in environments with pervasive digital technologies"* [63]. Due to digital development, many companies worldwide now include the concept of SM in their maintenance plans. Using relevant KPIs will help the implementation of SM while developing towards digital, productive and sustainable production [64]. The concept of SM is divided into four dimensions, shown in Figure 14. Data-driven decision-making could automate the decisions. Human capital resource revolves around utilising the knowledge, skills and abilities of the individuals in the organisation. Internal and external integration is about integrating the maintenance functions, both internal and external, in the company or organisation [63]. This formulation is based on a two-piece paper series published in 2020, based on interviews with experts from over 20 different companies. The four dimensions of SM are connected to both the plant's performance and the firm as a whole. The plant performance is divided into the performance of maintenance, manufacturing, safety and environment, while the firm performance is divided into financial and competitive performance. The ability to implement SM is also dependent on the ability to change, the ability to invest and the technological development inside the organisation [65]. The four dimensions of SM could also describe the concept of asset performance. Utilising the available data to make decisions, using the people's knowledge in the organisation, and integrating the assets as part of the entire organisation are essential aspects of AP. The development of SM and AP could, therefore, be seen in the context of each other.

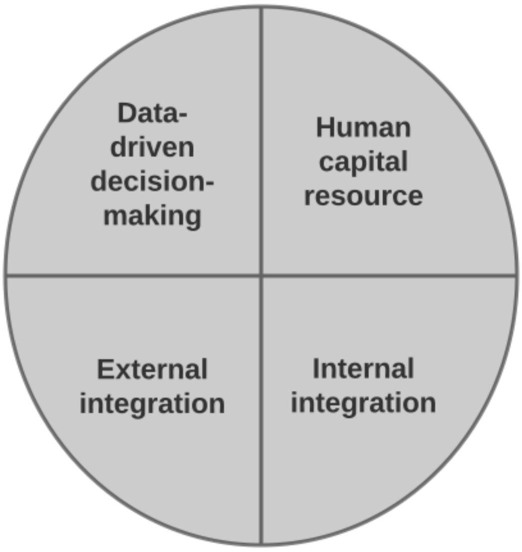

Figure 14: The four dimensions of smart maintenance

Source: Adapted from [63]

Both maintenance function and asset management is part of the development of SM. In the article by Rødseth, Eleftheriadis, Li Z., Li J. and No, a smart maintenance framework is presented. Figure 15 represent the framework, where criticality assessment is important. Insights about the business are found through data analytics performed on data made available through data lakes. Data on condition, data from different systems in the business and data from the suppliers could all create value through the application of SM. The article describes how SM is made possible due to the current digitalisation, the development of Industry 4.0 and principles from both artificial intelligence (AI) and machine learning (ML) [66]. Rødseth, Schjølberg, Wabner and Frieß also point to the importance of integrating maintenance planning and production. This is key for companies to stay competitive in today's society and is made possible due to digitalisation, industry 4.0 and predictive maintenance, especially by predicting the remaining useful lifetime [67]. The framework presented is also useful for evaluating asset performance. The data that says something about the assets must be made available through data clouds before analyses could be performed to get insight into the company's assets. Therefore, AP could be seen as one division of smart maintenance development.

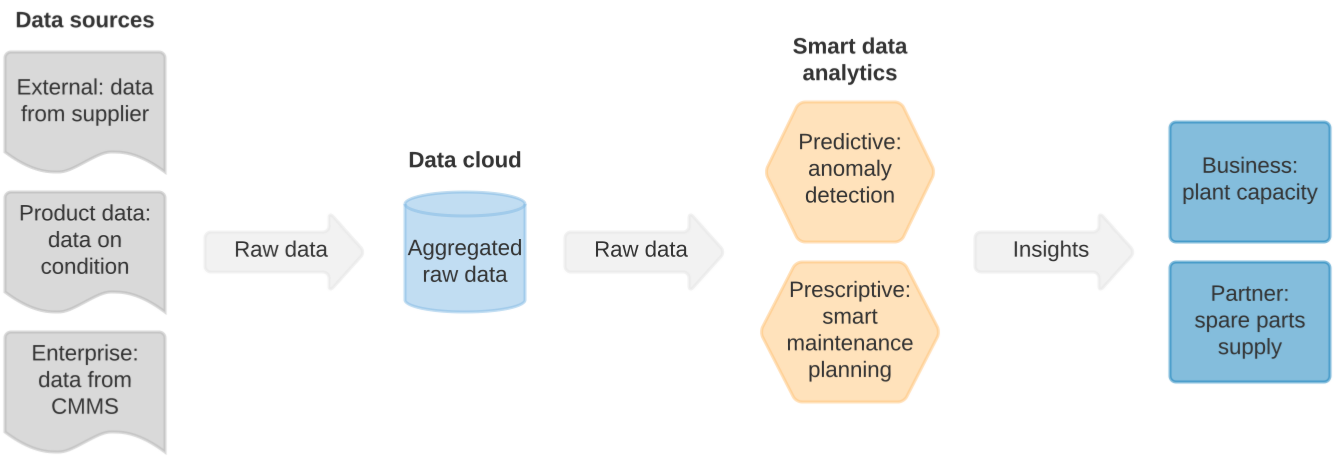

Figure 15: Smart maintenance framework

Source: Adapted from [66, 68, 69]

Smart asset management (SAM) revolves around using new technology for improving the regulation of the assets, connecting traditional AM with technology and decision-making. Important information is drawn directly from the assets, making them able to provide crucial information to better decision making from the managers. SAM makes it possible to develop from traditional asset management, where data from the assets was collected and analysed for reactive actions, to a proactive and predictive direction where information is analysed directly, in other words, the *"shift from asset status monitoring to asset performance monitoring"* [70]. The digitalisation of AM includes getting insight from both the different components and the whole system of assets and use this information for decision support [42]. While identifying both benefits and challenges of big data development, Khuntia, Rueda, and van der Meijden present the following three-step approach to SAM [71]. Through this definition of SAM, the connection between SM, AM and AP are made. Following the steps of the framework presented in Figure 15 and the steps below, the mutual goal of getting better control over the business through the assets is reached. The following section will describe how predictive techniques could be integrated into this idea.

1. Data gathering for estimating the component condition and defining thresholds as a basis for condition-based maintenance
2. Historical data analysis for pattern recognition for future failure predictions
3. Using analytics and component condition for evaluating economic, safety and environmental effects of failure

3.3.3 Predictive maintenance for asset performance assessment

Predictive maintenance (PdM) is defined as *"condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item"* [40]. Deloitte presents six steps towards predictive maintenance, as visualised in Figure 16. From a reactive response to failures, key process parameter could be visualised, and further warnings based on defined rules could be implemented. Through the identification of anomalies, the fourth step of getting early warnings of failures could be reached. The final step includes identifying failures and mitigating the cause of these failures [72]. Digital development is dependent on the organisational approach, security, equipment upgrades, data management and technology. To make decisions based on real-time analytics, the performance evaluation and the identification of processes and capturing value are needed [73]. For every step processed, more data is included. The conception is that the actions made would increase the performance of the assets and identify the value of the actions. The asset performance evaluation will progress from not being identified to visualisation, to continuously monitoring, and further towards being used as a basis for further analysis and decisions.

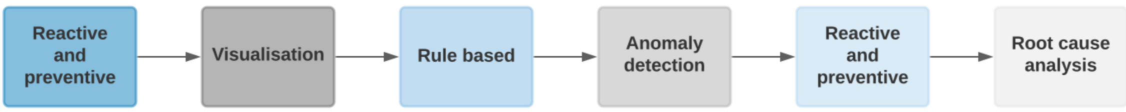

Figure 16: Steps towards predictive maintenance

Source: Adapted from [72]

PwC, on the other hand, identifies four steps towards PdM. From *visual inspections*, to *instrument inspections* and *real time continuous monitoring* based on rules, the final and fourth step of **PdM 4.0**, with *"continuous real-time monitoring of assets with alerts based on predictive techniques"*, is possible [12]. The assets and their performance are shown to be a huge part of the road towards PdM. PwC points to the need to rank the assets' value before selecting the assets with the most potential for the PdM journey. Then, reliability modelling and algorithms are needed to monitor the performance of the assets, which is considered the first step towards further development, including failure prediction and preventive task prescription [12]. This increases the importance of identifying the asset value and keep track of the performance the assets are delivering. Without this foundation, further development will be a challenge.

By developing the Standardisation Roadmap of Predictive Maintenance for Sino-German Industry 4.0/Intelligent Manufacturing, the need to capture the status and the performance of the assets is determined. This is often a challenge as the needed data comes from several sources. Standardisation for the available technology needed for CM, fault diagnosis, and fault prediction is explored by investigating Germany and China's status. In Germany, the focus lies on condition-based maintenance, and companies with continuous production are most interested. Handling the assets through asset management and implementing condition monitoring opens up tremendous possibilities. The functional structure of the PdM developed is presented in Figure 17. Sensing technologies are needed to assess the condition and the performance of the assets. The results from the condition status assessments work as the basis for both fault diagnosis and fault prediction. Repair measures are made based on the diagnosis, while maintenance actions are based on predictions. The diagnosis and predictions both give input to the maintenance management [2]. Asset performance here works as the foundation for further diagnosis and predictions. The current status of the condition and the actual performance of the assets must be identified before new technologies related to diagnostics and predictions could be implemented.

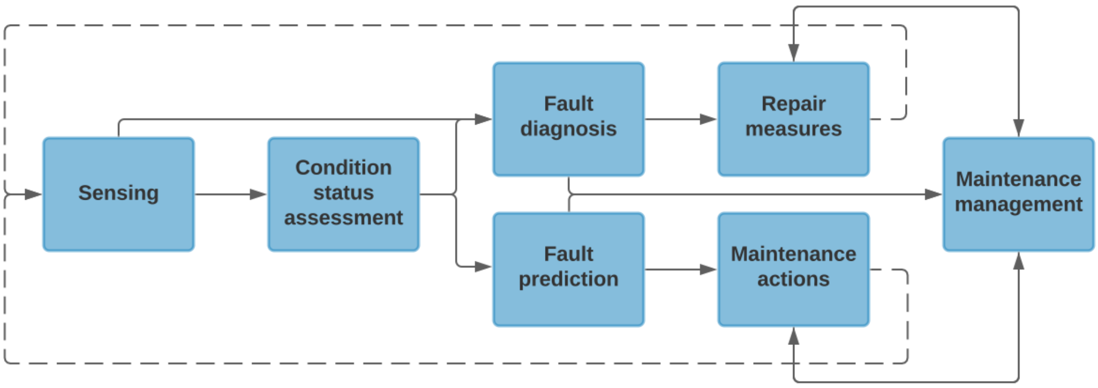

Figure 17: Functional structure for PdM

Source: Adapted from [2]

Aremu, Palau, Parlikad, Hyland-Wood and McAree state that the use of PdM techniques within the context of AM could improve *"savings in operational cost, productivity and safety"* [74]. The article points to three challenges in structuring data from asset to use for PdM procedures: the correlation between the raw data and the processed data, the reduction of complexity, and the use of new parameters. Domain knowledge of the assets is also crucial when processing the data, making it ready for predictive techniques [74]. By identifying these challenges and work towards them, asset handling and asset performance take advantage. As part of the PdM domain, the data usage for asset performance analytics will be further described in Section 3.4. The following section describes how the step from PdM and beyond would benefit the performance of the assets.

3.3.4 Beyond predictive maintenance for better asset performance

Bradbury et al. indicate that many companies focus too much on PdM techniques instead of working towards a digitalised maintenance and reliability strategy. When there are fewer and more understood failure modes, there are more accessible solutions than fully predictive methods. Therefore, companies should look beyond PdM and focus on the bigger picture of how digital and analytical processes will transform their entire organisation and ways of working. Overall better use of data could better the performance of their assets and free up the time used on manual work. The integrated approach to digital reliability and maintenance, shown in Figure 18, is presented with a program and an execution element. The idea is to separate the *"what"* from *"how"*, where digital enablers make sure the date available is taken to use. By managing both the assets, the available and future data, in addition to the people, asset reliability and maintenance performance could be improved [16].

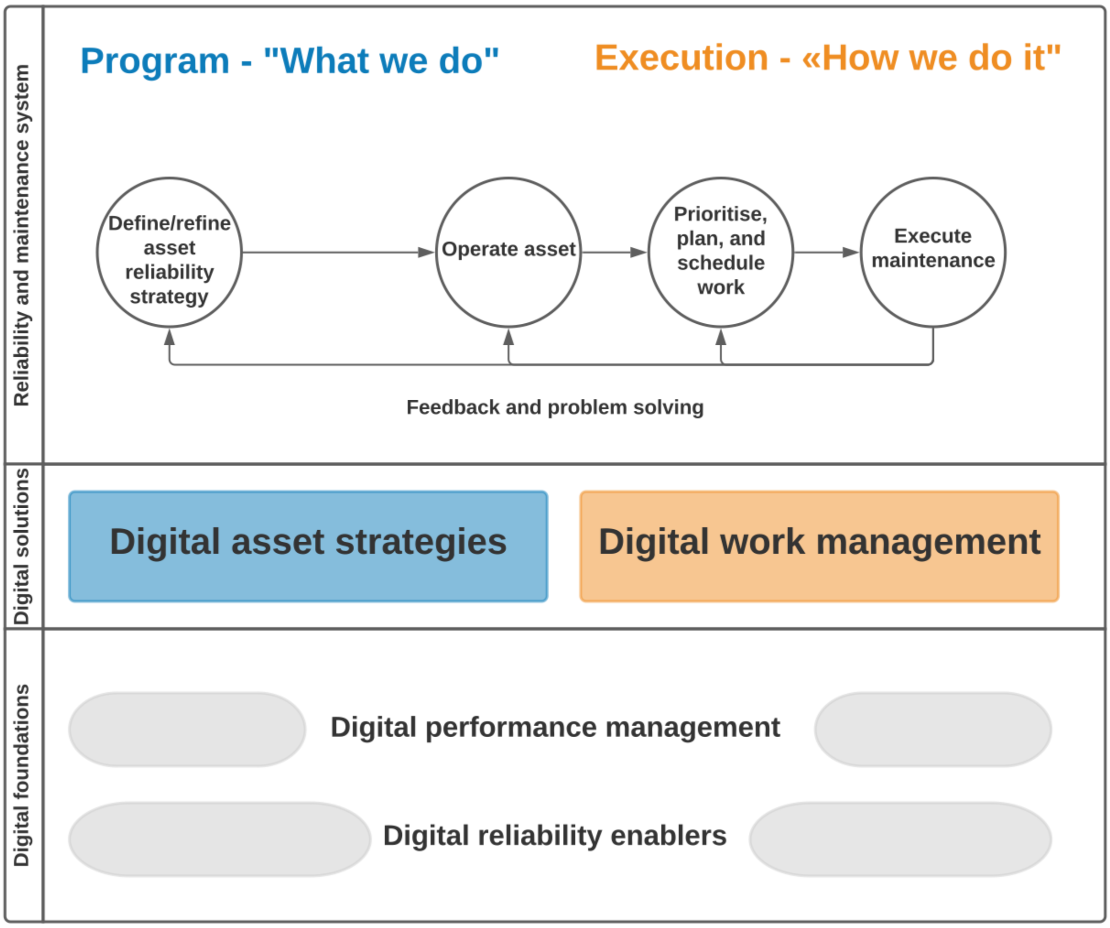

Figure 18: Integrated framework for digital reliability and maintenance

Source: Adapted from [16]

Solutions for collecting, storing and accessing data is needed to make it possible to use digital tools for reliability analysis, in addition to data-driven condition monitoring methods. Today's issues are often related to the existing systems not being set up for integration, causing people to spend lots of time analysing the available data and failure data described in free text. A data lake makes it possible to access data from multiple sources, and reliability analysis can be performed more consistent. Condition monitoring methods driven by data could raise alarms if thresholds are passed to supervise the assets' performance continuously, and available data from the entire life-cycle of the assets could be included when making important decisions regarding the asset. In the presented framework, the digital foundations and the digital solutions are connected with the reliability and maintenance system, opening the organisations for more digital opportunities [16].

The direction made by connecting the task being solved to how this shall be performed is linked through the development of asset performance and required function evaluation. Before taking new technologies to use, solutions for determining how the assets are doing their job and if this is in line with the given requirements is the first task to initiate improvement measures. As Figure 18 visualise, the asset strategy and the work management is separated. However, they are built upon the same foundation of reliability enablers and performance management. Both directions are included in the reliability and maintenance system, where feedback from the assets, the maintenance management and the maintenance executing is included in the work with the assets themselves [16]. This is also the foundation for asset performance analysis, where the available information can be used for evaluating the actual performance.

3.3.5 Condition monitoring for measuring asset performance

As described in Section 3.1.5, there is a strong attachment between the condition of the assets and the performance it delivers. Therefore, the concept of **condition monitoring (CM)** must be explored. CM is by EN 13306 defined by *"activity, performed either manually or automatically, intended to measure at predetermined intervals the characteristics and parameters of the physical state of an item"* [40], while Alan Wilson defines it as *"the purpose of monitoring condition indicators is to detect the onset of asset deterioration and provide a measure of the extent and rate of asset deterioration towards failure"* [47]. The Standardisation Roadmap of Predictive Maintenance for Sino-German Industry 4.0/Intelligent Manufacturing point to CM being the basis for developing PdM, making it possible to monitor the state of the assets and utilise this state data as an essential data source [2].

To determine the health state of the assets, several parameters are needed and the most important being the system state. A processing algorithm will identify the state of the asset. There are two categories for evaluating asset condition: numerical methods, including regression, or machine learning principles, such as neural networks or decision trees. The health state identified is used as input and reference values or a threshold number to identify the condition status. When performing fault diagnosis, there are four steps: fault detection, fault location, fault isolation and fault recovery. Three methods are used for diagnosing. The first is based on analytical models, typically estimations or mathematical models. The second is based on empirical knowledge delivered by experts, while the third is data-driven methods, such as AI. Fault prognosis, on the other hand, is monitoring different parameters. The data is processed and used as input in remaining life prediction models, where the asset's remaining life is estimated through, for example, data trend analysis [2]. This process can be solved both as complex and as more straightforward solutions. When performing condition monitoring for measuring asset performance, a solution for determining the asset's health must be solved. Further development builds further onto this, but a threshold or reference value must be established to monitor the assets.

Through the study performed by Candón et al., asset performance monitoring was addressed to identify potential reliability problems. The study built a model combining artificial neural network (ANN) and data mining (DM) techniques, showing that the ability to make better decisions increases when implementing the possibility to detect abnormalities in the system. This confirmed that using available data is crucial for making the best decisions regarding the assets. The study also points out that transforming data into useful information and knowledge still is a considerable challenge [75]. This visualises that more complex solutions are available, but the need for available good quality data in the correct format is essential for monitoring the assets' performance. The following section will look further into the data used for asset performance analytics.

3.4 Data for asset performance analytics

Lukens et al. state the importance of having maintenance data of good quality when using the data for asset performance analytics. Maintenance data today is often captured manually. However, it holds crucial information about the performance of the assets. The historical data gives valuable insight into the assets. Analytics performed of maintenance data is dependent on the data being as accurate as possible. Poor data quality is a challenge for every process plant in the world. Many companies still want to utilise their data and improve the available data for better quality. Figure 19 presents a framework for data quality improvement, developed by Lukens et al., to make it possible to perform asset performance analytics. It is pointed out that while implementing an APM strategy, it is important to work with improving the data quality continuously. For a company to improve the performance of their assets, the steps from Figure 19 are followed. While taking asset data to use, it is crucial to align it with clearly defined business goals [11]. This identifies asset performance evaluation as a clear goal for the available data. It is possible to extract value from what has been gathered throughout the years.

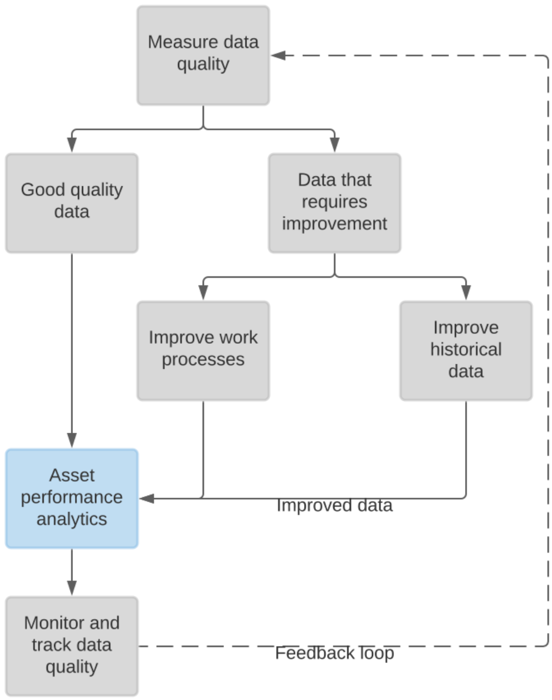

Figure 19: Data quality for asset performance analytics

Source: Adapted from [11]

The available data for companies today is often failure data from the equipment and maintenance data recorded by the maintenance personnel. Failure data often include the data, the failure mode, the failure mechanism, the failure cause, the failure impact, the operation condition at failure and the detection method. Maintenance data, on the other hand, often include the maintenance category, whether it is corrective or preventive maintenance, the condition of the equipment both before and after the performed maintenance, the man-hours spent on the maintenance activity, which spare parts that were used, the start and finish time of the maintenance activity, the active maintenance time and lastly the equipment downtime [27]. Bearing in mind that for assessing the performance of the assets, this information is significant to conclude the current performance.

The maintenance and failure data collected and made available in many companies today are often written in free text, which can cause difficulties when using the data as a basis for further analytics. A technique often used when improving data quality written in free text is natural language processing (NLP). The technique processes and analyses the text to make sense of the text-based data. Brundage, Sexton, Hodkiewicz, Dima and Lukens state that there is a need for including the technical aspect of the technique to avoid the risks of lack of verification and validation. They present the concept of technical language processing (TLP) to adapt NLP to engineering data. This will give better insight into the assets' history to base maintenance decisions on [76]. This is not outspread technology but shows the complexity of the problem it currently is when including free text in analysis for performance assessment or decision-making. It is also very relevant for asset performance evaluation when most of the available data regarding the assets up for analysis is maintenance history with diverse quality.

Madhikermi, Kubler, Robert, Buda and Främling refer to data being the competitive advantage for companies today and highlight the need for good quality maintenance data to make sure that decisions are based on the right insights [77]. Hence, issues regarding data usage must be solved to extract the most value and insights of the data already existing, to make it possible to utilise all the new possibilities from the digital change. Traditionally, maintenance decisions were based on intuition and not on the available data. Today's competitive market requires embracing digital development to make better data-based decisions. To adapt to this change, the organisation and the culture must transform and build the data foundation for the new digital tool. Data processing layers are needed to control the new data, but the employees' skills must also evolve in line with this development. To analyse and process the data collected, the workers' knowledge must adapt to integrate these tools into their everyday work. The people and the work culture must also believe in the new technology and recognise the value it adds to the organisation. This could be a change from the way people work today, and the workers must be willing to take on this challenge [61]. To monitor and analyse the current performance of assets, both the data, the knowledge, the people and the culture must be in line for gaining control over the assets.

Chin et al. point to several issues related to data availability and accuracy of the data needed to evaluate the assets. There would still be a need for characteristics of the assets and a large portion of historical data. There would be a risk of the data being censored or misinterpreted, and therefore, the data collection time is significant. Due to a lack of data or background knowledge, it would be difficult to understand the models' uncertainties for analysis, prognosis, or prediction. To continuously monitor the data, the data collected must also be closely monitored, and the issue of false alarms must be solved. Predictive models need much and specified data, which would required data acquisition and data cleaning. In written text, human errors could also lead to mistakes in the data. Massive data, in addition to knowledge about the system, is needed to reflect the accurate systems. For a model to capture a system, the correct data analytic framework must be chosen. A different issue is related to the evolution of the data. There is no guarantee that the historical data available would reflect the core of the system today. To implement AI and BD technologies for making the right maintenance decisions and determine asset performance, a combination of conditional data, operational data, written text and speech could be taken to use. A digital twin could also be used to simulate the asset and diagnose what effect the performance of the system [21]. This shows the variation in the future possibilities for further development of asset performance assessment. The first step toward an asset performance strategy must first be made, combining the available data, improving this data, new technologies, and a change towards better control of the assets. This is summarised in the next section.

3.5 Summary of the literature search and the presented theory

Throughout this literature search and presented theoretical background, the need for asset performance in asset-intensive production companies has been identified. The process industries depend highly on AP and asset condition due to the complex systems and the need for stable production [21]. The awareness of how investments in the assets lead to increased asset and business performance [35], which boosts the interest in AM and AP due to the impact it has on operations [10]. Control over the processes and the assets are through AP reached and contributed to continuous improvement, sustainability and effectiveness [37]. To manage the assets, the performance needs to be measured, and this complex issue has several challenges [7]. Performance monitoring can identify patterns, provide needed information for decision-making and deliver accurate status of the assets [38]. The six maturity steps presented can help asset-heavy companies realise the connection between AP and savings in maintenance and operations [6]. An asset performance system can replace the neglect in inspections, and maintenance [45]. Through the presented framework in Figure 8, the aspects of asset condition, asset performance and asset management are connected to avoid unscheduled downtime, waste and profit loss [49]. Different digital asset management methods are important to assess the status and health of the assets, and the operational parameters have a significant impact on the health of the assets [50].

The connection between AP and maintenance is essential due to the need for performing the correct maintenance at the right time [21]. Maintenance is a crucial part of asset life, and through lack of maintenance, companies experience losses and production downtime [51]. To evaluate the status of assets, the required function of the system must be identified, in addition to the consequences of a reduction in performance [27]. Digital development makes it possible to include data in decision-making, which can result in a better decision for the assets, and in the long term, better performance [16]. The available data can be included in an asset performance strategy that can improve savings, productivity and safety [74], resulting in a competitive advantage [77].

With a background in the presented theory, the following procedure for evaluating asset performance is proposed:

1. Identify the business case. Why is evaluation and analysis of asset performance needed?
2. Define the requirements of the system and the process.
3. Identify the main and sub-functions of the system, in addition to the functional failures and failure modes. Decompose the functional and physical construction of the system.
4. Collect and analyse the available data related to the system, including historical data, maintenance records, conditional data and operational data.
5. Decide on when and how to measure the performance. Which methods shall be used, and how can new technologies be included?
6. Implement the asset performance system in line with the requirement and needs of the system.

Keeping this in mind, the case study is introduced in the following section. The theory presented is used for the discussion, in Section 6, of the results from the case study, presented in Section 5. The problem statement related to how asset performance evaluation is beneficial and how analysis of available data could improve the carbon anodes transportation line at Hydro Årdal is explored.

4 Case study introduction

As described in Section 1.2, the case is presented by Hydro Aluminium Årdal and is related to the carbon facility. The system to be analysed is the transportation line between the green mill *(massefabrikken)* and the bakehouse *(anodefabrikken)*. The following sections will present relevant background information related to the case study before going further into the current system.

4.1 Norsk Hydro and Hydro Aluminium Årdal

Norsk Hydro ASA is an international company founded in 1905, with approximately 34 thousand employees in over 40 countries. The company is represented in the entire supply chain of aluminium and energy, metal recycling, renewable and batteries. Their business areas include Hydro Bauxite & Alumina, Hydro Aluminium Metal, Hydro Rolling, Hydro Extrusions, and Hydro Energy. Hydro is built upon the values of care, courage and collaboration, and is working for a more sustainable future [78]. In Norway, Hydro has over four thousand employees in 15 different locations. Husnes, Høyanger, Karmøy, Sunndal and Årdal are the facilities producing primary aluminium [79].

Hydro Aluminium AS Årdal has been producing aluminium since 1948. Today, there are over 500 employees. The plant consist of the primary aluminium facility, with two pre-bake lines, the casthouse, which delivers both sheet ingots and foundry alloys, and the carbon anodes production facility. The plant produces 204 thousand tonnes of primary aluminium, 279 thousand tons of casthouse products, and 172 thousand tons of carbon anodes. An industry-leading research centre is operated from Årdal [80].

4.2 Årdal Karbon

The carbon anodes production facility in Årdal produces anodes for the production of aluminium both in Årdal and Hydro's other aluminium producing facilities [80]. The anodes are a necessity for producing aluminium through the pre-bake technology used in Hydro. The anodes consist of a mix of petroleum coke, pitch and recycled anode pieces from used anodes and are moduled to a large block. The large carbon block is then baked in a large gas furnace. In the electrolytic cell, they are used for conducting the electricity in the aluminium production cell and are replaced when consumed [81].

In Årdal, the modelling process takes place at the green mill *(massefabrikken)*, before the anodes are transported through an overhead conveyor *(hengebana)* to the bakehouse *(anodefabrikken/brennovn)* where the carbon anodes are baked. There are two furnaces, named three and four. Furnace one and two is no longer existing and was used before three and four was built. There are several types of anodes produced, depending on which aluminium production facility they are made for. An unbaked anode is often described as *"green"*. The baking process takes up to two weeks, in temperatures above thousand degrees, which is needed to make sure the anode is ready for the conditions in the electrolytic cell, where the aluminium production occurs. The process is a cycle-based firing process, and delays due to the equipment's breakdowns could interrupt this process. The process can be delayed or reset *(tilbakesett)* to handle this, which causes a direct profit loss of **20 000 NOK** for every hour the process is delayed. After being baked, the anode is going through a final check before being packed ready for transportation to the different aluminium facilities in Norway. The carbon anode production process is visualised in Figure 20. The second step is marked due to this being the focus area of this thesis.

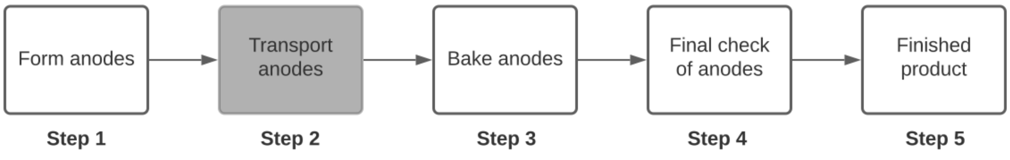

Figure 20: The production process

In the previous years, several investments have been performed at the facility to increase the production volume. Both furnaces have been expanded to keep track of the demand for larger carbon anodes. Updates on the purification facility were also demanded due to emission requirements. Today, an ongoing digitalisation project is initiated at the facility. This is further described in Section 4.3. The area of the facility being analysed in this thesis, the transportation line between the green mill and the bakehouse, is chosen due to the lack of control in the area. Available data of the area has not been analysed, but there is a common conception that this area reduces production efficiency, causes delays and is the reason behind profit losses. More details about this area are given in Section 4.4. The area is being analysed in light of how to assess the performance of the assets. The connection between Hydro's digital maintenance commitment and its asset performance strategy is described in the following section.

4.3 Digital maintenance in Hydro

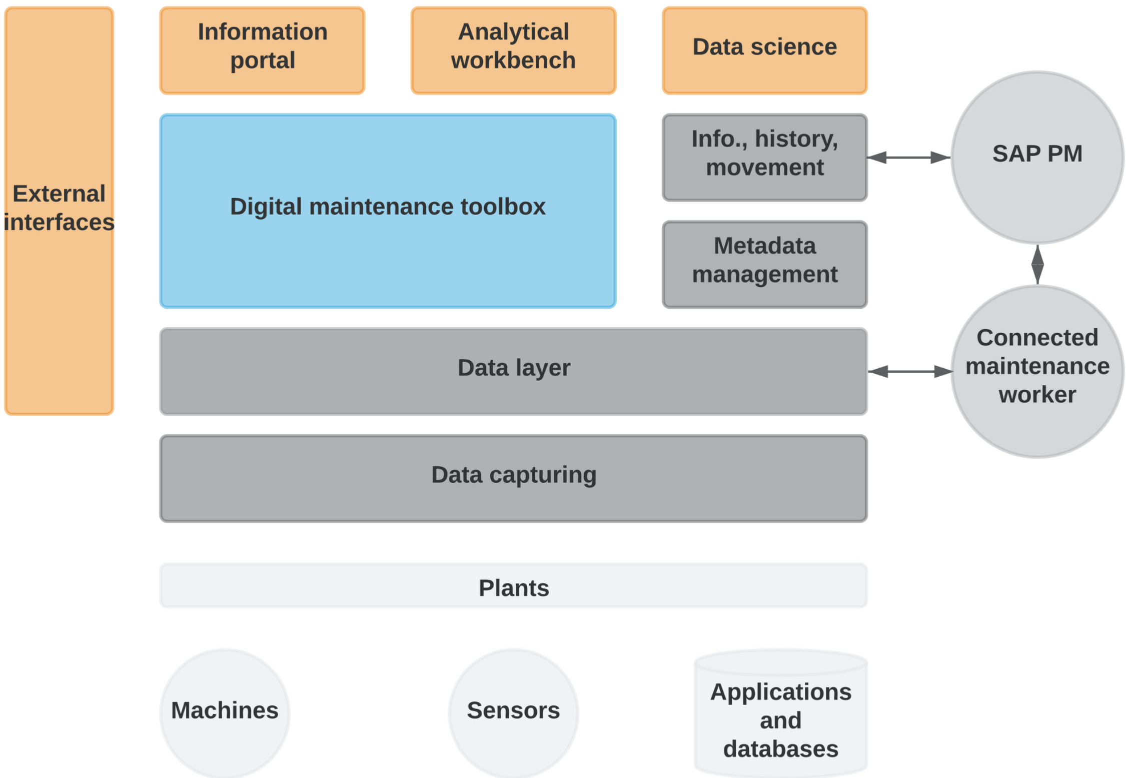

Figure 21: Hydro's conceptual architecture for digital maintenance

Source: Adapted from an internal figure in Hydro

Hydro is working towards a digital maintenance strategy, where the maintenance system, *SAP PM*, asset performance, IT and infrastructure and the organisation are set as focus areas. As the assets are ageing, new ways of working could capture the current situation to adapt the improvement measures towards a better path. An analytic workbench has been established in Hydro to keep track of the ongoing digitalisation. New tools have been included, and the idea is to liberate all the data gathered throughout the years. The conceptual architecture developed is visualised in Figure 21. Today, Hydro is working with data acquisition and data processing as the foundation for further condition monitoring and asset performance, in addition to machine analysis. The architecture involves capturing the data produced around the different plants from different sources, such as machines, sensors and different databases, with additional information. This data is made available in a data layer, the *trusted data layer (TDL)*. *Digital Maintenance Toolbox (DMT)* is developed for integrating new digitised tools in maintenance everyday life. The expansion of the *DMT* is visualised in Figure 22. From *root cause analysis*, the plan is to develop step-by-step until reaching *digital twin*. The steps include *visualisation*, *rule-based* alarms, *anomaly detection* and *machine learning*, where every step include more data and increases the complexity of the solution. Following this development, the step from inspection of failures on-demand to identifying failures automatically will be taken. This includes visualising important parameters, getting warnings from defined rules based on experience and utilising historical data for failure detection.

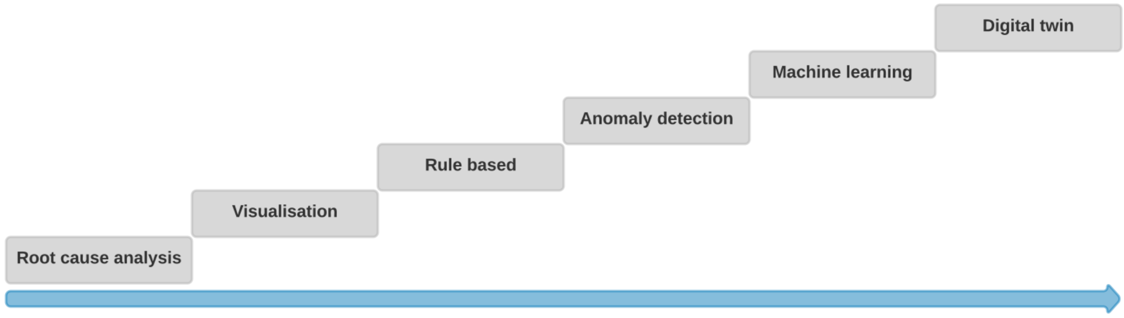

Figure 22: Overview of Hydro's digital maintenance development

Source: Adapted from an internal figure in Hydro

In Hydro, there are a lot of historical data available, both concerning maintenance and operations. The issue has been the accessibility of the data, but more and more data are now made available through the data layers. *SAP PM* has been Hydro's maintenance system since 1999, and most of their maintenance data, such as costs, hours spent, materials and maintenance strategies, are found here. This data is now made available through the cloud solution *SAP HANA*. The two new tools *SAP Analysis for Microsoft Office and SAP Asset Strategy and Performance Management Software (ASPM)* are integrated into Hydro's platform through the work with the *DMT*. These tools make use of the data from *SAP PM* and make the data more available.

APICS (Aluminium Production Information and Control System) is the MES solution used in Hydro, and it consists of different modules corresponding with the steps in the aluminium production process. It is developed in-house, and the different modules are built within a common development framework. The system can be operated through a web browser interface and is run off the local infrastructure. The module *APICS Carbon* is used at the carbon facility in Årdal. The *APICS PPP (Plant Performance Portal)* visualises the plants' current performance, where production stops and losses are reported, which is the basis for the overall equipment effectiveness (OEE) calculations. The information registered in *APICS* are stored in *TDL*, and reports are presented in *APICS PPP*.

Data from both of these tools, *SAP* and *APICS*, could be analysed to say something about the current status of a system. By combining it with condition data directly from the system, the performance of the assets could be evaluated, which is the idea behind the ongoing digital maintenance project, further described in the next section.

4.3.1 Ongoing project

As previously mentioned, there is an ongoing project with digital maintenance at the carbon facility in Årdal. The project initially was set in motion in Sunndal but has now transitioned to the green mill *(massefabrikken)* in Årdal. The project shall investigate asset performance and condition-based maintenance. The data to be used is available in *TDL* and visualised through *Grafana*, the solution Hydro has chosen as a dashboard for monitoring the alarms. This open-source tool combining data from several sources to a dashboard is used to visualise the assets and handle the alarms. The data used is data from the *SCADA* system throughout the facility, which is seen as a better solution than adding additional sensors. The data already generated by the system is now going to be used. This dashboard will be the user interface for the departments of both maintenance and operations. An additional alarm system connected to *Grafana* will be used for alerts if the condition measures reach a given threshold. The dashboard visualises the trends in the measurements. The idea is that a connection to *SAP* will make it possible to create maintenance orders easier. If an alarm goes off, it shall be able to investigate previous maintenance orders directly, to give a good indication for the cause behind the alarm.

The project is now in an initial phase, where the system and the available data is being analysed. The next step is to implement surveillance before taking a step towards measuring asset performance. The dashboard is then implemented before the goal is to update the maintenance plans and processes. The idea is to handle one area of the facility at a time. Before initiating the project, it was essential to identify the real business cases related to reducing the time spent on preventive maintenance due to the implementation of condition-based maintenance. The number of urgent maintenance actions could be reduced whilst also lowering the cost of the materials. When the integration of the digital tools is completed, it will be easier to identify root causes. This project, therefore, integrates the three first steps on Hydro's development plan towards digital maintenance, from Figure 22.

4.3.2 Maintenance strategy

The idea of making an integrated dashboard for both the maintenance department and operations is in line with Hydro's new maintenance strategy. The goal is for these two divisions to work together for the same mutual target. In order to improve the performance of the asset, the production efficiency, reduce profit loss, and work for continuous improvement, there is no room for internal competition, and everyone must therefore work toward the same target. Detecting and visualising profit losses and continuing down the digitalisation path are parts of the revised maintenance strategy. Another essential part of Hydro's maintenance strategy is integrating the new digital tools into the working process. Every step of the maintenance process could be strengthened by incorporating the new tools.

4.3.3 Asset performance

Asset performance will be necessary for Hydro's further development. This development is also significant beyond the aspect of maintenance. When transitioning from time-based inspections to condition-based maintenance through digital monitoring, time will be saved. By integrating the available data, optimisation of the operations is possible. The focus in Hydro is also to spend time on training to make sure that the development is understood and accepted. The development is for the entire organisation, and everyone must therefore be included. Hydro is working on several other projects regarding digital development and taking their data to use, and Hydro's future maintenance process is visualised in Figure 23, which is the direction Hydro is working towards. Digital tools are included throughout the entire maintenance process. Asset monitoring and analytics of collected data will be part of the daily work, enabling decision-making based on the collected data. The new digital tools will bring it all together for the future.

Required function is seen as necessary for the development towards asset performance in Hydro. Today, it is difficult to quantify the assets regarding loss in function, cycle times and availability. The different systems and assets consist of several components, and several parameters are affecting the availability. There are also several one-of-a-kind machines, which makes it even more difficult. Therefore, it is important to define the required function and compare what the asset delivers towards this requirement, which must first be completed on the assets with high criticality. By measuring the current asset performance, the awareness of how well the assets deliver will increase.

Decisions regarding what to measure and the requirements of the assets must be made to make this happen. The data available must be assessed and utilised. By surveying the performance, anomalies could be detected, linking condition monitoring and asset performance ideas. Profit losses could further be included. By increasing the awareness of the asset requirements, the asset performance, and the losses between them, asset performance management is possible. The balance between the performance of the assets, the costs and the risks must be found. Hydro focuses on the three aspects influencing this process, the assets, the people and the systems. By analysing

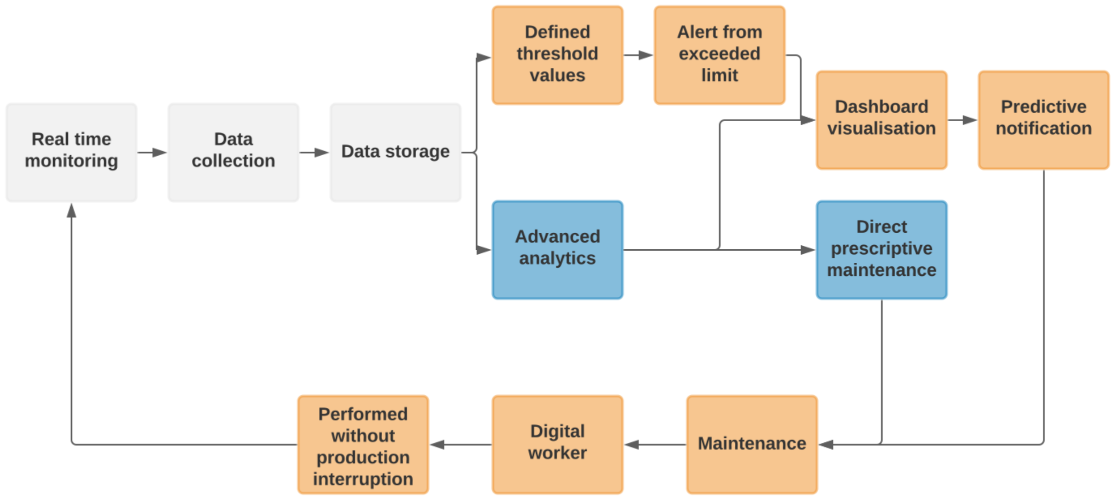

Figure 23: Hydro's future maintenance process

Source: Adapted from an internal figure in Hydro

the system chosen for this case study, the first step towards this direction is made. The following section will describe the process where the system of analysis, the transportation line of anodes, is used.

4.4 Process description

This area of the carbon anode production process is chosen due to the lack of control over the area. As outlined earlier, the area and system of analysis is the transportation line between the green mill *(massefabrikken)* and the bakehouse *(brennovn)*. The connection between this area and the rest of the facility is demonstrated in Figure 24. The figure shows the technical hierarchy of the transportation line, as used in *SAP PM*, Hydro's ERP solution. The boxes with ... indicate there being more sections of the hierarchy, but they are not included in the figure. The structure of the transportation line itself and the connection between the technical hierarchy and the functional location is further described in Section 5.1. The following paragraphs will elaborate on the process fulfilled by the transportation line of analysis.

After being moduled in the green mill, the carbon anodes are delivered to the bakehouse. The anodes are transported from the green mill with an overhead conveyor system *(hengebane)*, with attached customised hangers. When reaching the bakehouse facility, a shove stabilises the hangar and pushes the anode onto a lifting table. This table adapts to a roller conveyor *(rullebane)*, where a stopper makes sure the anode does not fall off. Four anodes make one package, and the conveyor transports them until reaching a scanner, registering the anode type. Six different types of anodes are produced at the facility. A stacker will further pile two anodes of the same kind on top of each other.

The anode package has now reached the storage unit for unbaked anodes *(grøntlager)*. The storage is automated, with an overhead travelling crane. The crane will collect packages of eight anodes (or four if it is the larger anode type) at a defined area of the roller conveyor. They are then placed in the storage unit while registering the type of anode, date, and storage location. When the time has come for ordering new anodes for the bakehouse, the automated crane will fetch the anodes stored the longest of the needed type, following the First In, First Out (FIFO) principle. The crane places the anodes back on the roller conveyor, where they will continue towards the furnaces. Another stacker makes sure the right amount of anodes will be delivered. The automated crane places the excess anodes back into defined positions at the storage. Due to this storage, there is a buffer of carbon anodes in case of stops in production at the green mill or breakdown in the overhead conveyor *(hengebane)*.

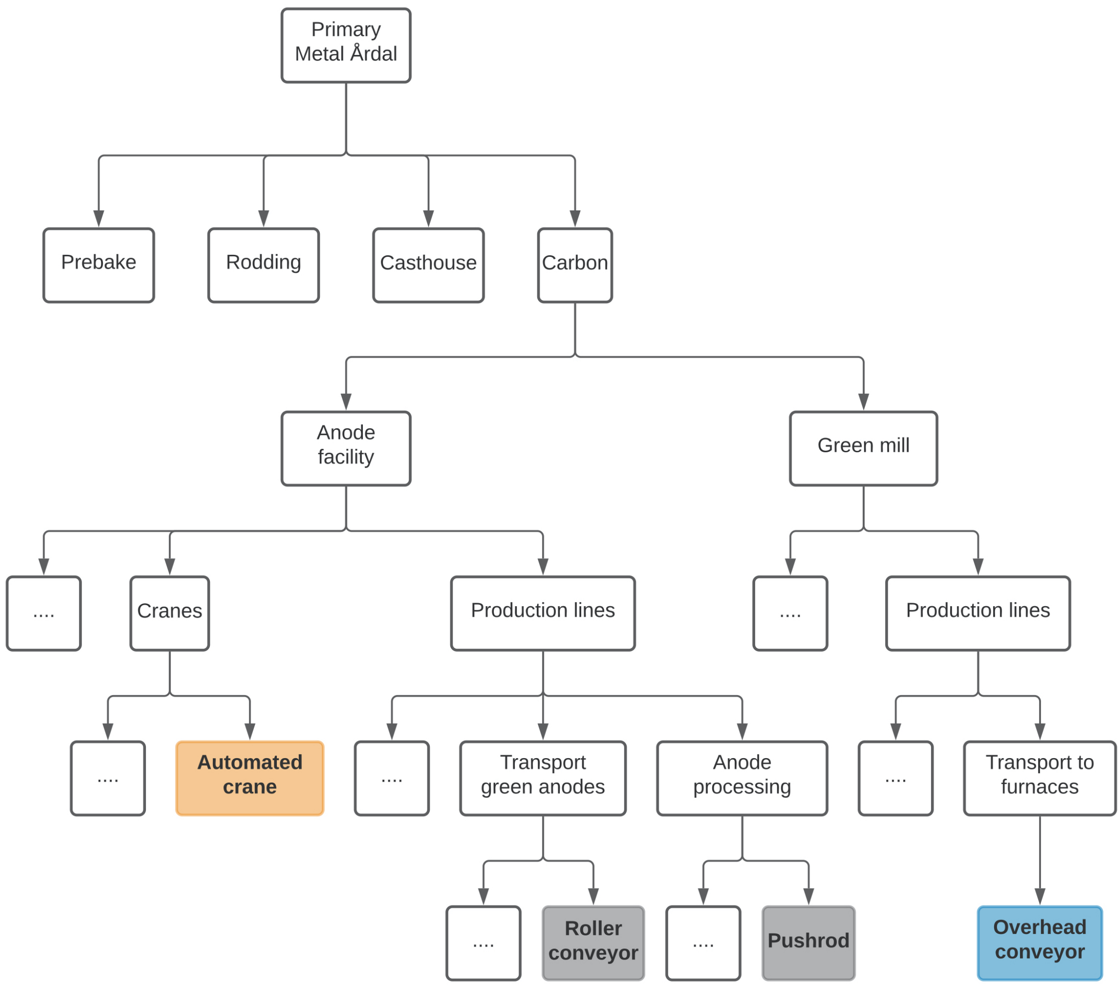

Figure 24: Overview of the technical hierarchy for the transportation line

Using a lowering table, the anodes moving towards the two furnaces are now at the right height for the turners, which turns the anodes into a standing position. Another lifting table will lift the anodes ordered for the first furnace. They are shoved towards the turner, where the anodes are turned and finally reaches another hydraulic conveyor *(pushrod)*, where an overhead transporting crane will lift the anodes to their destination in the furnace. If the anodes are for the second furnace, they continue beyond the first furnace's turner, reaching the shove pushing the anodes to the turner for the second furnace, which turns the anodes. The anodes will then be pushed onto the *pushrod* for this furnace. After the anodes are backed in the furnaces, they are transported through the *pushrod* and into the control facility *(sluttkontroll)*, which is the last stop before the anodes are ready for transportation to the aluminium production facilities.

This describes the process fulfilled by the transportation line, which is to be analysed as described in Section 2, for the need to get control over the transportation line and determine the line's performance. The available maintenance and operation data for this process and transportation line will be elaborated throughout Section 5. This data and the results of the data analysis, together with a functional overview and required function analysis performed, will result in an overview of the performance of these assets.

5 Case study results and analysis

The transportation line fulfilling the process described in Section 4.4 was analysed, as described throughout Section 2 and in line with the theoretical background in Section 3. As described in the methodology, the case study was divided into an analysis of the system itself and an analysis of the available data. The following sections report the results before discussing the results in Section 6. The results are divided into four parts. The first defines the system before the functional and physical architecture is analysed. The third part reports the findings of the data analysis, while the fourth and final part analyses the required function of the transportation line, based on the system and data analysis.

5.1 System definition

Figure 25 gives an overview of the transportation line's interaction with the rest of the facility. From the green mill *(massefabrikken)*, the first part of the transportation line, **the overhead conveyor** *(hengebana)*, transports the carbon anodes to the second part of the line, **the roller conveyor** *(rullebana)*. The third and final part of the line is **the automated storage** of green anodes *(grøntlager)*. The roller conveyor transports the anodes further to the furnaces *(brennovn)*, before the anodes reach their final step, where the standard is checked, before finished product *(sluttkontroll)*. The three parts of the transportation line got one colour to separate the parts throughout the report. The three sub-systems together compose the transportation line analysed, which fulfils the function of transporting the green anodes from the green mill to the furnaces.

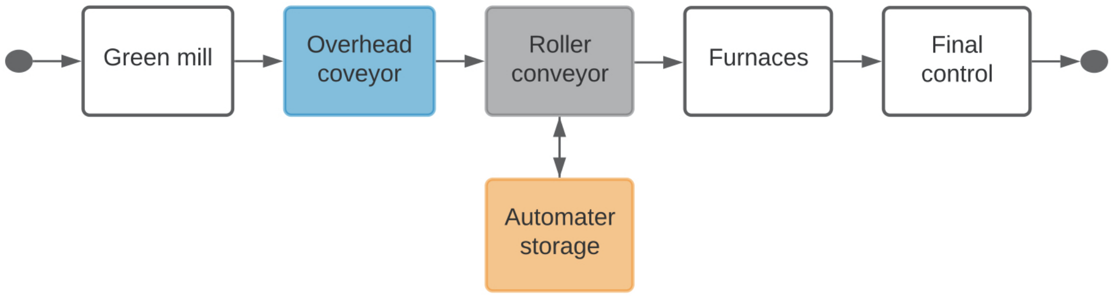

Figure 25: Overview of the transportation line

The transportation line consists of several components, 36 in total. An overview of the different components is found in Figure 26. The abbreviations used for the components are shown in Table 4, in Appendix B.1. The different components each fulfil a task along the transportation line. The same colours separating the parts of the transportation line in Figure 25 are also used in Figure 26. The function of each component is further described in the next section while describing the task of each sub-system. The component overview is based on the technical hierarchy, visualised in Figure 24, in *SAP PM*, the ERP system used at the facility. The hierarchies are found in Appendix A. In addition to the information found in *SAP*, internal documents and procedures in Hydro describing the transportation line and the process formed the basis for this system analysis.

When performing the system analysis, the environment, the interactions, the life-cycle, and the transportation line's requirements are investigated. The line is managed by the operator at work in the facility and controlled by *ABB's* operational control system. The environment of the transportation line is therefore affected by the control system. The maintenance personnel interacts with the assets for failure repairs and preventive inspections. The transportation line is affected by the energy supply and power source system. The other environmental aspects of the transportation line are the green mill and the rest of the anode production facility, acting as external systems influencing the assets. The assets themselves are in the operational and maintainable phase of their life cycle. There is no alert given before transitioning from a normal condition to a degree of failure. There is no pattern to when maintenance is needed, except the time-based

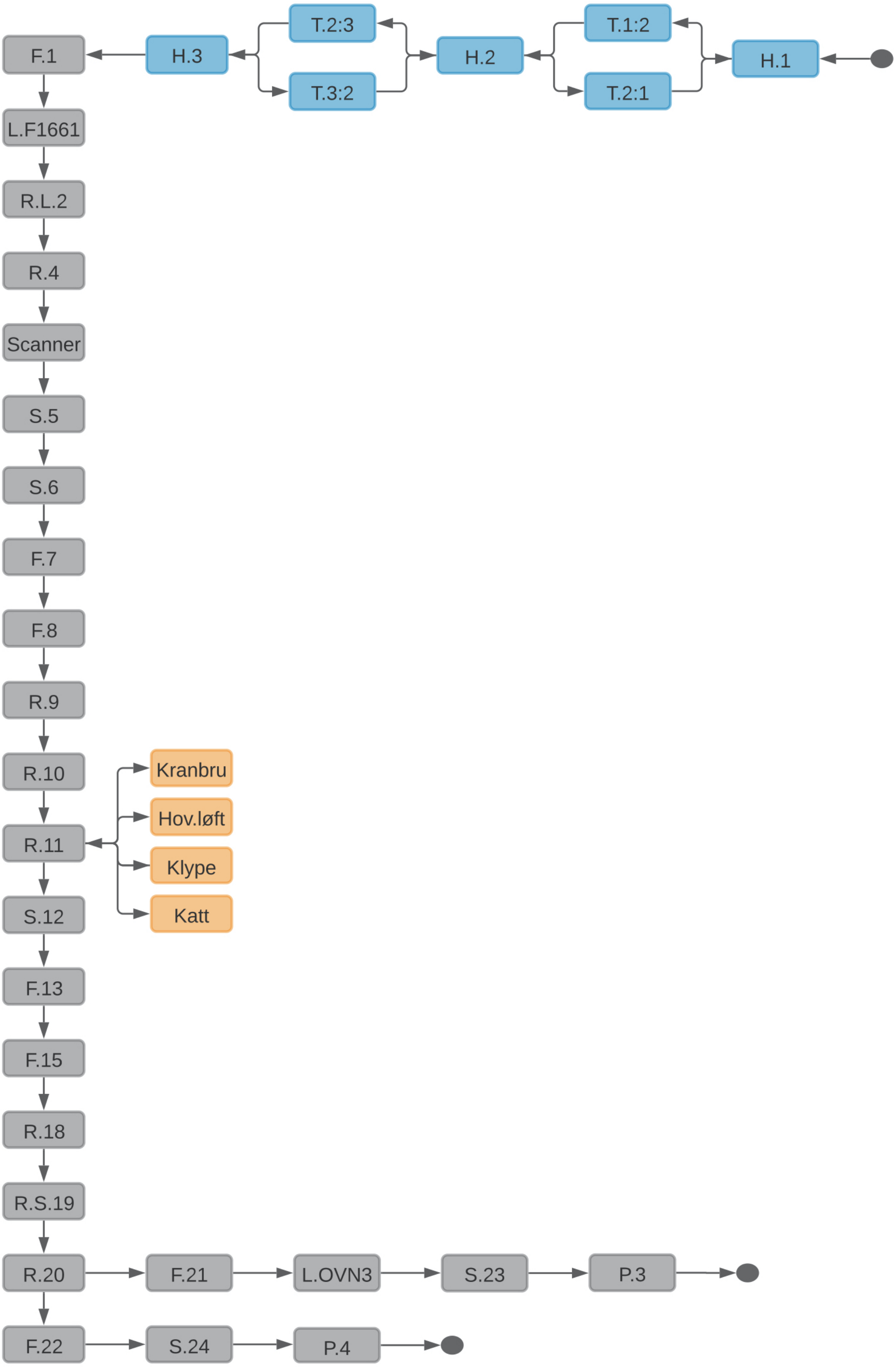

Figure 26: Overview of the components in the transportation line

preventive inspections completed on the transportation line. The system requirements are related to the transportation line being available whenever there is a need for transporting anodes. The transportation line must be safe, and the anodes delivered when required.

5.1.1 Sub-system 1 - Overhead conveyor *(hengebana)*

The overhead conveyor transports the anodes on hangers from the green mill to the anode-baking facility. This transportation line consists of seven components, as shown in Figure 26 and 40, found in Appendix B.2. *H.1*, *H.2* and *H.3* are the three parts of the conveyor, while the other four components are transfer links between the conveyor divisions. In addition to these seven components, an electrical control component handles the conveyor and the components. The conveyor is the only transportation line for the anodes. Hence, there is no redundancy in case of failures. The conveyor is used whenever the green mill modules anodes and is crucial for getting the anodes to the storage unit, where then anodes are stored while cooling down. The green mill produces anodes minimum 14 of 18 shifts during the week, which imply up to **32 hours** of downtime. The transportation process depends on *the overhead conveyor's* availability anytime there is a need to transport the anodes. Throughout the week, the conveyor transports every anode produced in the green mill. The goal is approximately **4000 anodes**. The transportation time from the mill to the storage unit is about **45 to 60 minutes**.

5.1.2 Sub-system 2 - Roller conveyor *(rullebana)*

The roller conveyor transports the anodes from the end of *the overhead conveyor* to *the automated storage* and further along to the furnace's baking the anodes. The process is described in Section 4.4, and the system is visualised in Figure 26 and 41, found in Appendix B.2. This sub-system is the biggest of the three and consist of 25 components, all fulfilling their task. The first twelve components transport the anodes from the overhead conveyor to the storage. The anodes are first shoved *(F.1)* from the hanger on *the overhead conveyor* to a lifting table *(L.F1661).* When a package of anodes, consisting of four anodes (or eight), is ready, this package is then transported on the rollers *(R.L.2* and *R.4)* past the *Scanner*, registering the type of anodes transported. Further, two components are stacking the anodes *(S.5* and *S.6)*, two shoves for pushing the packages towards the pick-up for the automated storage *(F.8* and *F.8)* and three components of rollers *(R.9, R.10* and *R.11).* At *R.11*, the packages are picked up for storage, or delivered by the crane whenever the furnaces need anodes.

The 13 components left is responsible for transporting the anodes from *the automated storage* towards the furnaces. Another stacker *(S.12)*, two shoves *(F.13* and *F.15)* and three rollers *(R.18, R.S.19* and *R.20)* all play their part in further transportation of the anodes. At *R.S.19*, the anodes are lowered towards the first furnace, before *F.21* shoves the anodes onto *L.OVN3*, which raises the anodes to reach *S.23*. The anodes are flipped and reach their destination at *P.3*, where an overhead travelling crane will take over and place the anodes into the furnace. If the anodes are for the second furnace, *F.22* will push the anodes further towards the transportation line, where *S.24* turns the anodes onto *P.4*, equivalent to the first furnace. This sub-system, similar to the remaining transportation line, consists of components performing their specific task. Since the transportation line is a series of components, there is no redundancy at the conveyor in case of failure, and the line is required to perform when transporting anodes to the storage from the overhead conveyor and the furnaces orders anodes. About **4000 anodes** per week are transported from the end of *the overhead conveyor* towards *the automated storage.* From the storage until the furnaces, about **3800 anodes** are transported throughout the week. The furnaces orders anodes around **3.7 times** per day (furnace three every 14 hours, every 14.5 hours for furnace four), and every time anodes are transported towards the furnaces, the number of anodes varies between **147 and 168** per production order. Every order consists of 21 parts, where the transportation time of the first is about **15 minutes**, while the transportation time of the entire batch is **1.5 hours**.

5.1.3 Sub-system 3 - Automated storage *(grøntlager)*

The third and final sub-system consists of the anode storage with an automated overhead travelling crane. The crane fetches anode packages of either four or eight anodes from *the roller conveyor* and places them in the storage, as described in Section 4.4. This sub-system is visualised both through Figure 26 and 42, found in Appendix B.2. This storage acts as a buffer if something happens during the first part of this transportation line. If there is downtime at the green mill, *the overhead conveyor* or the first part of *the roller conveyor*, this will not affect the furnaces directly since the anodes are distributed from this storage and not directly from the green mill. The anodes coming to the storage requires cooling time for **24 hours** before these anodes could be put into the furnaces. The storage could deliver anodes for the furnaces for a few days, in case of breakdowns at the green mill, or *the overhead conveyor*. The crane itself consists of four main parts, the bridge of the crane *(Kranbru)*, the main lifter *(Hov.løft)*, the trolley *(Katt)* and the clamp *(Klype)*, in addition to the electrical control of the crane. This sub-system is required to deliver when anodes are stored and ordered for the furnaces. The automated crane at the storage transports up to **4000 anodes** into the storage every week, while the furnaces demand about **3800 anodes** per week. **3.7 times a day**, the production orders anodes for the furnaces, and every time the storage delivers an average of **156 anodes**. Similar to the entire transportation line, there is no redundancy. The interaction between the functional and the physical architecture of the transportation line is further described in the next section.

5.2 Functional and physical architecture

The system architecture merges the point of views of the transportation line and is helpful for complex industrial systems. The operational aspect, the role and the needs of the transportation line is already described in Section 5.1, 4.2 and 4.4. There is a need to detect the transportation line's problem areas to investigate further how asset performance could be helpful for this system. Hence, investigations of the functional physical architecture establishes the integration between the functions and the components of the transportation line, as described in Section 2.2.1.

The transport line's function is to distribute the anodes for the baking process, which could be divided into the sub-functions of transportation and storing, as visualised in the top part of Figure 27. The transportation function could further be divided into overhead convey transportation, which fulfils the transporting of the anodes, and rolling convey transportation. *The rolling conveyor* accomplishes the tasks of shoving, lifting, transferring, stacking and rotating the anodes. The sub-function of storing the anodes completes the functions of logging and lifting the anodes. These are all the functions required for delivering the anodes to the furnaces. This assignment of main and sub-functions aligns with the standard NORSOK Z-008:2017, based on the technical hierarchy. By connecting the technical components with the functions, this develops a functional hierarchy [27].

While looking further into the transportation line's physical architecture, identification of the components fulfilling the function was performed. Section 5.1 describes the components in the transportation line. The assets themselves are divided into the sub-systems earlier identified, *the overhead conveyor*, *the roller conveyor* and *the automated storage*, visualised from the bottom of Figure 27. The different components belonging to the sub-systems are identified with the same colours used in Section 5.1. The interaction between the parts and the functions of the transportation line is then made. These are shown with the different colour lines between the functional architecture and the physical architecture. This decomposition of the functional and physical role of the transportation line gives an overview of how the required function of the system is fulfilled through the components, as described through the *Risk based maintenance and consequence classification* standard [27].

As demonstrated in Figure 27 several components are fulfilling the same function due to the creation of the transportation line, which is not unambiguous with other parts being able to fulfil their task in case of breakdowns or failures. The different components perform different functions along the transportation line, even though several parts are doing the same job. As identified in Section 5.1, the transportation line is built in series, with no redundancy (*"the entire system is required*

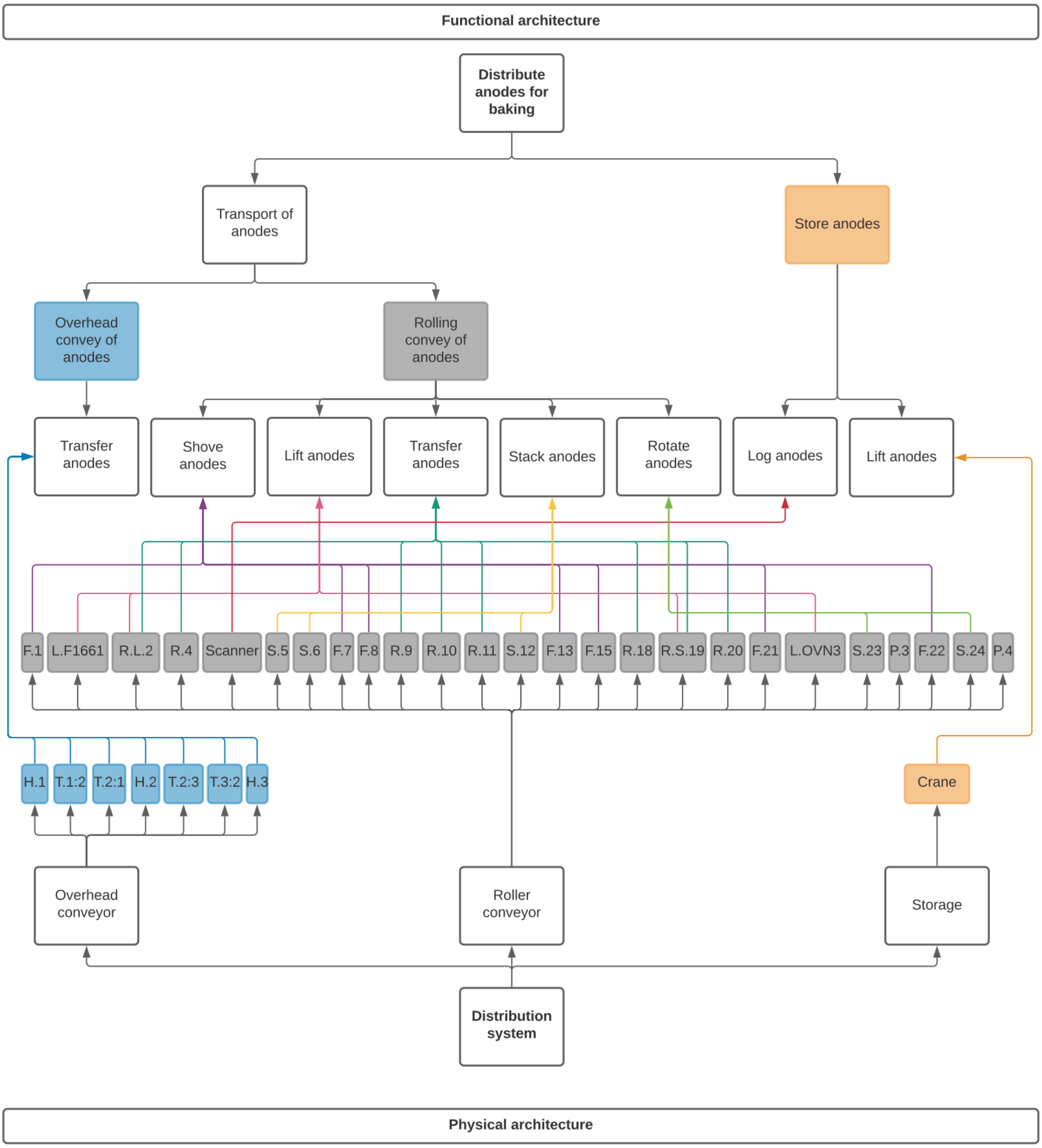

Figure 27: Functional and physical architecture of the transportation line

to avoid any loss of function" [27]). If failures occur along the transportation line, this would therefore affect the production process. A failure before the automated storage will not affect the baking process directly due to the storage acting as a buffer since the anodes are delivered from the warehouse. The warehouse has the capacity to deliver anodes to the furnaces for a few days. Failures with the automated crane at the storage are more critical, just as failures at the conveyor towards the furnaces. The baking process of the anodes demands anodes **3.7 times** a day, with a transportation time of minimum **1.5 hours** per batch. Another important aspect if a failure occurs right in front of the two furnaces. There is no redundancy, and breakdowns here could affect both of the furnaces, which is further described throughout the results. The following section will look closer into the available data for the transportation line, identifying the current state of the line and the areas most critical for possible downtime, profit loss and reduced production efficiency. Together with this system analysis, the results from the data analysis will build the foundation of the assessment of the required performance of the transportation line in Section 5.5.

5.3 Data analysis

For evaluating the condition of the transportation line and identifies areas where improvements are needed, an analysis of the available data is needed. This data could point towards the identification of profit loss and help recognise the transportation line's challenges. The available data to analyse for the transportation line are the *SAP* records, the maintenance information about the transportation line, the downtime records of the operational process and the setback records *(tilbakesetting)* for identifying direct profit loss. Condition data directly from the transportation line would also be relevant, but this data was not available for this analysis. The available data has been through data collection, data cleaning, and data visualisation to gain insight into the transportation line. The next sections will elaborate on the analysis performed and the results and perception of the data. The results is discussed in Section 6.

5.3.1 Maintenance history *(SAP records)*

The maintenance history available for the transportation line is the maintenance data collected in *SAP*, where all the maintenance activities are managed. Inspections, notifications, work orders and repairs are found in the system, gathered around the technical objects and the functional locations [82]. Through using transaction codes and the functional locations of the transportation line analysed, the data available was collected. By using transaction code *IW39* in *SAP*, the maintenance work orders were displayed. This data is structured and possible to fetch into an excel sheet. Information about what type of maintenance, the costs of maintenance actions, the duration of the repairs and inspection is found using this transaction. The maintenance notifications, giving information about which component of the transportation line, the problem identified and the cause behind the failure, was found using transaction code *IW69.* Information about the priority, date and maintenance category can be found using this transaction. The maintenance notifications are made when a problem occurs, while the maintenance orders are created when the repair is scheduled. Data from both of these transactions were collected to be further analysed.

The data collected in excel sheets from *SAP* was analysed using scripts written in *Python.* The scripts were written in *Jupyter Notebook*, to get instant feedback when transforming and visualising the data [83]. *Pandas*, a data analytic and manipulations tool [32], was used for systematising and grouping of the data, while the tool *Matplotlib*, was used for data visualisation [34]. The data was analysed through the written scripts found in Appendix C, where some transformation of the data was performed to visualise the key information. A ten-year duration from **2011-1-1** to **2020-31-12** was chosen. By analysing these *SAP* records, information related to maintenance cost, maintenance frequency, duration of maintenance activities, functional locations demanding more frequent maintenance, repeated failures, failure causes and failures with high priority was found. The following results highlight the most important features found, mapping the current status of the transportation line.

In *SAP* seven maintenance categories are used, *Z001, Z002, Z003, Z004, Z005, Z006* and *Z010*. The most frequently used are the first two, preventive and corrective maintenance. The other categories are variations of modifications, investments and more complex repairs. The bar plot in Figure 28 show the distribution of these different maintenance categories. The number of maintenance orders per functional location is plotted for the various categories. As shown, there is an overweight of maintenance orders for *Z002 (orange)*, which indicates corrective maintenance. For some of the locations, the frequency of maintenance orders for *Z001 (blue)* is highest, indicating more preventive maintenance. Areas that demands a high frequency of maintenance actions is *P.3*, *P.4*, *Hydraulikk*, *Klype*, *H.1*, *H.2*, *R.11*, *R.20* and *S.23*, when using the abbreviations used in Section 5.1, found in Appendix B.1. *Hydraulikk* was not identified as a unique part of the transportation line during the system definition, since it includes the hydraulics for the entire system. One explanation for there being a high rate of maintenance orders for *P.3* and *P.4*, is that this part of the transportation line is also used for transporting the anodes after the baking process is finished. Thereby, maintenance actions not directly connected to the transportation line of the anodes is included for exactly that part of the system.

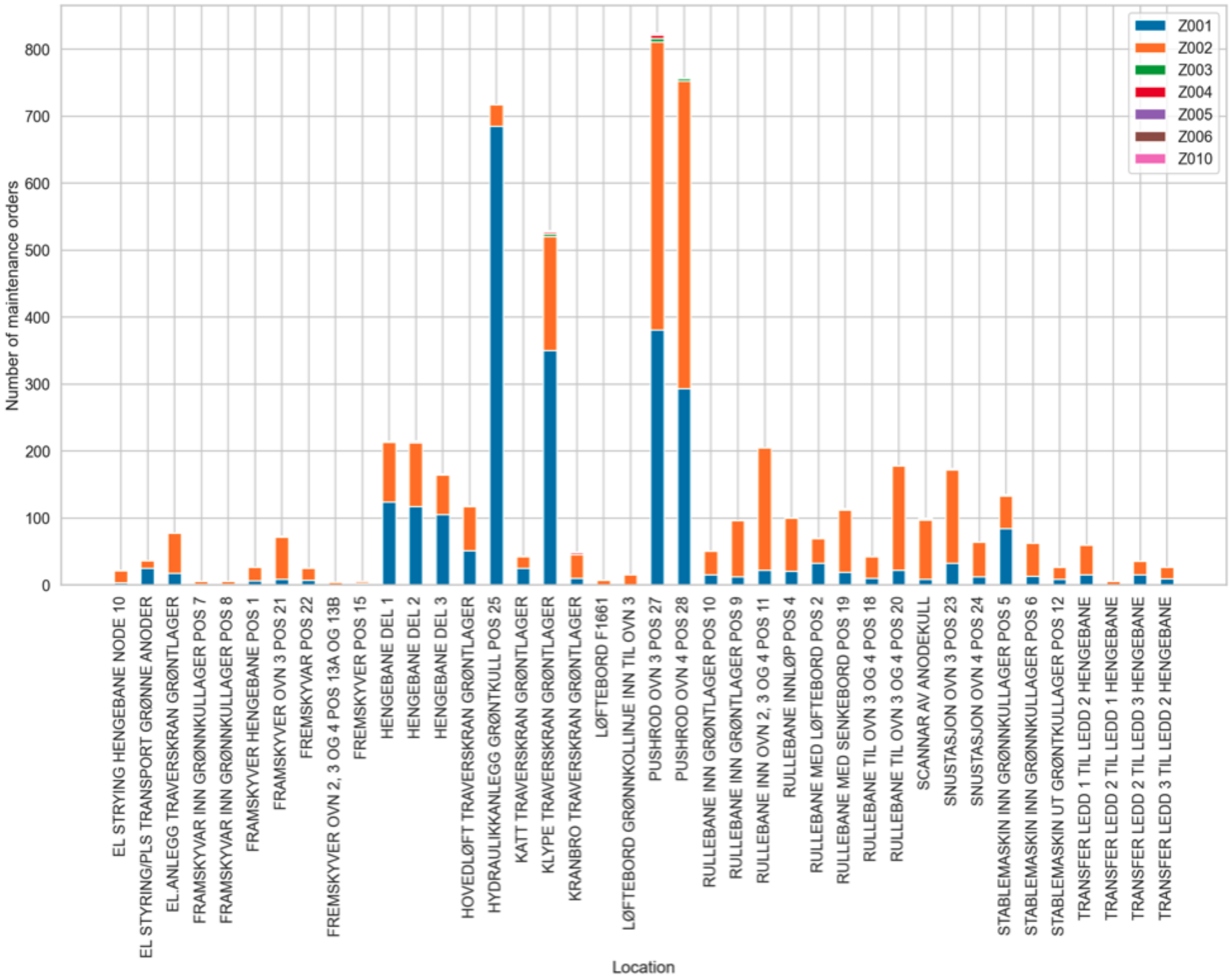

Figure 28: Number of maintenance orders per functional location

During the ten years of this analysis, there was a total of **5469** maintenance orders completed, which indicates **1.5** maintenance order per day over the last ten years. **2559** of these orders was preventive maintenance actions, while **2862** of them was corrective actions. The remaining **48** was distributed over the five other categories. The 5469 maintenance orders give a mean number of maintenance orders per location of **273**, which shows that both *P.3*, *P.4*, *Hydraulikk* and *Klype* clearly brings this average up. These are also the same parts with a higher portion of preventive maintenance actions. Together these four areas contribute to **2847** of the maintenance orders, equalling to **52%** of the maintenance orders.

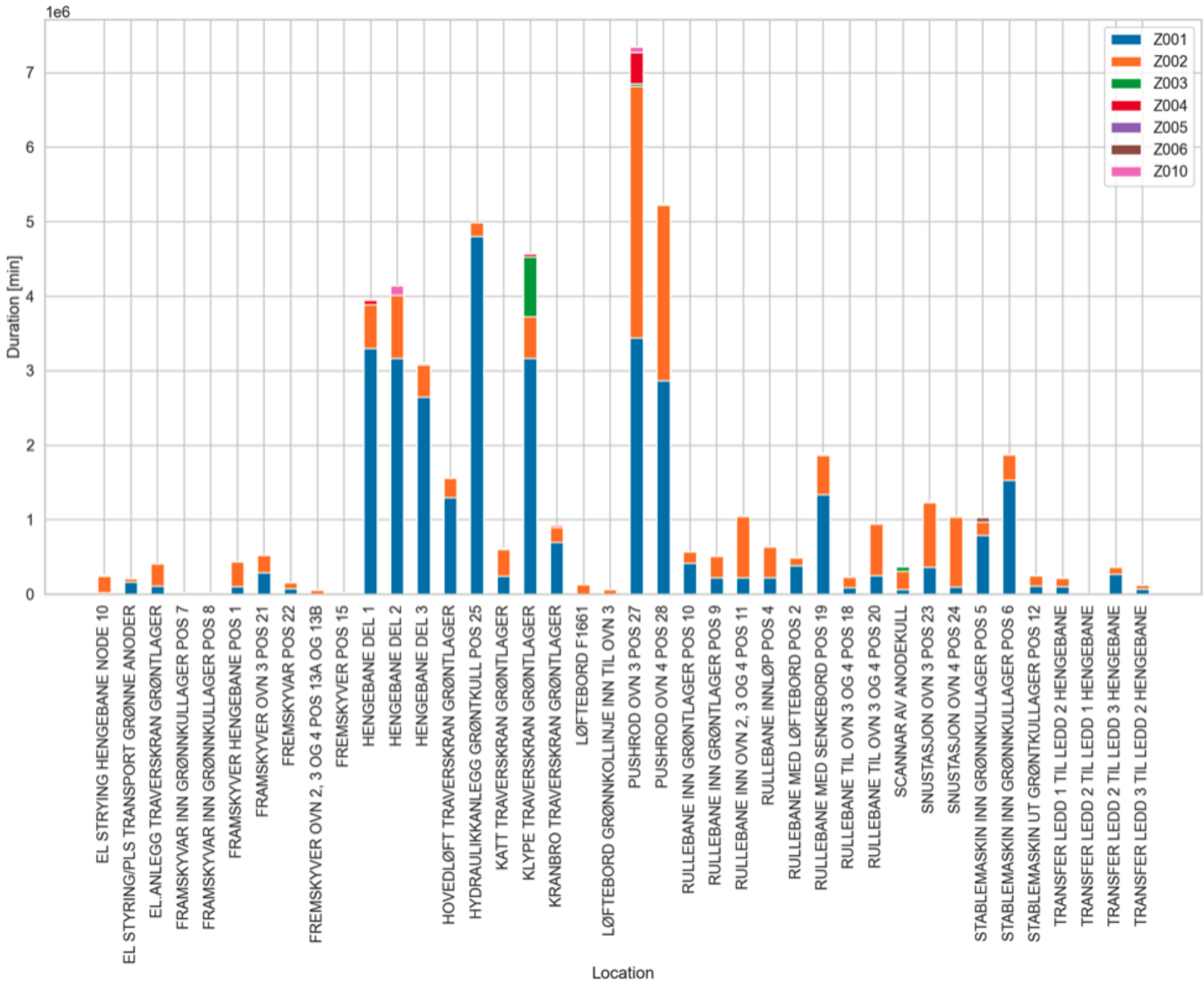

Figure 29: Duration of maintenance orders per functional location

While looking further into the duration of the maintenance actions, the bar plot in Figure 29 was created. The tendency found in Figure 28, where there is an overweight of corrective actions, are not reflected in this plot. A considerable amount of the time spent is on preventive actions. For *P.3* and *P.4*, the duration is more evenly spread between preventive and corrective actions. Throughout these 10 years, *32 916 751 minutes* was spent on preventive maintenance actions, equalling over **62 years**, while *16 783 424 minutes* was spent of corrective actions, equalling almost **32 years**. The other categories adds up to *3.6 years* of maintenance actions. Mean duration of maintenance actions per location balances out to *1 289 739 minutes*, equalling **128 974 minutes** or **0.25 years** of maintenance actions on average per location in the transportation line. This means that *P.3*, *P.4*, *Hydraulikk*, *Klype*, *H.2*, *H.1*, *H.3*, *R.19*, *S.6* and *Hov.løft* are clearly above the average. These locations stand for **75%** of the total duration spend on maintenance actions. This means that one fourth of the different parts of the transportation line utilise three fourths of the maintenance resources measured in time spent.

While investigating the cost of the maintenance actions, there is a predominance of the cost related to corrective maintenance, as visualised in Figure 30. Figure 29 shows that most of the time spent on these same locations were preventive maintenance orders. The same functional locations with a larger portion of the maintenance orders and duration related to preventive maintenance have a higher cost of corrective actions. The locations with the highest number of maintenance actions, duration and cost related to preventive maintenance are also the locations spending most on corrective maintenance. Total maintenance cost over these last 10 years are **31 715 330 NOK**, which gives an average of **792 883 NOK** per location over these years, or **79 288 NOK** per location per year. *P.4*, as the location with highest cost, is clearly above the average with its cost of **4 136 029 NOK** over the years, and **13%** of the total maintenance costs. *P.3*, *Klype*, *H.1*, *H.2*, *H.3*, *Hov.løft*, *Hydraulikk*, *S.23*, *R.11*, *Kranbru* and *R.20* are also clearly above average. The five locations with the highest cost of these 40 locations, contributes with **55%** of the total maintenance costs.

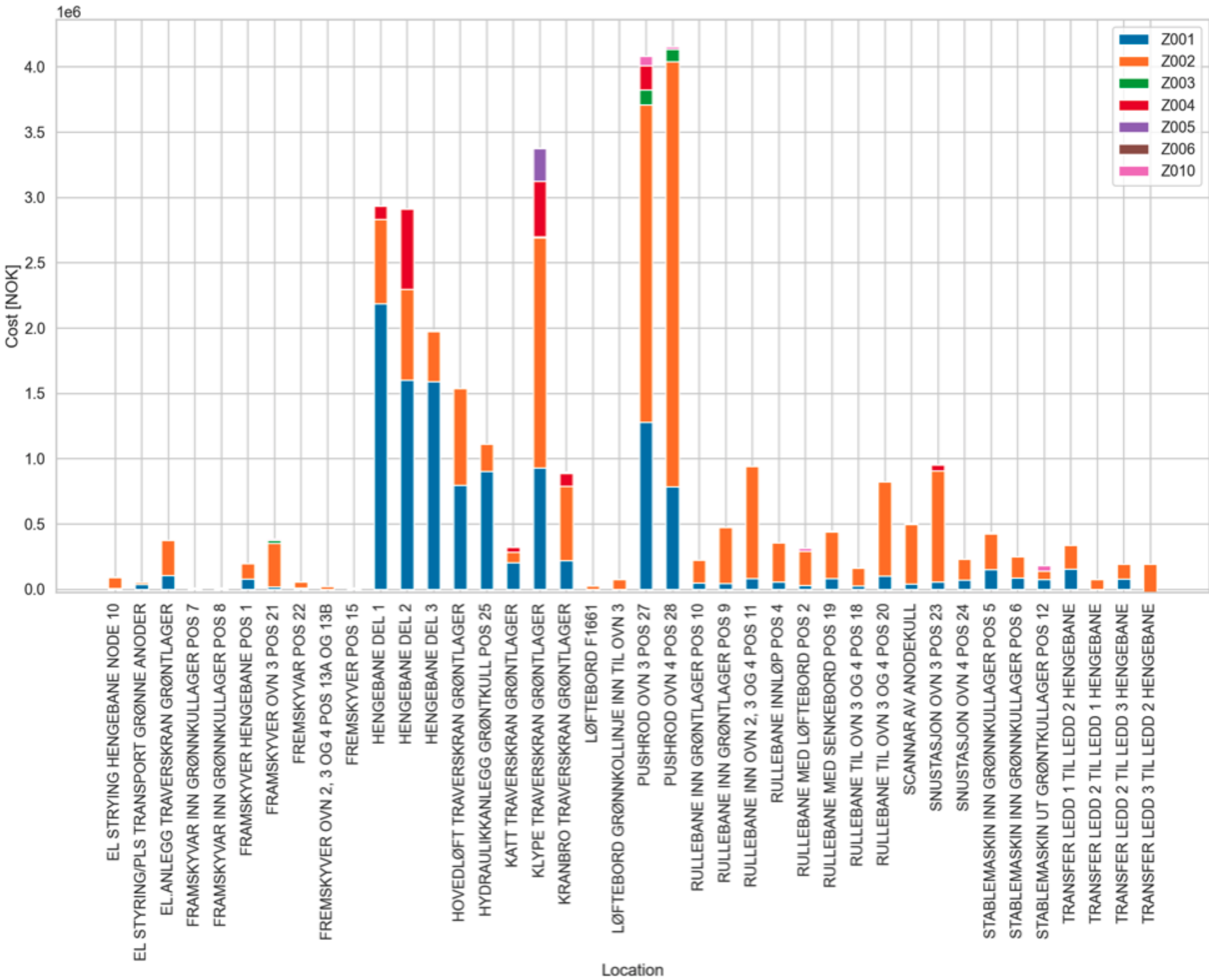

Figure 30: Cost of maintenance orders per functional location

From the plots in Figure 28, 29 and 30 it is shown that most of the maintenance actions, both related to frequency, duration and cost are related to the categories from *SAP* representing preventive and corrective maintenance. The preventive maintenance performed are mostly inspections, and routine based actions, such as lubricating and cleaning. When investigating this data in total, the areas requiring the most maintenance orders, the most time and money, is *P.3*, *P.4*, *Hydraulikk*, *Klype*, *H.1*, *H.2*, *H.3*, *R.11*, *R.20* and *S.23*. When there is a sense of not being in control of the assets, this is related to the corrective maintenance, which are failures leading to stops and breakdown. There is no warning before failures. Traditionally, inspections are performed to identify degradation. Hence, the further analysis of this data will be limited to the corrective maintenance orders and notification, represented with *Z002* in *SAP*.

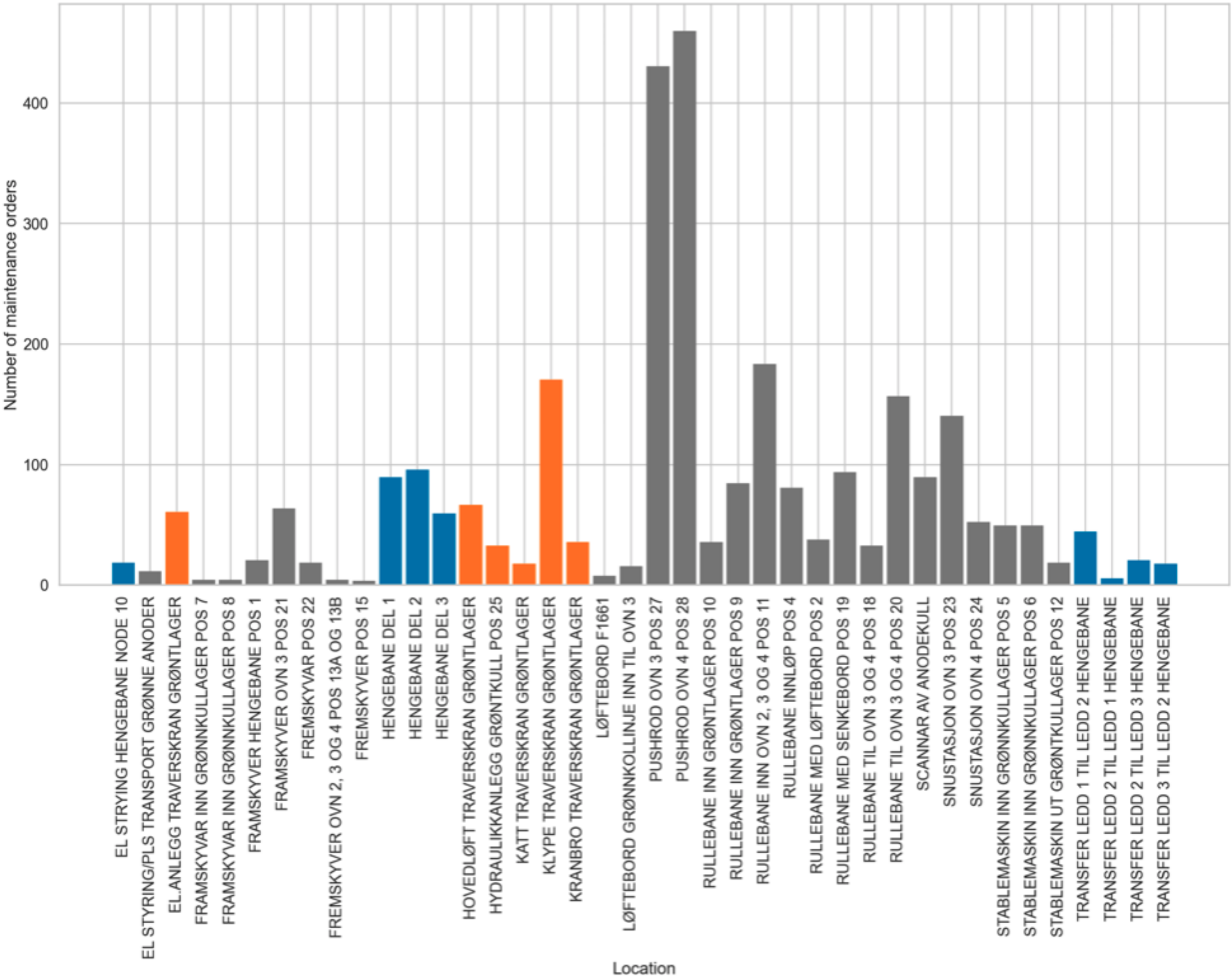

Figure 31: Number of corrective maintenance orders per functional location

In Figure 31 the number of corrective maintenance order per functional location is visualised. The different locations has the same colours as used in Section 5.1. The *grey* locations represent *the roller conveyor* and the *blue* locations represent *the overhead conveyor*, while the *orange* represent *the automated storage*. Over these 10 years, there was a total of **2862** corrective maintenance orders, indicating **0.8** corrective maintenance orders per day over the last ten years just for the transportation line. The location with the most maintenance orders is *P.4*, with its **459** maintenance orders, equalling **16%** of the total number of orders. The average number of maintenance orders is 72, making *P.4*, *P.3*, *R.11*, *Klype*, *R.20* and *S.23* clearly above average, all with over 100 corrective maintenance orders over these last ten years. These six locations contributes to **54%** of the total corrective maintenance orders. Looking closer to the three sub-systems defined in Section 5.1, *the overhead conveyor* contributes to **12%** of the maintenance orders, less than *P.4* alone. *The automated storage* provides **14%**, while *the roller conveyor* is the cause of the rest of the corrective maintenance orders, equalling **74%**.

Figure 32 represent the duration of the corrective maintenance orders. From the transportation line, the locations of *P.3*, *P.4*, *S.24*, *S.23*, *H.2*, *R.11* and *R.20* differs from the other in aspect of duration length. During these ten years, **16 783 424 minutes** are spend on corrective maintenance orders, giving a mean duration per location of **419 586 minutes**. This means that in addition to the six locations already mentioned, *H.1*, *Klype* and *R.19* are above the average. *P.3* with the highest amount of minutes spend on corrective actions, contributes with **20%** of the total duration.

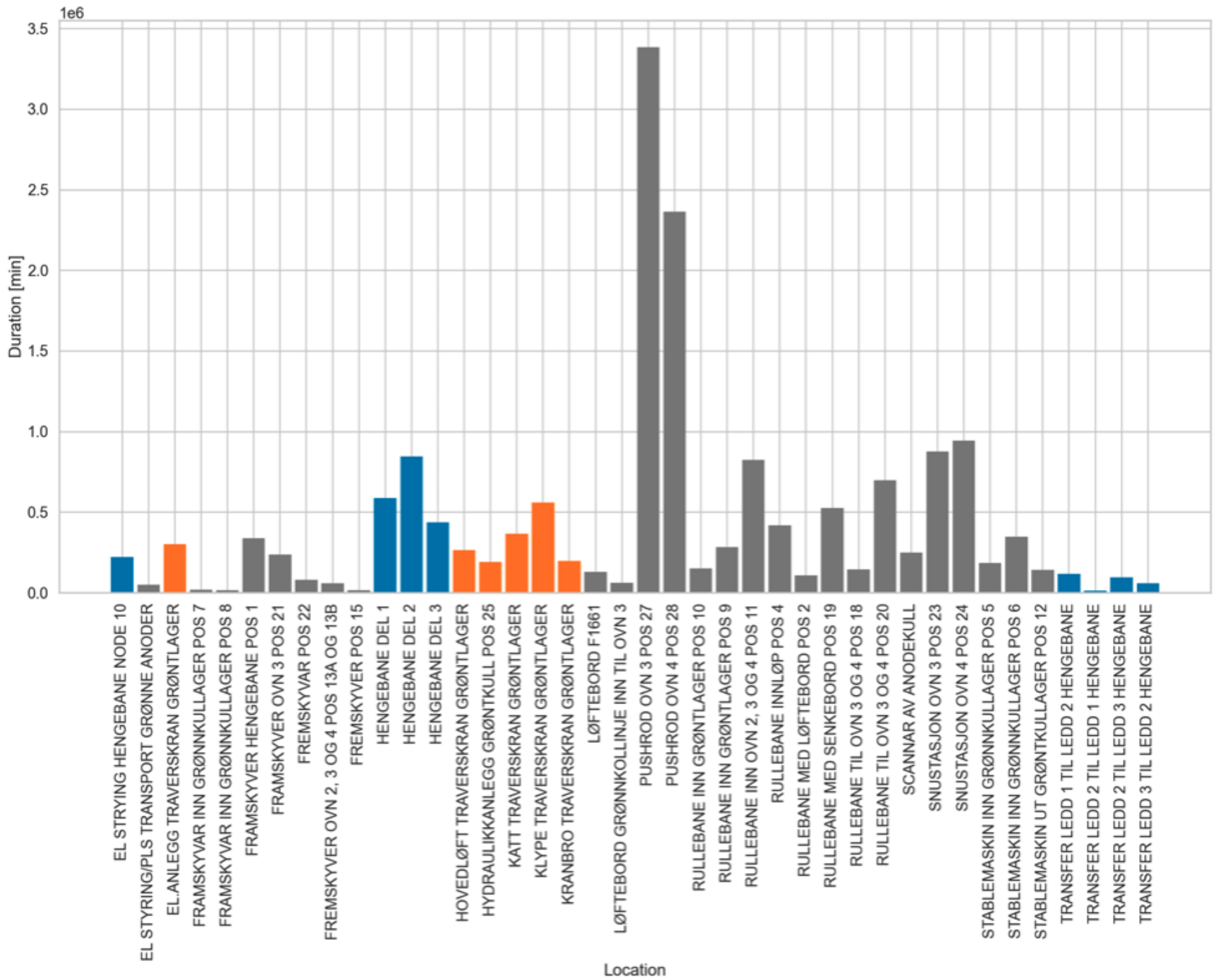

Figure 32: Duration of corrective maintenance orders per functional location

When looking at the cost related to the corrective maintenance actions, the locations of *P.4*, *P.3*, *Klype*, *R.11*, *S.23*, *Hov.løft*, *R.20*, *H.2*, *H.1* and *Kranbru* are above average, as shown in Figure 33. The total cost related to the corrective maintenance actions over these ten years adds up to **17 579 134 NOK**, which gives an average per location of **439 478 NOK**. The areas mentioned is all above this average. *P.4* and *P.3*, as the two parts costing way above the others, stands for **32%** of the total costs related to the corrective maintenance actions.

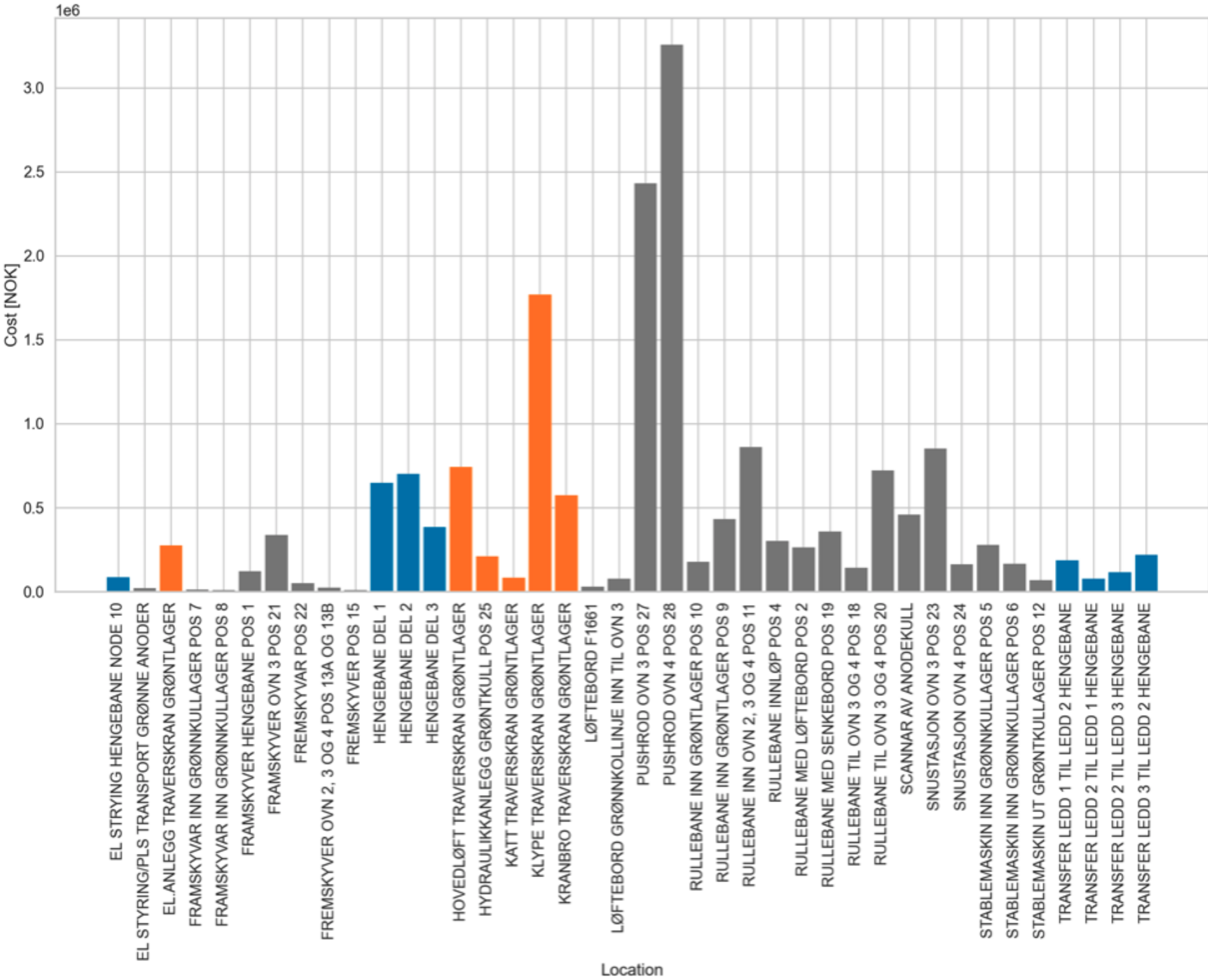

Figure 33: Cost of corrective maintenance orders per functional location

Comparing the plots in Figure 31, 32 and 33, the areas *P.4*, *P.3*, *R.11*, *S.23*, *R.20*, *H.2* and *Klype* is repeated as the parts of the transportation line with the highest number of maintenance actions, highest duration of maintenance duration and highest maintenance cost. These are some of the same areas identified when looking at all the maintenance categories. These corrective actions give insight to where the unplanned actions take place, and where production latency and profit loss are caused.

The areas that have stood out from the other functional locations will be further investigated in Section 5.4. This far, the system function and the maintenance orders have been investigated. The maintenance notifications play a more significant role when looking for the components failing and their cause, and is evaluated in 5.4. The downtime registration and the setback record for the production will first be analysed to identify components causing excessive downtime and the components behind direct profit loss. Combining this data with what has been highlighted in this section will identify the critical areas affecting the overall asset performance of the transportation line. The maintenance notifications will then be analysed to look for components failing and cause behind in light of the criticality. The following section will look closer at the downtime registration caused by, among others, failures at the transportation line being analysed.

5.3.2 Stops and downtime registrations *(stopptidsregistrering)*

The downtime and stop registration are recorded by the operators at work to identify the production losses. Here, the downtime and every stop of the production are registered by what is causing the stops and following downtime. These records are presented in *APICS PPP*, making it easy to evaluate what are causing the downtime and stops. The information related to the transportation line was investigated. There is history back to **2016**, which is when the system was taken to use at this facility. Therefore, the information from this first year is not consistent, but since the downtime and stops are evaluated from **2016** and until **today** and not by each year, all the data is included. In Appendix D, the plots generated by the system is attached. Both visualisations of downtime and the number of stops are induced.

Transportation at the furnaces is the area with the most downtime, which is the area that includes the *pushrods*. The downtime recordings here show that *P.3* has more recordings compared to *P.4*. *Transport to furnaces*, which is the transportation line analysed throughout this thesis, is second after *Transportation at the furnaces*. As explained earlier, the *pushrods* are included in the transportation line analysed here, even though it serves other functions than only being the last step of the distribution system for the carbon anodes. *The automated storage* is the fourth location causing downtime, while *Transport to storage*, the part between *the overhead conveyor* until *the automated storage*, has fewer recordings. This is all visualised in Figure 43, showing the downtime registrations, in Appendix D. While looking at the stop recordings, the most interesting here is that *the automated storage* is up to a second after *Transport at the furnaces*, which means that this has more frequent stops, but demanding less downtime per stop. This is shown in Figure 44.

When looking closer into *Transport to furnace* in Figure 45, for an overview of the recorded downtime, and Figure 46, for the stop records, it is clear that *S.23*, *R.11*, *F.21* are repeated failure areas. These areas was also highlighted when analysing the *SAP* records. When looking isolated at 2020, the same ares still requires the most downtime, but now *R.11* has the highest recorded downtime, not *S.23*. By searching the records of *the green mill*, *the overhead conveyor* is identified from Figure 47 and 48, as the third most common reason of stops and the sixth most common reason for downtime at this area of the facility. *The overhead conveyor* itself from Figure 49 and 50, has *H.2* as the parts causing the most downtime throughout the years. There is a clear overweight of mechanical errors all over, compared to electrical failures.

Throughout this period, **528** records of stops and downtime due to the transportation line analysed is recorded. **38%** of these records are related to the area of *the roller conveyor* from *the automated storage* and until the *pushrods*, which is also clear since the three parts of the transportation line identified the most throughout the records are *S.23*, *R.11* and *F.21*. In the system used for these recordings, it is possible to add a comment when registering stops and downtime. By analysing these comments, they present the same view of the transportation line of analysis. Sudden failures lead to downtime and stops, which identifies the lack of control of the transportation line today. The performance is varying, and there are no clear trends of when the requirements are fulfilled.

Today, this data is used for among other *OEE* calculations and presenting reports of the current status regarding downtime and stops in the production facilities. When analysing the data now, *S.23*, *R.11*, *F.21* and *H.2* are all identified as critical areas for the transportation line, causing downtime and stops in the production. The *SAP* records must be taken to use to identify the actual cause of the failures leading to downtime. This combination of data is not arranged for today, causing it to be a demanding process, which is further investigated in Section 5.3.4. The following section will look closer at the losses caused by downtime at the transportation line.

5.3.3 Records of production setbacks *(tilbakesettingar)*

As described in Section 4.2, the baking process of the furnace's baking anodes must be delayed or reset *(tilbakesetting)* if the production processes are behind schedule or if a breakdown occurs. For each hour the process is delayed, it causes a **direct loss of 20 000 NOK per hour**. Every hour of delay equals twelve anodes. Every ton of carbon anodes are worth approximately *1600 NOK*, and the average anode weighs *1.025 ton*. Every time this is the case, it is recorded in a database.

These data are recorded manually, and available data from back to 2015 has been analysed. Since the records are recorded manually, the comments of the delays have diverted standard.

Some comments are very detailed, while for some of the delays, the reason behind it is not described. In 2015 and 2018, no comments on the delays were made, and in 2017 only part of the resets was commented. Missing data affects the analysis, then trying to determine the reason behind the delay. Regardless of the lacking data, the records were analysed to find if the transportation line was the reason behind some of these losses, thus being the reason behind direct profit losses. The analysis of the records was performed in *Python*, which required some data cleaning, grouping and filtering. The results were visualised graphically. Since the comments were manual entries, there were no standardisation and the grouping of comments had therefore to be performed manually due to lack of common denominator. Some of the delays were caused by several issues, making the delay belong to several categories, causing a mismatch between the total number of delays and the sum of the hours of the delays per category.

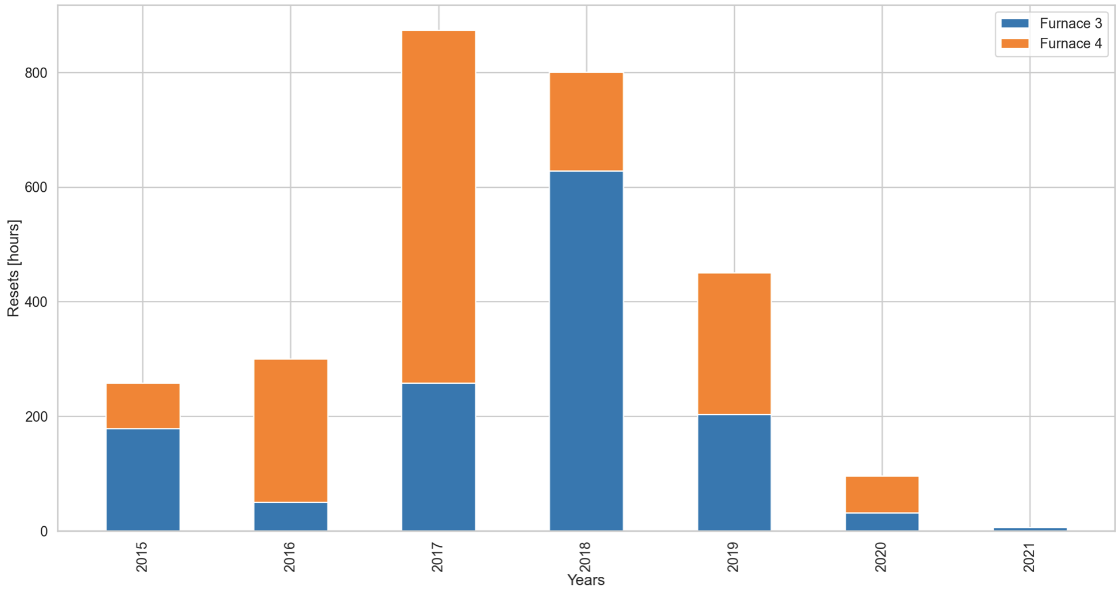

Figure 34: Setbacks of the baking process per year

Figure 34 shows the resets or delays of the baking process per year over the last years. The data from 2021 is until March. The total number of resets are higher in 2017, 2018 and 2019 compared to 2015 and 2016. This is caused by developments and improvements made during these years. Examples are elevating the furnaces and upgrades to the purification facility. The resets were also reduced from 2018 to 2019 before 2020, again caused a drop in resets. Regardless, the more interesting factor is what is causing these delays. The following categories were established: *transport to furnace, cranes, baking process* and *others*, to be able to investigate it. The categories were split into furnace three and furnace four. The categories **Transport to furnace 3** *(blue)* and **Transport to furnace 4** *(purple)* are therefore the categories relevant for the transportation line analysed. This distribution is visualised in Figure 35. Delays caused by the cranes are found in the crane category, while the baking process includes the factors that have something to do about the firing pattern. All other reasons for delays were collected in one category. As shown, it is an overweight of resets caused by the *Baking process*, and *Other* reasons. Delays caused by **Transport to furnace 3/4** is noticeable, but not the most common reason. Since there were no comments made in 2015 and 2018, there is no available data from these years.

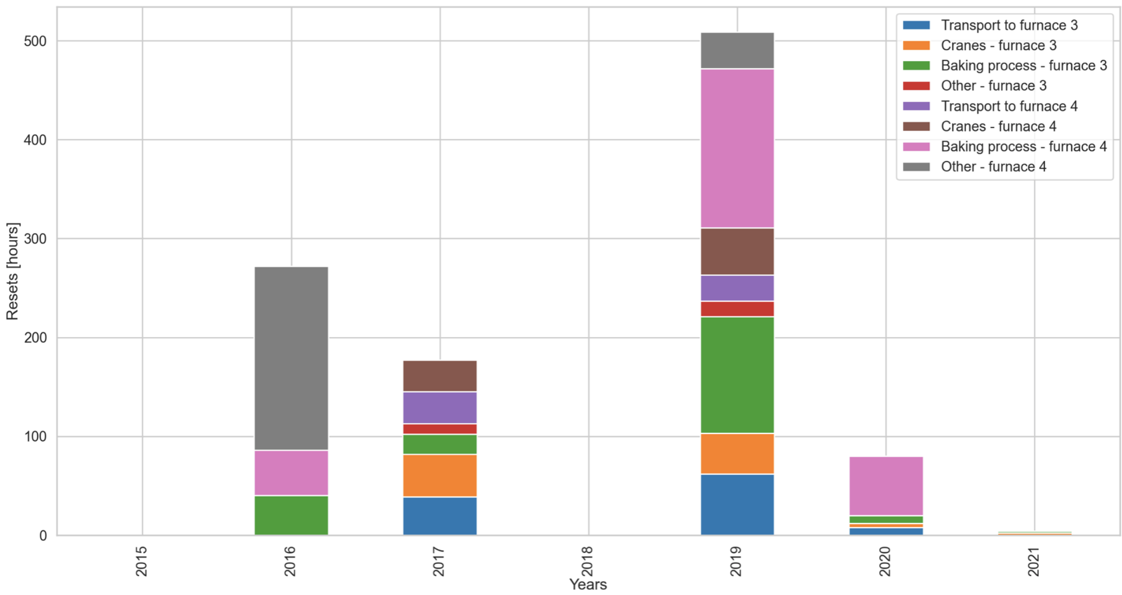

Figure 35: Setbacks of the baking process grouped by categories per year

In total, from the entire data set, there were *2758* hours of delays, where *167* of these hours was because of the transportation line, which equals **6%** of the total resets. These hours were recorded in 2017, 2019 and 2020, and was the reason behind the direct profit loss of **3 340 000 NOK**. Compared to the total profit loss of *55 million NOK* over these *6,25 years* it does not appear much, but it is still significant. When looking isolated at the years of 2017, 2019 and 2020, **Transport to furnace** represents **8%**, **20%** and **8%** of the direct profit loss caused by resets that year. Since there is a lack of reasoning behind the delays, the resets caused by the transportation line could be even more significant. Areas located in the transportation line, mentioned specifically in the comments of the delays, is *the automated storage*, the rollers of the conveyor, the rotator before furnace three *(S.23)* and lift before this rotator *(L.OVN3)*. Other comments revolve around the transportation line as a whole. The following section will visualise how the different sources of data can be combined to give light to the interaction between them and more insight into the transportation line being analysed.

5.3.4 Combining the data from the different sources

Three different sources of data have been used throughout this data analysis. The data from *SAP* captured using transaction codes *IW39* and *IW69*, show the maintenance order and the maintenance notification. As explained, the notifications are established when failures occur, and the orders are made when maintenance is performed. Since the maintenance orders will contain information about the costs and the repair duration, while the maintenance notification gives information about the component failing and the problem and cause behind the failure, this information has to be joined to visualise the entire picture. The stop and downtime records from the production give information about downtime caused by the failures, while the setback records give details about when the furnaces had to be delayed and the cause behind it. This chapter will therefore give an example of what information can be captured when combining these three sources.

Starting with the setback records, the following information is found: during **week 9 of 2019** (2019-02-25 to 2019-03-03), the baking process is delayed **8 hours**, causing a direct profit loss of approximately **160 000 NOK**. The reason behind this was related to *"challenges with transportation of green anodes to the furnace"*. Checking the downtime registrations, seven records are recorded related to this incident, and all registered as unplanned maintenance. They are all related to *the roller conveyor* from *the automated storage* until the furnaces and demanded both a mechanic and an electrician for call up. The records are shown in Table 1. The comments made for the registrations describe the turner, the rollers, chains, the shove and a fuse being defect. The incident caused a downtime of **13 hours and 57 minutes**, causing the delay of the baking process of **8 hours**. The reaming 6 hours must be caught up with by the operators at work.

Downtime registrations					
Downtime cause	Specified cause	Area of facility	System part	Type of failure	Specification of failure
Maintenance	Unplanned maintenance	Transport to furnace	Turner for furnace 3	Mechanical	N/A
Maintenance	Unplanned maintenance	Transport to furnace	Turner for furnace 3	Mechanical	Chain
Maintenance	Unplanned maintenance	Transport to furnace	Turner for furnace 3	Mechanical	Chain
Maintenance	Unplanned maintenance	Transport to furnace	Turner for furnace 3	Electrical	Thermal
Maintenance	Unplanned maintenance	Transport to furnace	Turner for furnace 3	Electrical	Rollers
Maintenance	Unplanned maintenance	Transport to furnace	Turner for furnace 3	Electrical	Failure on photocell
Maintenance	Unplanned maintenance	Transport to furnace	Shove for furnace 3	Mechanical	N/A

Table 1: Downtime registrations between *2019-02-25 to 2019-03-03*

SAP records							
Date	System part	Failing component	Problem	Cause	Duration (min)	Cost (NOK)	Priority
2019-02-27	S.23	Construction	Defect	Component failure	4608	0	3.0
2019-02-27	S.23	Engine	Stopped	Component failure	256	5196	1.0
2019-02-28	S.23	Signal transmitter	Defect	Component failure	128	2598	1.0
2019-02-28	F.21	End joint	Defect	Incorrectly constructed	352	9021	1.0
2019-02-27	S.23	Engine	Disconnected	Short circuit	64	682	1.0
2019-02-28	R.20	Electrical installation	Reduced performance	Short circuit	4512	5934	3.0
2019-02-28	R.20	Roller	Defect	Incorrectly mounted	4576	0	3.0
2019-02-28	F.21	Construction	Damaged	Incorrectly constructed	4480	5010	3.0

Table 2: Maintenance orders and notifications between *2019-02-25 to 2019-03-03*

The maintenance records in *SAP* must be analysed to determine the problem and cause of failure and the maintenance costs and duration of the repair. This information is found through conducting two different transactions, and, therefore, both the maintenance orders found through transaction *IW39* in *SAP* and the maintenance notifications found through transaction code *IW69* must be fetched. When combining the maintenance orders and the notifications on their common denominator, eight records are related to the incident. Four of them are tied to *S.23*, the turner of the anodes towards the end of the transportation line, before reaching furnace three. The remaining four records were divided between *F.21*, the shove, and *R.20*, a part of *the roller conveyor*. The *SAP* records are reproduced in Table 2. These records show the failing component, the problem and the cause behind it. For this incident, both components failures and incorrectly performed maintenance actions recur as the cause of failures. In total, these repairs lasted **18 976 minutes**, or just above **316 work hours**. The cost of the repairs adds up to **28 440 NOK**, which is additional to the bigger profit loss, of **160 000 NOK**.

This incident, causing downtime in production and setback of the production process, show how spread the information about the incident are. The setbacks are recorded in one excel sheet, the downtime in one application, and the maintenance records in another. For combining the information, as presented, both resources and time are required. Several examples could be presented and reviewed, but the example presents how the data concerning the transportation line is spread throughout several systems, making it hard to control the transportation line, and analysing the data requires lots of resources. Therefore, ways of measuring the asset performance of the transportation line to stay in control are needed. This will be further described in Section 5.5 and during the discussion in Section 6. The critical areas of the transportation line will be investigated in the next section.

5.4 Critical areas of the transportation line

Throughout the previous section, the data analysis, several areas have been detected as the parts of the transportation line demanding several maintenance orders, a lot of maintenance hours and higher costs than the rest of the transportation line. The downtime and setback records from the production also point to areas being critical for impacting the production process. This section will look closer into some of these areas, identifying the components causing failures, the problem and the causes of the maintenance notifications. The system analysis pointed to the lack of redundancy in the transportation line, requiring high availability for all areas of the transportation line. Only some of the areas will be analysed to limit the extent of this result chapter. The plots for the analysis will be added to Appendix E, while the results are described throughout this section.

This system was chosen for this case study due to the lack of control over the transportation line. The feeling of not knowing when failures would occur was widespread. The analysis performed this far points to some areas being more critical, and this section will therefore look closer to **S.23**, **R.11**, **R.20**, **P.3** and **P.4**. In addition to the system and data analysis, this identification of critical areas will present the current state of the transportation line for the anodes. When looking closer to these areas, the data extracted from *SAP* using the transaction code *IW69* is taken to use, which gives information about which components is causing failure, the problem behind and the maintenance notification cause. The focus has been on the failures with high priority, categorised with *1.0* and *2.0* in *SAP*, with combination of the need for call up for technicians *(VAKT)*.

5.4.1 *S.23*

A critical area of the transportation line is *S.23 (SNUSTASJON OVN 3 POS 23)*, which flips the anodes into a standing position before reaching *P.3*, when the anodes are destined for furnace three. When evaluating the number of corrective maintenance orders over these last ten years for *S.23*, they wary between three and 29 orders per year. From 2017, 2018 and 2019, a reduction into 2020 is shown in Figure 51 in Appendix E. While looking further into the maintenance notifications, which show the failing component, the problem, the cause and the connection between them, there is no clear combination of component, problem and cause behind the troubles. Throughout the ten years of data extracted, few combinations repeat themselves. Looking at the components causing failures, **the bearing**, **the construction**, **the engine** and **"Not defined"** has the highest frequencies in decreasing order of all the maintenance notifications register to this part of the transportation line. The construction and the engine also demanded call ups and actions of high priority. The components causing failure and their frequency is shown in Figure 52.

The problem of the components is a clear predominance of **defective** components, which is plotted in Figure 53. Components that has **stopped**, **reduced performance**, **leaks** and **injuries** is also registered frequent. Both **defective**, **stopped** and **injured** components demanded high priority and call up activities, in addition to short-circuiting, cheating components, low oil level and tears. When analysing the causes of failures, the most frequent causes stated are **overstressing**,

component failure, **"Not detectable"**, **incorrectly construction**, **inflicted damage** and **fatigue fracture**. Overstressing, component failure, "Not detectable", incorrectly construction, inflicted damage, and ageing all caused actions of high priority and call ups, as visualised in Figure 54 in Appendix E.

5.4.2 *R.11*

R.11 (RULLEBANE TIL OVN 2, 3 OG 4 POS 11) are the position of the transportation line after *the automated storage* and towards the furnaces. While looking at the development of failures throughout the years, it ranges between 5 and 36 corrective maintenance orders. The last three years are fairly stable, with an average of 27 maintenance orders, equivalent to one order per fourteenth day. This is shown in Figure 55 in Appendix E. Analysing the components causing failures at this part of the transportation line, **the bearings**, **the bearing housings** and **the rollers** are frequent. Failures at these same components, in addition to the engine, the electrical unit, the end limit switch and the initiator, has led to high priority and call up maintenance notifications, as shown in Figure 56.

Investigating the problem causing failures, in Figure 57, **defective** components has a clear predominance here, as it had for *S.23*. **Loose** and **injured** components is also registered frequent. Defective, loose and cracked components, has in addition to component with reduced performance led to maintenance notifications with high priority. From Figure 58 the causes of failures at the components of this part of the transportation line is plotted. **Inflicted damage**, **overstressing**, **vibrations** and **degradation** are all frequent causes of failures. The combination of **bearing, defective and inflicted damage** and **bearing, defective and overstressing** are repetitive.

5.4.3 *R.20*

R.20 (RULLEBANE TIL OVN 3 OG 4 POS 20) are the position of the roller conveyor just before the entrance to the furnaces. For this part, there has been an increase in the number of corrective maintenance orders from 2011 until 2020, from 2 to 35 maintenance orders per year, visualised in Figure 59 in Appendix E. The component of the transportation line causing most failures are **the chains**, in addition to **the bearings**, **the electrical unit**, **the bearing housings**, **the initiators** and **the construction**. The components causing high priority maintenance notifications are the chains, the electrical unit, the bearing housings, the construction, the engines and the cogwheels. This is shown in Figure 60.

The problems of the components causing failures are visualised in Figure 61. The most common problems are **defective** components, components with **reduced performance**, **loose**, **cheating**, **stopped** and **worn** components. The most frequent causes behind these problems are related to **degradation**, **"Not detectable"**, **overstressing**, **ageing**, **inflicted damage**, **vibrations** and **component failure**. The causes of the problems leading to component failure are plotted in Figure 62 in Appendix E. Degradation, overstressing, ageing, components failure, incorrectly construction and incorrectly assembly have all led to maintenance notifications with high priority and call ups of technicians. The combination of **initiator, reduced performance and ageing** and **bearing, defective and inflicted damage** are repetitive.

5.4.4 *P.3* and *P.4*

The final steps of the transportation line *P.3 (PUSHROD OVN 3 POS 27)* and *P.4 (PUSHROD OVN 4 POS 28)* are the most critical areas of this transportation line, when looking at the maintenance history. To get a better understanding of these areas, the development throughout the years in aspect of number of corrective maintenance orders was plotted, as shown in Figure 63 and 67. Visualised from the plots, the number of maintenance orders per year varies from year to year with variations of about 22 to 70 maintenance orders for *P.3*, and between 21 and 68 for *P.4* per year over these last years. When analysing the components leading to failure for *P.3*, as shown in Figure 64, **the chains**, **the electrical unit**, **the brackets**, **the construction** and **the rollers** are registered frequent. For *P.4* there is a clear predominance of **the construction**. **The brackets**, **the electrical unit**, **the chains**, **the rollers** also has several registrations, as visualised in Figure 68. The same components lead to failure for both *P.3* and *P.3*, but the number of maintenance notifications vary between them.

Problems leading to failure for *P.3* are visualised in Figure 65, and there is a clear overweight of **defective** components. **Injured**, **worn** and **loose** components, in addition to components with **reduced performance** are all registered. *P.4* also has the highest frequency of **defective** components, as shown in Figure 69. The same problems leading to failures as for *P.3* are mentioned for *P.4*. Causes of the problems leading to components failures for *P.3* are related to **inflicted damage**, **degradation**, **overstressing**, **"Not detectable"** and **vibrations**. This is plotted in Figure 66. *P.4* has the same causes of failures, but the number of messages per cause vary, as shown in Figure 70 in Appendix E. There are few combinations of components, problems and causes that are repetitive for this part of the transportation line, both for *P.3* and *P.4*.

The information from the system analysis, the data analysis, and the identification of the critical areas form the basis for the next section, where the required asset performance of the transportation line is compared to the system's delivered performance. This will be discussed in Section 6.

5.5 Required asset performance compared to delivered performance

An important part of the work with continuous improvement is to establish the gap between the requirements made to a system, and what is delivered by the system. Through the data analysis performed, critical areas are identified, and the connections between the functional and physical aspect of the transportation line are established. In addition to this, the actual requirements of the transportation line must be set, to be able to identify when the performance of the assets is reduced. In Hydro this is usually done by completing an evaluation using the table presented in Table 3. The required function of the transportation line is to be established, and the requirements for the performance of the line must be found. Whenever the requirements are set, ways of identifying the current performance must be found to be able to identify the gap between the required and the delivered asset performance. The profit loss that occurred due to this loss in function is then distinguished. The condition data coming directly from the transportation line is relevant for such an analysis, but this data was not available in Hydro's systems for this evaluation.

Table 3 is filled in light of how the required function (*"function, combination of functions, or a total combination of functions of an item which are considered necessary to fulfil a given requirement"* [40]) and asset performance measurements of the transportation line evaluated should be. Today, there are no possibilities in determining the current performance, and therefore this must be solved before the loss of function could be identified. The transportation line is evaluated through the three different sub-systems identified in Section 5.1, that is **the overhead conveyor**, **the roller conveyor** and **the automated storage**.

First, a closer look at the required asset performance. When it comes to availability (*"ability of an item to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided"* [40]), there are requirements for the transportation line in always being available. Whenever anodes are produced at the green mill, the conveyor must be able to transport the anodes to the storage unit. There is continuous production at the facility, with twelve eight-hour shifts and six twelve-hour shifts. At the green mill 32 hours of stops and downtime is possible throughout the week. Hence, *the overhead conveyor* must have high availability and be able to function when needed. This is equal to both *the roller conveyor* and *the automated storage*, which has to be available both when anodes are arriving from the green mill heading toward the storage, in addition to when anodes are needed for the furnaces. The furnaces has continuous production. When it comes to capacity, there is no monitoring of this today. *The overhead conveyor* transports about **4000 anodes** per week, which is further transported into *the automated storage*. The furnaces demand **3800 anodes** per week, which the automated crane at the storage and *the roller conveyor* transports towards the furnaces. The transportation line must be able to handle the anodes when transportation of anodes are required. The cycle time, the

	Required asset performance				Delivered asset performance				
Machine	*Availability*	*Capacity*	*Function*	*Quantified requirements related to function*	*Availability*	*Capacity*	*Function*	*Cost of operations*	**Effect of loss of function**
Overhead conveyor (*hengebana*)	Functioning when needed	1) Cycle time (about 45-60 minutes) 2) 4000 anodes per week	Transport anodes on hangers from the green mill to the furnaces	1) The anodes reaches their destination 2) Transportation time 3) Power draw	Digitally monitor availability	Digitally monitor cycle time and number of anodes transported	1) Digitally monitor signals 2) Action criteria 3) Visually check	1) Maintenance cost 2) Energy cost	Minimal loss due to buffer at the storage
Roller conveyor (*rullebana*)	Functioning when needed Transporting anodes to the furnaces 3.7 times a day	1) Cycle time (about 90 minutes) 2) 4000 anodes for storage, 3800 to the furnaces per week	Transport anodes from the overhead conveyor to storage and further to the furnaces	1) The anodes reaches their destination 2) Transportation time 3) Power draw	Digitally monitor availability	Digitally monitor cycle time and number of anodes transported	1) Digitally monitor signals 2) Action criteria 3) Visually check	1) Maintenance cost 2) Energy cost	Production loss (20000 NOK every hour of production set-back)
Automated storage of anodes (*grøntlager*)	Functioning when needed Anodes for the furnaces 3.7 times a day	1) Cycle time 2) 4000 anodes in, 3800 out (per week)	Sort, stack, lift and store anodes from the green mill. Deliver right type of anodes to the furnaces	1) The anodes reaches their destination 2) Time used for storage 3) Time used for pick-up of anodes	Digitally monitor availability	Digitally monitor cycle time and number of anodes transported	1) Digitally monitor signals 2) Action criteria 3) Visually check	1) Maintenance cost 2) Energy cost	Production loss (20000 NOK every hour of production set-back)

Table 3: The required asset performance compared to the delivered performance

time spent moving from one place to another, could be measured, to be able to detect anomalies. Through measuring the cycle time, depredations could be detected. Today, only approximate times are available for cycle times. The transportation time at *the overhead conveyor* is about **45 to 60 minutes**. The transportation time of the first anodes from the storage to the furnaces is **15 minutes**, while the entire batch demands a minimum **90 minutes**. The furnaces requires anodes **3.7 times** a day, and about **156 anodes** per time.

The function of each of the sub-system is described in Table 3 and is further elaborated in Section 5.1. Today, no quantified retirements related to the function are used. As long as the anodes reach the furnaces, the function has been fulfilled. In addition to this, it could be useful to look closer at the transportation time used. The power supply could also be another requirement to evaluate. This is relevant both to *the overhead conveyor* and *the roller conveyor*. Especially the transportation time from the storage until the anodes reaches the pushrod is relevant since this could affect further production. Only approximate measures are used today. Due to the storage unit, the transportation from the green mill to the storage is not that crucial. For *the automated storage*, the time to both store the anodes and to put them back onto the conveyor for further transportation should be measured.

The delivered asset performance is not measured today. In the future, both availability and capacity could be monitored digitally. The transportation line itself collect lot's of data today, and by making it available through Hydro's new digital solutions, it is possible to monitor the delivered performance related to both availability and capacity. This is possible for all three of the sub-systems. The function and the requirements related to the function could be evaluated through digitally monitoring the signals coming from the transportation line. Based on defined action criteria, actions are made when needed based on the digital monitoring and possible alarms raised. Visuals checks based on what's monitored would be needed. Controls on components in the transportation line not possible to monitor digitally, must also be performed frequently. The cost of operations is related to both maintenance costs and energy cost, for all three sub-systems.

When it comes to the effect of loss of function, the losses caused by *the overhead conveyor* is minimal due to *the automated storage*. Since the furnaces orders anodes from the storage, and not directly from the green mill, this creates a buffer, reducing the potential losses. If failures occur at *the overhead conveyor*, it would not affect the subsequent production. The storage are capable of delivering anodes to the furnaces for a few days. Gaps between the required asset performance and the delivered asset performance related to *the roller conveyor* and *the automated storage* have bigger consequences. If the requirements are not fulfilled, and prolonged downtime arises, direct losses caused by delayed production is set to 20 000 NOK per hour. This is when the failure is extended, causing setbacks in the baking process at the furnaces. Shorter repairs do not cause this, but will instead affect the production and the operator at work, which must recover from this downtime.

The problem of evaluating the asset performance of the analysed transportation line is an extensive issue. It is requested due to the need for knowing the condition of the assets in the production facility. The sense of not being in control of the asset has increased, and steps towards getting the control back must be identified. The system documentation and the available data has been analysed to map the current state of the transportation line. This analysis shows several issues related to the transportation line today, which is further discussed in the next section. The condition data of the line are needed to monitor the performance. This data is currently being collected but not made available for analysis yet, and therefore the gap between the required and the delivered performance in Section 5.5, is used as a starting point. The critical areas identified in Section 5.4, as a result of the data analysis performed throughout Section 5.3 can be evaluated through their performance. This is further discussed in Section 6, along with the reported results in light of the theoretical background from Section 3, the system definition and system analysis in Section 5.1 and 5.2.

6 Discussion

In light of the problem statement, the research questions and the research objectives, the issue of not being in control over the assets was investigated both throughout the theoretical background in Section 3 and the case study in Section 4 and 5. As described during the introduction in Section 1, several actors are pointing towards getting control of and monitoring the assets as the solution for the difficulties with today's ageing production faculties [1, 2, 8, 9, 10]. The same initiative is presented in Hydro, and therefore this thesis investigates how analysis of asset performance is helpful for improvements and precisely how it would be helpful for the transportation line at the carbon facility at Hydro Årdal. The theoretical background focused on how asset performance is helpful for getting control over the assets, and through the case study, the current status was mapped. The results will be discussed and interpreted through the relevant theory in this section.

6.1 Asset performance

Following the presented research objectives and the methodology presented in Section 4, theory around asset performance and its effects on the production, including new technologies, was investigated. The asset performance will in asset-intensive production companies directly determine the performance of the business [9], and the need for improving the performance of the assets in the process industry is identified [8]. It is therefore important to be aware of the actual performance and condition of the assets. This control is currently lacking at the transportation line, but actions towards utilising the best performance of the assets are wanted. As identified, there is a great potential in utilising the available maintenance and operational history to understand the failure occurrence and consequences [3], but the problem is the lack of utilisation of existing data. Hydro has developed a plan for utilising the data in the organisation. Clear goals are set, and the work is initiated to be able to use maintenance data for asset performance analytics, as described by Lukens et al. [11], in line with the idea of taking the data to use as a competitive advantage [77].

The increased focus on asset management in the industry is driven by how investments in assets could lead to better business performance caused by the increased asset performance [35], and by monitoring of the processes and the assets to improve the process reliability [44]. As a company with many assets, this awareness between asset performance and overall company performance justifies funding for better performance and better decisions in Hydro. There are lots of possibilities, and the starting point must be set somewhere [2]. Data management and condition monitoring are key activities for the assets, for realising and understanding the value of the assets [36, 41, 42], and in the long run, give a more sustainable performance [10].

As the Standardisation Roadmap of Predictive Maintenance for Sino-German Industry 4.0/Intelligent Manufacturing describes [2], and as in line with Hydro's strategy, it is helpful to start simple and build further on top of this solution. In this way, the simple solution will answer the needs and make sure that the concept will answer the actual requirements all the way when growing bigger. Only the technologies needed will be taken to use by pursuing this development, ensuring that the solution is not more complex than it has to be. The smart analytics, as described in Rødseth et al. and Khuntia et al. [66, 71], do not have to be so compound. Both Bradbury et al. and the Standardisation Roadmap identified the enlarged focus of complicated technologies. The big picture should be evaluated, and only solutions fitted for the exact problems are necessary, excluding redundant fancy technology [16, 2].

As identified throughout Section 3 and presented in Section 3.5, several steps towards a future state with digital control over the asset performance are possible. Through identifying the business case, the requirements of the assets, the functional and physical functions and sub-functions of the assets, the three first steps towards better control are made. By collecting and analysing the data about and generated from the system, a mapping of how and when the continuous performance measurement could be made. The last step includes implementing an asset performance system. Performance is measurable results related to how the assets fulfil the required function. What and when to monitor and measure, when to analyse and evaluate the results, establishing requirements for the required process, and gain control over the process to following these criteria and work with continuous improvement related to both sustainability and effectiveness [36], are important aspects related to increasing the asset performance. Since Hydro is in the chemical process industry, asset maintenance optimisation is essential for the performance and the condition of the assets. This is important due to the complex systems and the need for stable production [21]. The correct maintenance must be performed at the right time to minimise downtime, loss of production and profit loss [36, 48].

The business case for looking further into the asset performance in Hydro's facilities is evident. The actual status and performance of the plants are in demand, and today there is often no clear answer for the current condition. Digitalisation is a prerequisite for development, and through the increased availability of the data, it is now possible to base decisions and extract value and insights from the data. The sense of not knowing the status of the assets is expanded, but now it is possible to use the data and new technology to map the status, thereby reducing downtime and profit loss. This could also change the maintenance plans, prioritising the resources to where they are most needed and the right tasks. There is no way to know the carbon facility's status, especially the transportation line until the consequences strike. Therefore, a solution making it possible to map the performance and current status is required. There are difficulties in identifying the numbers and value of the failures and consequences today. The profit loss due to excessive downtime is often not connected to the maintenance tasks, and by identifying where the challenges lie today, the gap between no control and knowing where the shoe pinches could be decreased.

6.2 Current state of the transportation line

The second objective of this thesis revolves around the current condition of the transportation line analysed. After analysis, the overall results confirm the impression of not being in control of the status of the assets. The system analysis points to the lack of redundancy through the transportation line, which leads to the process demanding high availability and capacity of this distribution system of anodes. The *SAP* data show how a few of the parts of the transportation line is the reason behind most of the maintenance orders and notifications, the duration of the maintenance activities and the costs related to the maintenance activities. The downtime records visualise how the transportation line is the second most common reason behind downtime in the production facility.

On the other hand, the setback records do not directly point to the transportation line being the problem behind most of the direct profit loss caused by reduced production. The combination of the data shows how resource-demanding the process of connecting the different data sources to visualise the entire picture and highlights the insight that lies in this combination. While comparing the required function to the delivered function, the lack of requirements previously set for the transportation line was visualised. Condition data could improve this situation. The data from the different sources all show the same picture, the lack of control and not knowing the actual status of the equipment, leading to the impression of failures occurring at the least convenient times.

The system analysis identified the functional and physical aspects of the transportation line. The requirements related to the transportation line are not clearly defined today. If the anodes reach their destination, the function of the transportation line is met. Over the years, both the size of the anodes and the total production volume has increased. The furnaces have been expanded, making it possible to deliver more anodes for aluminium production. The one transportation line still handles all the distribution of the anodes. One of the biggest challenges of the transportation line is the lack of redundancy, causing downtime if failures occur. The transportation line is built in series, where every part fulfils its task. Due to the automated storage, a safeguard is established in case of failure at the overhead conveyor or the roller conveyor before the automated storage. The consequences of failure between the storage and the furnaces are more significant, possibly causing profit loss.

The data analysis performed combined the *SAP* records, the downtime registrations and the setback records to map the current status and identify the actual problems. Before the analysis was performed, the status of the transportation line was based on the impression of a complete lack of control, where the transportation line caused excessive downtime and profit loss. The *SAP* data showed a high frequency of maintenance orders, long duration of maintenance actions and high costs related to *P.4*, *P.3*, *R.11*, *R.20*, *S.23*, *H.1* and *H.2*, in addition to *Klype* and *Hydraulikk*. The data analysis confirmed the impression of not being in control. Over the last ten years, there has been completed around **1.5** maintenance orders per day at the transportation line, where about **52%** of these actions were corrective, and **47%** preventive maintenance. **1/4** of the parts of the transportation line is the reason behind **3/4** of the time spent on all the maintenance actions related to the transportation line. This points to some parts of the transportation line being more critical than the others, causing downtime and profit loss. The maintenance records also show that the part of the transportation line from the automated storage until the furnaces is the cause of **75%** of all the maintenance orders related to the transportation line. Five of the 40 parts of the system is the cause of **55%** of the maintenance costs.

The *SAP* records show that lots of preventive maintenance are performed. It seems like this does not improve the status of the transportation line. The areas with the most corrective actions also have the most preventive actions. If the condition of the assets could be monitored, the time spent on these preventive actions could be spent on other actions. The facility is ageing, and there may be so much degradation at the assets that the preventive actions do not improve the status. The failure rate of the plant is unstable, and failures could happen at any time. Therefore, if the condition is monitored, the resources could be aimed to where there is most need and improve the performance of the assets. More money is spent on corrective actions, while preventive actions demand the most prolonged duration spent on maintenance actions. When the preventive actions do not lead to better performance, this causes a mismatch between where the investments are made, and the results gained. The asset performance is influenced by the way the maintenance actions and investments are performed [39]. The technical condition of the assets are affected by the maintenance actions [27], and the maintenance process steps are all relevant for delivering the best possible condition and performance of the assets [55], showing the important link between asset performance and maintenance.

The downtime records point to *P.3*, *P.4*, *S.23*, *R.11* and *F.21* as the most frequent cause behind the downtime and stops recorded. Both *transport at the furnaces*, where *P.3* and *P.4* are included, and *transport to furnace*, which cover the area between the automated storage and the furnaces are the most common reason for downtime, with **38%** of the records related to the transportation line. The downtime records also imply that most stops are at the crane at the automated storage, but these stops do not cause much downtime. The *SAP* and downtime records both imply the lack of control at the facility, where a few of the parts at the transportation line is often the cause behind it. The setback records show that the transportation line is the cause of **6%** of the profit loss due to production delays over the last years. This suggests that even though the transportation line causes lots of downtime and maintenance resources, it is only responsible for a small portion of the profit loss. Another aspect to keep in mind is the pressure downtime causes on the operators at work. Even though it is constantly repeated to work safely, the work will be affected if production runs behind. Unplanned corrective maintenance does not always cause profit loss, but delays still have to be caught up, which comes down to the operator performing the task. As the combing of data showed, a series of incidents led to maintenance cost and profit loss of a total of 188 440 NOK, 316 man-hours of repairs, and almost 14 hours of downtime, but only eight hours of production setbacks. This show how failure affects other aspects than just maintenance cost and loss in production. After incidents like this, the operators must often handle the pressure of performing their tasks more efficiently than normal. This show how both the people, the knowledge and the culture also is important for the overall performance [61].

Through analysing the required function of the transportation line, areas of improvements are identified. The data analysis completed sheds light on this, meeting the third and fourth objective of this thesis. As described throughout Section 4.4 and 5.1, *P.3* and *P.4* are the last steps of the transportation line, where the anodes are turned onto by *S.23* or *S.24*, and where an overhead travelling crane will pick up the anodes before placing them in the furnaces. *P.3* is the final step before furnace three, while *P.4* is the final step before furnace four. If something fails here, there is no redundancy, and the failure must be handled before the production process could continue. In light of the high number of maintenance orders, time spent on corrective and preventive actions, and the money spent on these maintenance actions, this is important. As mentioned before, this technical location includes more than just being the final step of the transportation line between the green mill and the furnaces, which could explain the big difference between these two parts of the transportation line compared to the others, while analysing the data presented in the plots in Section 5.3. Causes of failures related to the pushrods are often inflicted damage, degradation, overstressing and vibrations, causing defective, injured, worn, loose and components with reduced performance. By monitoring the performance of the assets, some of these failures could be detected earlier on, reducing the following downtime.

S.23 is another critical area of the transportation line. When failures occur here, it hinders the anodes from reaching furnace four. When the production orders anodes for one of the furnaces, these anodes will occupy the roller conveyor until there is room for anodes for the other furnace. In case of failures at *S.23*, it is not possible to send these anodes further to furnace four since they are destined for furnace three, and there are no way anodes for furnace four to pass the anodes waiting at the conveyor for the failure to be handled. Hence, a failure here could lead to significant delays. Therefore, the question of expanding into two separate lines from the automated storage and until the furnaces has been raised. There is overweight in failures related to overstressing and component failure, pointing to the transportation line not being designed and constructed for the load it correctly handles. There is no clear trend in connections between the component failing, the problem leading to failure and the cause behind, which identifies the uncertainty and the difficulties in keeping control over the area of the transportation line.

The operators at work at the plant have a clear view of what is wrong with the facility. Areas such as *S.23* has been identified as a crucial point of the transportation line for several years. This show how important it is to include the operations into the maintenance department, to show the entire picture and all the different aspects of the facility, which is in line with Hydro's new maintenance strategy, where the idea is that the different departments work together for the common good, not independent from each other [6, 47]. The idea of having two separate distribution lines from the automated storage until the furnaces have been discussed among the operators every time an incident here causes delays in the production. This is mainly due to the consequences it has for the furnaces and the burden placed on the operators for keeping up with the delays.

At *R.11*, as a critical area of the transportation line, there are several maintenance notifications with defect components. *R.11* is used when anodes come from the green mill towards the storage and when the production orders anodes for the furnaces. Four thousand anodes arrive for storage, and 3800 anodes are destined for the furnaces per week, which can explain the overstressing causing components to fail. There are also several notifications with inflicted damage. The anodes have throughout the years grown in size, and the number of produced anodes has increased. The bearings being defected caused by inflicted damage or overstressing is repeated on the maintenance notifications. *R.20* is another part of the roller conveyor with more maintenance orders and notifications compared to the rest of the system. Both reduced performance and defective components are common problems, often caused by ageing or inflicted damage. Some of these causes could be detected earlier by monitoring the performance and condition of the system [72]. Degradation often affects the performance before failure occurs, as with overstressing. Measures of vibrations could also say something about the current condition. From these areas analysed, there are several registrations of overstressing and inflicted damage as causes of failure, raising the question: Is the transportation line constructed for handling the amount and size of anodes being transported today?

While analysing the data available, it is shown that the lack of control is expanded. In the analysis area, the transportation line was described as a critical area that caused massive delays. The downtime records show that the roller conveyor from the storage until the furnaces is the second most common reason for downtime. Analysing the setback record shows a different picture where this transportation line is the reason of **6%** of the delays causing direct profit loss. It is essential to keep in mind that the reasoning behind the resets is of low quality, possibly causing underreporting. Despite this, the data show that even though the transportation line causes downtime, the effects of the profit loss are minimal, highlighting how easy it is to get the wrong picture of the condition of the assets when possible thinking about the one incident that caused massive delays. When there is no actual control of the condition of the assets, it is easy to believe that one asset is so much worse than the rest of the facility based on a few episodes. When analysing the maintenance records from *SAP*, they show that some areas are more critical than others, possibly giving a wrong impression on the transportation line as a whole. When using the available data to identify the current state, the data would either confirm or decline the beliefs around the system's state [50, 45, 49]. Today, many decisions are based on feelings and assumptions, but they could be made on the proper foundation by including data into the decisions. Therefore, by including the concept of asset performance and the available data into everyday work, the transportation line can transition into a state of control.

6.3 Future state of the transportation line

This thesis was initiated for finding ways to take back control of the assets and elaborate on how to monitor the performance of these assets digitally. Through the fifth objective of the thesis, this was investigated. How can the sense of being in control over ageing assets be exposed? How can the performance of the assets be improved and monitored? During Section 5.4 and 5.5, the critical areas of the transportation line and the required and delivered performance of the transportation line was analysed. This indicates where improvements should be made.

The current status of the transportation line is characterised by not being in control of the assets, which is a complex issue that demands several improvements measures [7]. Based on the results presented in this thesis, the work of implementing integrated asset performance solutions could be accomplished. Today, the operations and maintenance both contain lots of information, but the information is buried in different systems, making it hard to contextualise the information and knowledge [7, 2]. Better cooperation between the divisions could shed light on difficult situations and be one step towards better performance. Another aspect of this is to integrate the different data sources [2, 63, 63]. Hydro is currently in this process, and the benefits are enormous. When combining the data, the insights will be given directly, and the resources demanded to dig through the data to discover, for example, root causes are no longer necessary [6, 2]. The combination of the data needed for looking closer to one incident is shown in Section 5.3.4. As described, the information is found through different systems, and the combining process is today demanding. If the asset performance of the systems is continuously measured, this would not be necessary, since the current status of the system always would be available [45, 49, 50, 72].

Overstressing is a common cause of failures at the production line, implying a mismatch between the tolerated and actual load. How one failure at the roller conveyor towards the furnaces hinders the anodes to both of the furnaces and therefore causing delays is elaborated. *S.23* is also one of the parts of the transportation line with the highest frequency of failure, making this a common situation. A few areas of the transportation line were highlighted as more critical than others throughout the analysis performed. Improvements to these areas and asset performance systems for measuring the current condition could help improve the overall performance of the transportation line and further the entire carbon facility.

It is important to keep in mind that the data recorded in *SAP* is manually reported data, which means that human errors are possible. Reporting on the maintenance actions are often seen as excessive, which is seen by frequently use of categories such as *"Not defined"* and *"Not detected"*. Therefore, it is essential to keep in mind that the quality of the analysis based on this data will not extend the quality of the raw data reported into the system. The analysis performed on the maintenance and operational data is no more reliable than the data themselves. The records used throughout this analysis are all recorded manually, which could prolong human errors. Data quality has previously been an obstacle, but by continuously working towards improving the existing data and the future collected data, the improved data could play a more significant role [11, 77]. Over the last year, Hydro has focused on the quality of the records, causing an increase in the quality. With more focus on quality, the accuracy also improves. By utilising tablets for both the technicians and operators, records could be made directly when performing maintenance actions or production processes, making it less comprehensive to give detailed recordings. The ongoing project at the carbon facility would make it possible to transition from preventive maintenance to maintenance based on the condition, which will save both costs and time [16]. This is also visualised through the analysis of the current state. Substantial resources are spent on preventive actions, but this is not resulting in a direct better condition of the assets. With much time and money spent on preventive maintenance, the same areas of the transportation line also use a considerable amount of resources on corrective actions. This implies that the condition is not improved even with lots of preventive actions.

As the situation is today, there is no easy way to compare the required performance of the assets with the accurate, delivered performance. Therefore, different aspects to evaluate when measuring the performance was described. Today's availability and capacity are based on whether the anodes reach their destination, thereby fulfilling the function. No strict requirements are set, causing no follow-up on loss in function since this is hard to detect. There are no measures of cycle times or power draw to detect irregularities. By making it possible to use the condition data of the system, this could be monitored, hindering unwanted situations. This does not mean that all unwanted situations and unnecessary downtime will be minimised by implementing asset performance monitoring systems, but the awareness of the actual condition would be visualised [6, 49].

Further, this could also affect the maintenance planning and actions performed and gain better control of the assets. If failures are detected beforehand, maintenance and downtime are often still necessary for repairs and improvements, but by knowing the condition and be aware of reduced performance, planning is made more accessible. Preventive actions performed regularly could also be minimised and be performed when actually needed, condition-based. This also raises the question of what to measure. By utilising the condition data from the system, measures from the entire system could easily be included [49, 50].

The early conception of this thesis was to include condition data of the transportation line into the performance evaluation. Today, this data is collected through the SCADA systems throughout the transportation line, and some of it is visualised through the control system of the production, delivered by *ABB*. The data is not yet available to extract for analysis, but the potential here should be exploited. Measurements such as where the anodes are currently located are available, and therefore the transportation and cycle times could easily be calculated. Then, it is possible to track how often the anodes are delayed toward the furnaces, thereby affecting the performance. The exact time for transportation through the overhead conveyor and the roller conveyor, in addition to the time the automated crane at the storage uses for both pick-up and delivery of anodes, are relevant. Measurements of the power draw could indicate whether or not the conveyor works appropriately and is, therefore, a valuable measure of performance. An asset model where all asset data is included and knowledge about the operations, the equipment, the data solutions needs, and the industrial communications would make it possible to perform better decisions regarding asset management, improving the overall performance of the assets [45].

It is necessary to keep in mind that the maintenance records analysed for the last ten years show that each critical area has approximately one to two corrective repairs every year. If it is possible to minimise these incidents' consequences by monitoring the condition and eliminating the excessive downtime and profit loss, the situation will improve. With no control of the assets and things that happen out of nowhere, the expanded perception of today could be eliminated, and therefore, the organisation would be better prepared when the biannual incidents occur. By monitoring the performance, it is also possible to make sure that these breakdowns do not coincide. Asset performance is not just about the assets and the maintenance performed. If the wanted performance should be accomplished, all the plant divisions must work together to improve the conditions leading to reduced performance. The performance of the assets consist of several factors, and only one of them could be enough to reduce the performance significantly [7].

The business case for initiating projects related to asset performance and the required function of the assets is to get better control of the assets and their condition. By analysing the maintenance and operational history, the current status is mapped. This process must be repeated continuously if no system for current condition monitoring is implemented. When the condition data is taken to use, the next step is towards failure prediction and prognosis. Some situations are significantly improved when mapping and monitoring the performance, while this also is the first step towards a more complex solution, or failure detection [2, 16].

For this case, the control of the asset must first be gained. In Hydro, solutions as the ones implemented with the development of the digital maintenance strategy would help visualise the condition data. Through dashboards and pre-defined thresholds, alarms are raised if measures are below or over given values. This could trigger warnings of failures before their arrival. The performance is often reduced before complete failure, and by identifying this early, it is possible to plan for maintenance actions and thereby reduce the consequences. After the awareness of the condition is better visualised and the sense of control is gained, this could affect the maintenance plans and result in updates in the way of working. With continuous monitoring of the assets, this would affect several of the steps in the maintenance processes [55]. In this way, through implementing continuous monitoring of the asset performance, it is possible to regain control of the assets.

6.4 Asset performance for gaining back the control of the assets

In light of the research questions, asset performance has been investigated to improve production overall and specifically at the transportation line between the green mill and the furnaces. After identifying business cases, requirements, functional and physical functions of the system, and analysing the available data that could say something about the current condition of a system, something could be done about the performance of the assets. By deciding when and how to measure the performance and measuring this delivered performance towards the required performance, the awareness of the actual condition of a system is visualised. The steps towards a fully integrated asset condition monitoring system for measuring the performance could then be implemented [45, 49, 50].

When analysing the transportation line both in the context of the system itself and the available data, the impression of not being in control of the performance and condition of the assets is confirmed. When realising that no actual requirements are made to the system for identifying losses of function, there is great potential for improvement. Showing how the condition of the assets is mapped through utilising the available data while waiting for solutions to assess the condition data and integrating the different data sources is also important in other settings. Completing simple analysis on this data being generated for years gives an impression of the condition at once. Then, this could be used as a foundation for more complex solutions for measuring asset performance. It also builds the foundation for what is needed in an asset performance monitoring system and highlights what is important in such a system [49, 2, 6, 16].

In light of the recent report presented from the incident at Equinor's facility at Melkøya, it is crucial to keep in mind that follow up of the maintenance is needed [19]. Behind Hydro's commitment to the digital change, the idea is to go from performing time-based maintenance to actually performing the maintenance when needed, condition-based maintenance founded on the condition data from the systems themselves. It is then vital to not blindly trust the current condition but make sure that follow-ups are still made to avoid major incidents. Being aware of the current condition of the facility and the assets are important for both safety, and sustainability [71].

Hydro's digital change is in line with the Norwegian Ministry of Local Government and Modernisation's idea of utilising the data and the new technologies as essential resources for increasing the value all over the company [20]. As an asset-intensive company with critical equipment, it would be crucial for Hydro to apply the available data to get a better insight into the assets since they are such an essential part of the production processes [9]. The condition data directly from the system should give the best insights, but while waiting for the digital lift of including this data in the new ways of working, the other data sources must be used [49, 50]. Therefore, the maintenance and operational history are relevant, in addition to other available data sources. The analysis throughout this thesis shows that insights into the assets and their performance could be found in traditional maintenance records. This data is often collected but not utilised.

When completing this digital shift, it is also important to update the way of working to ensure that all of the resources spent on the shift comes to use [16]. If an asset performance system monitoring the system's condition is implemented, the maintenance actions must be adapted to use this condition when working. The plans must be adapted, and it must be made sure that the resources invested are constructive. One must keep in mind that even though such a solution is based on the condition data from the system, errors are made in the digital world, and therefore the maintenance still must be followed up to hinder significant incidents. Utilising the asset's condition could hinder some breakdowns, but unplanned situations causing excessive downtime and profit loss could still occur. It is crucial to keep in mind that all the data in the world can not control the future, even with excessive predictive techniques. Therefore, control of the asset must be gained to ensure a bright future.

The issue of mapping the performance of the assets and taking back the control of the assets is a complex issue with several factors [7]. There is no easy solution to the problem. However, the work has to start somewhere. It is a continuous process, and the goal must be to continuously work towards greatness. It is vital to gain control of the assets, making it possible to identify the current status [49]. There is no step-by-step solution to accomplishing this, but including the available data to identify the asset performance and the gap between the required and delivered functions would indicate where the road must continue.

The analysis completed throughout this thesis, where different data sources are utilised for mapping the current status of the transportation line, is extensive and time-demanding. It is not realistic to perform such an extensive analysis for every system in huge facilities, but it identifies how the data works together to gain insight into the status of the assets. The digital shift that Hydro is undergoing will make it possible to integrate the different data sources and present this insight easier. The analysis performed throughout the thesis shows where improvement measures could be made and how important it is to identify the system's status in the facilities. The concept of asset performance is essential as it integrates the different divisions of the company and sheds light on the actual condition of the plant. Evaluating the performance of the assets shows where work is needed to improve the overall performance of a company.

7 Conclusion

This master thesis was initiated with a background in the lack of control of ageing production facilities and the need for increasing the performance of their facilities and assets, to reduce downtime and profit loss. The concept of asset performance was investigated for this task, and a study of the transportation line of anodes at Hydro Aluminium's carbon facility in Årdal was conducted in light of how to improve its performance. The analysis performed included a system evaluation and a data analysis of the available maintenance history, downtime records and records of production setbacks. Initially, condition data from the transportation line was intended to be included, but this was not possible during the thesis period.

The analysis resulted in confirming the lack of control of the transportation line. Unlike the initial belief, the transportation line as a whole is not the most significant issue related to profit loss caused by downtime and stops. Analysing maintenance and operational history visualises how it is possible to get insight into the current asset condition. The function of the system was analysed in order to identify gaps between the delivered and required function. Previously, no requirements have been set to the transportation line, causing it difficult to identify the loss of function between the required and delivered performance. Some of the transportation line areas were identified as being more critical areas, including among others *S.23*, *R.11*, *R.20*, *P.3* and *P.4*. By monitoring the condition data from the system, continuous measurement of the current asset performance will be delivered. In the future, an integrated asset performance monitoring system can continuously evaluate the current status and easier identify loss of performance.

The results show how the concept of asset performance is important to identify where the resources must be placed for increasing both the condition and function of the assets and how it is part of the work with continuous improvement at production facilities. When using maintenance and operational history, it is possible to map the system's current performance, taking the first step towards better control of the assets. This show how data not intended for such a task can be utilised while waiting for more integrated and complex solutions. When such a mapping is completed, it is easier to identify what has to be included in an asset monitoring system. Since much of the data available in companies today are manually recorded, data quality could be an obstacle. While keeping this in mind and continuously improve the quality, it is still possible to utilise the data. Increasing the performance of the assets will, in the long term, reduce downtime and profit loss and lead to more sustainable production. Condition data directly from the asset will, together with integrated solutions for visualising this data, be necessary for improving the asset performance. In conclusion, asset performance is important for integrating a plant's different divisions towards the same goal. When the awareness of the accurate status and performance is visualised, it will be easier to work together to improve the overall performance.

7.1 Further work

Further work should include extracting the condition data related to the transportation line and including this data to evaluate the required function of the line. Additionally, this condition data should be included in a continuous performance monitoring system of the system, in line with Hydro's digital strategy. Furthermore, these solutions could be expanded into including prognosis and predictions based on the incorporated data. Simulations based on the data could also give a better foundation when making decisions.

Further research should also contain how the theoretical aspects in the field could be better aligned with the current condition of production facilities today. This study show how records not intended for asset performance evaluation could still be helpful when trying to get control of a production facility. This could further make it easier to take additional steps toward a more digital future, where the different data sources are integrated for giving better insights into the condition and performance of the assets and the plant as a whole. Additional research should look further into how the identified gap between the theory and the reality in the factories could be closed.

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Appendix

A Technical hierarchy from SAP

The following technical hierarchies are extracted from *SAP PM*, Hydro's system for recording their maintenance activities. They are used as the basis for understanding the functional and physical architecture of the system, in addition to other available documents in Hydro. The functional locations of each of the components, shown in the hierarchies, are also used for extracting the relevant data from *SAP*. Figure 36 shows the technical hierarchy for *the overhead conveyor*. Figure 37 gives the hierarchy of *the roller conveyor*. Figure 38 deliver the hierarchy for *the automated storage*, while Figure 39 shows the hierarchy for *the pushrods*.

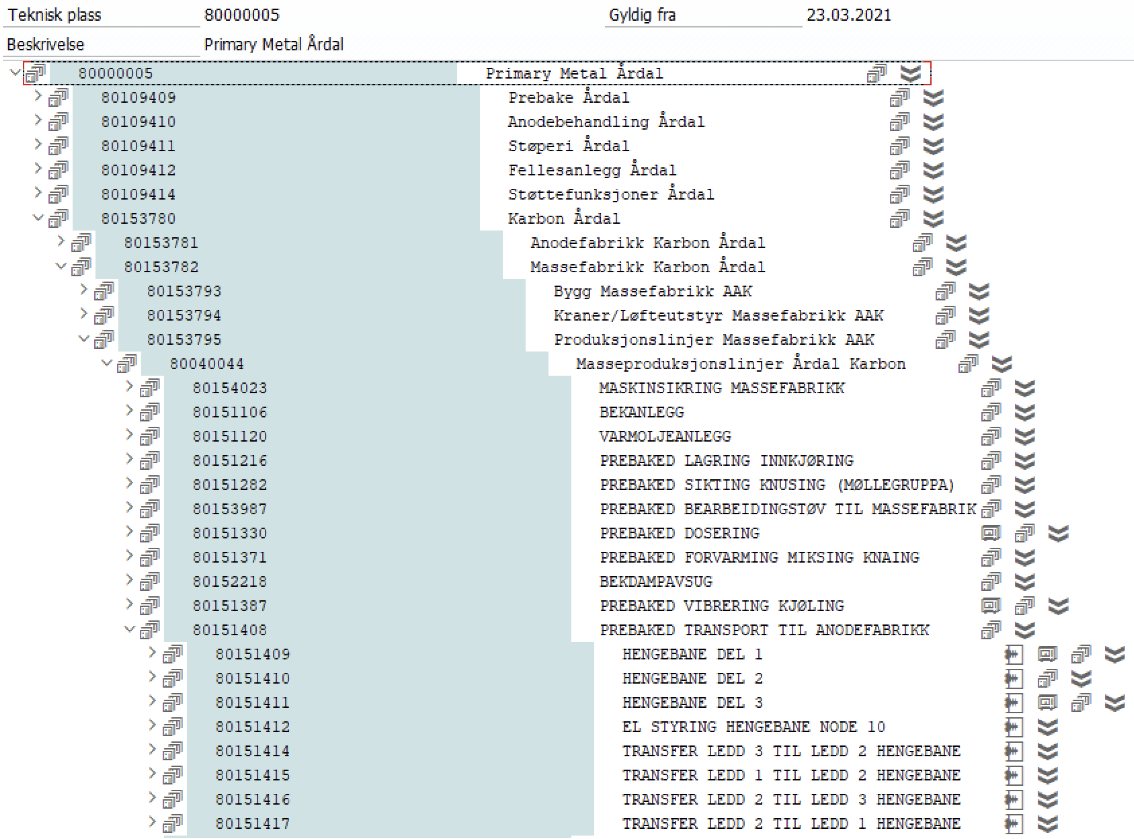

Figure 36: The technical hierarchy for the overhead conveyor *(hengebana)*

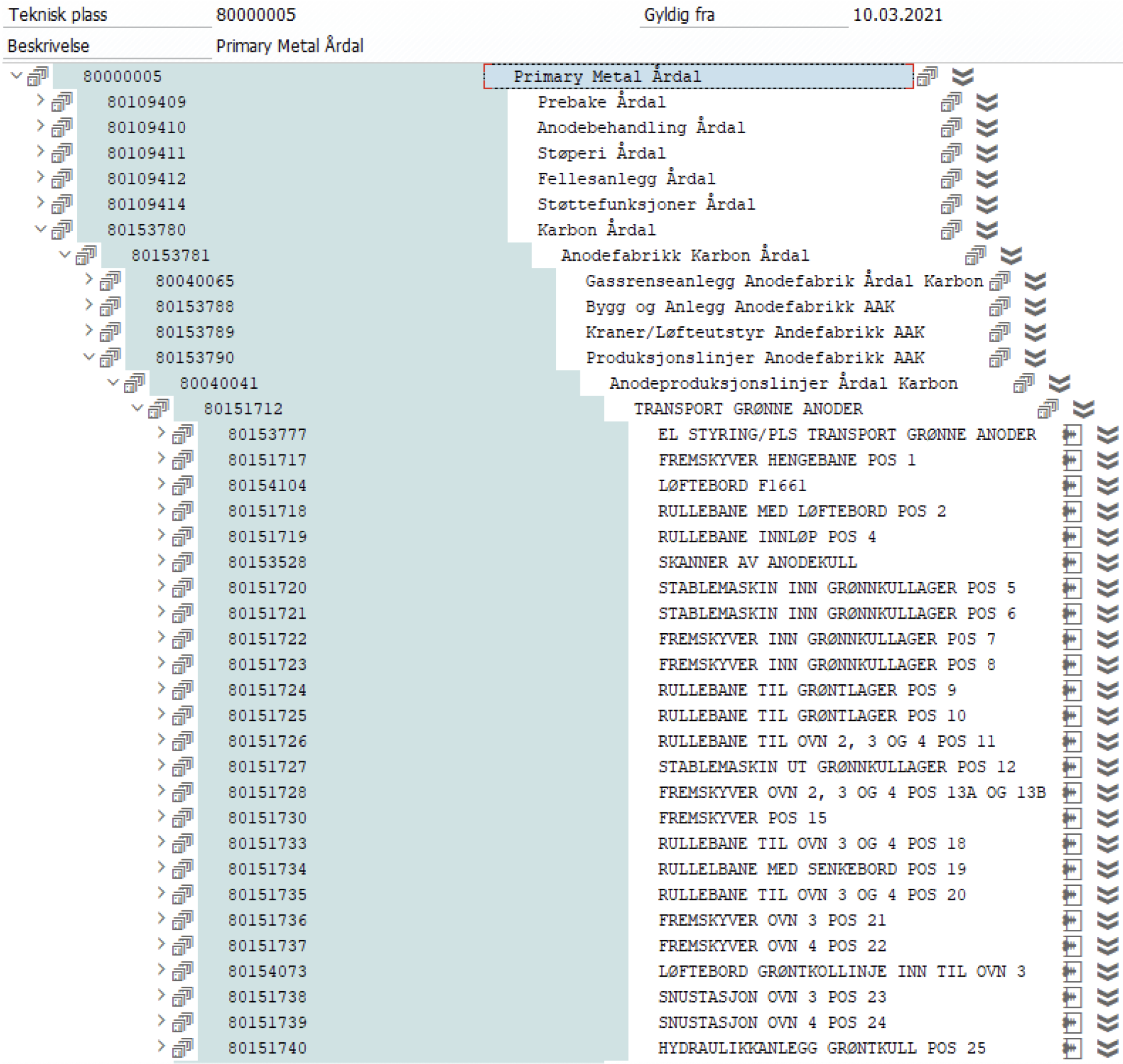

Figure 37: The technical hierarchy for the roller conveyor *(rullebana)*

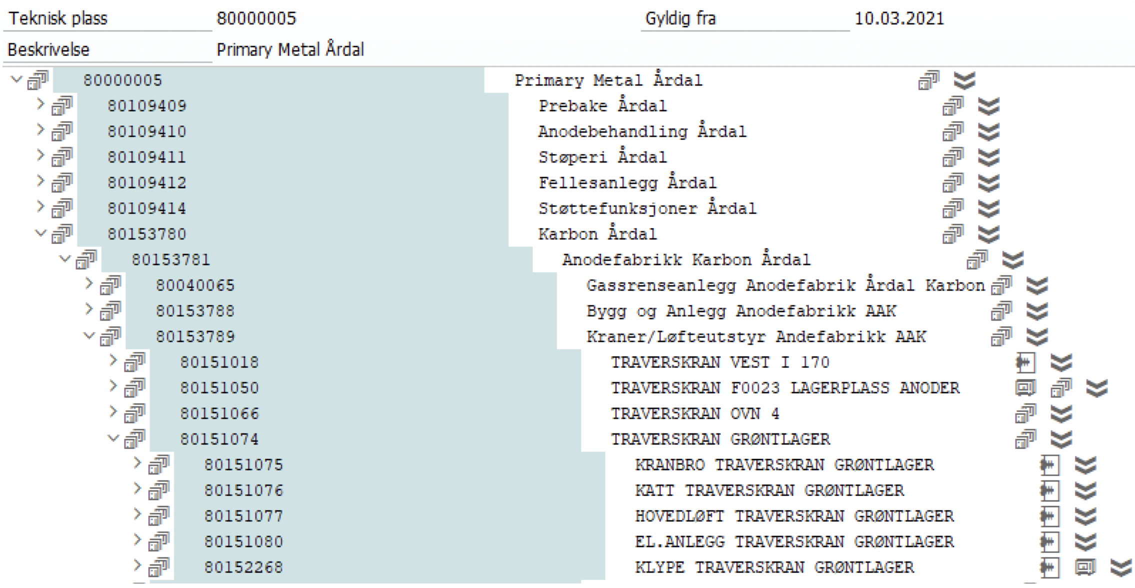

Figure 38: The technical hierarchy for the automated storage *(grøntlager)*

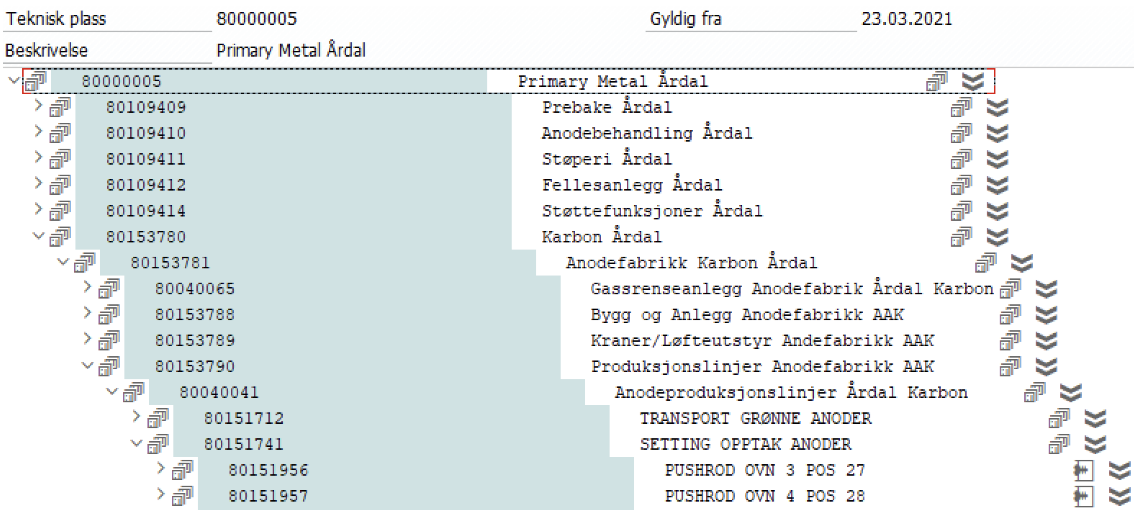

Figure 39: The technical hierarchy for the *pushrods*

B System analysis

B.1 System analysis abbreviations

The abbreviations for the different parts of the transportation line in Table 4 are used first in Figure 26, and are continuously used throughout Section 5 and 6. The shortenings are also used in Figure 27, 40, 41 and 42.

Abbreviation	Full name of system part
H.1	HENGEBANE DEL 1
T.1:2	TRANSFER LEDD 1 TIL LEDD 2 HENGEBANE
T.2:1	TRANSFER LEDD 2 TIL LEDD 1 HENGEBANE
H.2	HENGEBANE DEL 2
T.2:3	TRANSFER LEDD 2 TIL LEDD 3 HENGEBANE
T.3:2	TRANSFER LEDD 3 TIL LEDD 2 HENGEBANE
H.3	HENGEBANE DEL 3
F.1	FREMSKYVER HENGEBANE POS 1
L.F1661	LØFTEBORD F1661
R.L.2	RULLEBANE MED LØFTEBORD POS 2
R.4	RULLEBANE INNLØP POS 4
Scanner	SKANNER AV ANODEKULL
S.5	STABLEMASKIN INN GRØNNKULLAGER POS 5
S.6	STABLEMASKIN INN GRØNNKULLAGER POS 6
F.7	FREMSKYVER INN GRØNNKULLAGER POS 7
F.8	FREMSKYVER INN GRØNNKULLAGER POS 8
R.9	RULLEBANE TIL GRØNTLAGER POS 9
R.10	RULLEBANE TIL GRØNTLAGER POS 10
R.11	RULLEBANE TIL OVN 2, 3 OG 4 POS 11
S.12	STABLEMASKIN UT GRØNNKULLAGER POS 12
F.13	FREMSKYVER OVN 2, 3 OG 4 POS 13A OG 13B
F.15	FREMSKYVER POS 15
R.18	RULLEBANE TIL OVN 3 OG 4 POS 18
R.S.19	RULLELBANE MED SENKEBORD POS 19
R.20	RULLEBANE TIL OVN 3 OG 4 POS 20
F.21	FREMSKYVER OVN 3 POS 21
L.OVN3	LØFTEBORD GRØNTKOLLINJE INN TIL OVN 3
S.23	SNUSTASJON OVN 3 POS 23
P.3	PUSHROD OVN 3 POS 27
F.22	FREMSKYVER OVN 4 POS 22
S.24	SNUSTASJON OVN 4 POS 24
P.4	PUSHROD OVN 4 POS 28
Kranbru	KRANBRO TRAVERSKRAN GRØNTLAGER
Hov.løft	HOVEDLØFT TRAVERSKRAN GRØNTLAGER
Klype	KLYPE TRAVERSKRAN GRØNTLAGER
Katt	KATT TRAVERSKRAN GRØNTLAGER
Hydraulikk	HYDRAULIKKANLEGG GRØNTKULL POS 25

Table 4: List of abbreviations used for the system parts

B.2 System analysis figures

Figure 40 show the interaction of sub-system 1, *the overhead conveyor* with the rest of the system. Figure 41 focuses on sub-system 2, *the roller conveyor*, while Figure 42 show the interactions of sub-system 3, *the automated storage*. These three figures are all variations of Figure 26, focusing of each of the three sub-systems at a time. The figures are built on the foundation of the technical hierarchies visualised in Figure 24 in Section 4, and the figures in Section A.

Figure 40: Overview of sub-system 1 - The overhead conveyor *(hengebana)*

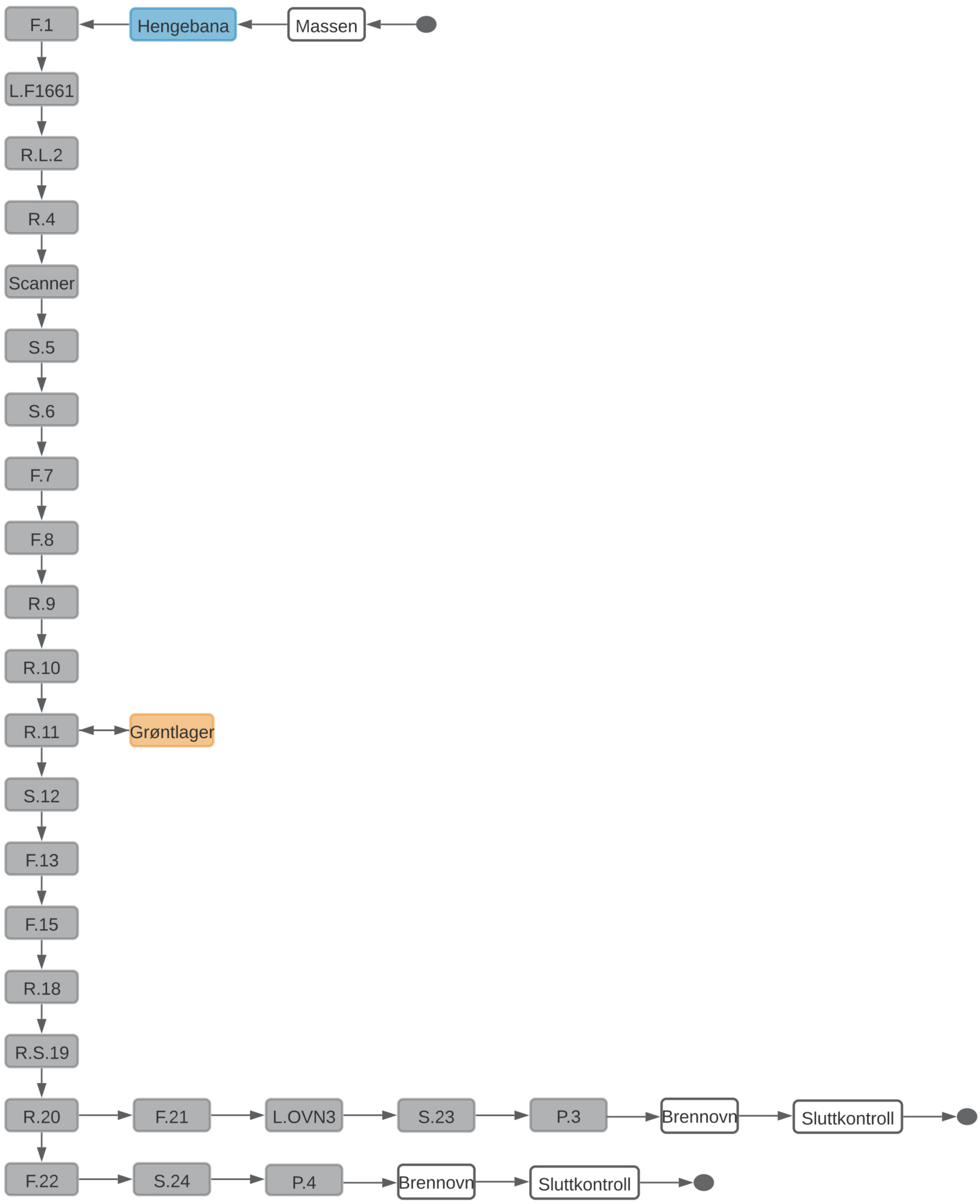

Figure 41: Overview of sub-system 2 - The roller conveyor *(rullebana)*

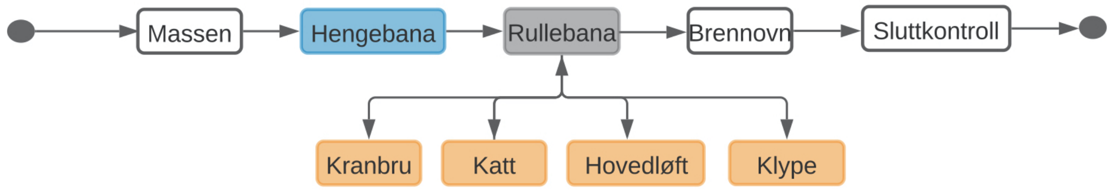

Figure 42: Overview of sub-system 3 - The automated storage *(grøntlager)*

C Python scripts for data analysis

In the following sections, the *python* scripts for the data analysis of the *SAP* records are attached. The scripts were written in *Jupyter Notebook* to get instant feedback. *Pandas* was used for systematising and grouping of the data, while *Matplotlib* was used for data visualisation. Section C.1 include the analysis of the data extracted from *SAP* using transaction code *IW39*. This data included the maintenance work orders. Section C.2 include the analysis of the data extracted from *SAP* using transaction code *IW60*. This data included the maintenance notifications. Section C.3 include the script for analysing the records of production setbacks, which was performed for detecting profit loss caused by the transportation line analysed.

C.1 Analysis of extracted data from SAP using IW39

```
import pandas as pd
import datetime
import matplotlib.pyplot as plt
import numpy as np
import seaborn as sns

del1 = pd.read_excel("transport_til_anodefabrikk.xlsx")
del2 = pd.read_excel("traverskran_grontlager.xlsx")
del3 = pd.read_excel("transport_gronne_anodar.xlsx")
del4 = pd.read_excel("pushrod.xlsx")
frames = [del1, del2, del3, del4]
df = pd.concat(frames, ignore_index=True, sort=False)

df["Teknisk plass"] = df["Teknisk plass"].apply(str)

# Duration
df["Start kl."] = df["Start kl."].replace(["24:00:00"], "00:00:00")
df["Slutt kl."] = df["Slutt kl."].replace(["24:00:00"], "00:00:00")
df["Start"] = pd.to_datetime(df["Basisstarttid."].apply(str) + " " + df["Start
↪  kl."])
df["Basissluttidsp."] = df["Basissluttidsp."].fillna(df["Basisstarttid."])
df["Slutt"] = pd.to_datetime(df["Basissluttidsp."].apply(str) + " " + df["Slutt
↪  kl."])
df["Varigheit"] = (df["Slutt"] - df["Start"]).astype("timedelta64[m]")

# Selecting columns
viktig = ["Teknisk plass", "Ordretype", "Korttekst", "Basisstarttid.",
↪  "Varigheit", "Tot.kostn. fakt"]
df = df[viktig]

# Date
df = df.rename(columns={"Basisstarttid.":"Dato", "Tot.kostn. fakt":"Kostnad"})

# 10 year duration: 1.1.2011 to 31.12.2020
df = df[df["Dato"] >= "2011-01-01"]
df = df[df["Dato"] <= "2020-12-31"]
df = df.reset_index(drop=True)

# Removing component
df = df[df["Teknisk plass"] != "80151712"]  # del1
df = df[df["Teknisk plass"] != "80151074"]  # del2
df = df[df["Teknisk plass"] != "80151408"]  # del3

# Changing names
```

```
teknisk_plass = ["80153777", "80151717", "80154104", "80151718", "80151719",
↪  "80153528", "80151720", "80151721", "80151722", "80151723", "80151724",
↪  "80151725", "80151726", "80151727", "80151728", "80151730", "80151733",
↪  "80151734", "80151735", "80151736", "80151737", "80154073", "80151738",
↪  "80151739", "80151740", "80151075", "80151076", "80151077", "80151080",
↪  "80152268", "80151409", "80151410", "80151411", "80151412", "80151414",
↪  "80151415", "80151416", "80151417", "80151956", "80151957"]
namn = ["PLS TRANSPORT", "FRAMSKYVAR POS 1", "LØFTEBORD F1661",
↪  "RULLEBANE/LØFTEBORD POS 2", "RULLEBANE POS 4", "SCANNAR", "STABLEMASKIN POS
↪  5", "STABLEMASKIN POS 6", "FRAMSKYVAR POS 7", "FRAMSKYVAR POS 8", "RULLEBANE
↪  POS 9", "RULLEBANE POS 10", "RULLEBANE POS 11", "STABLEMASKIN POS 12",
↪  "FREMSKYVER POS 13A OG 13B", "FREMSKYVER POS 15", "RULLEBANE POS 18",
↪  "RULLEBANE/SENKEBORD POS 19", "RULLEBANE POS 20", "FRAMSKYVAR POS 21",
↪  "FREMSKYVAR POS 22", "LØFTEBORD OVN 3", "SNUSTASJON POS 23", "SNUSTASJON POS
↪  24", "HYDRAULIKKANLEGG POS 25", "KRANBRU GRØNTLAGER", "KRANKATT GRØNTLAGER",
↪  "HOVEDLØFT KRAN GRØNTLAGER", "EL KRAN GRØNTLAGER", "KRANKLYPE GRØNTLAGER",
↪  "HENGEBANE 1", "HENGEBANE 2", "HENGEBANE 3", "EL HENGEBANE", "TRANSFER LEDD 3
↪  TIL 2", "TRANSFER LEDD 1 TIL 2", "TRANSFER LEDD 2 TIL 3", "TRANSFER LEDD 2
↪  TIL 1", "PUSHROD OVN 3", "PUSHROD OVN 4"]
z = dict(zip(teknisk_plass, namn))
df["Teknisk plass"] = df["Teknisk plass"].replace(z)

# Dividing maintenance orders into maintenance categories
Z001 = df[df["Ordretype"] == "Z001"]  # Preventive maintenance
Z002 = df[df["Ordretype"] == "Z002"]  # Reactive maintenance
Z003 = df[df["Ordretype"] == "Z003"]  # Modifications
Z004 = df[df["Ordretype"] == "Z004"]  # CAPEX
Z005 = df[df["Ordretype"] == "Z005"]  # CAPEX
Z006 = df[df["Ordretype"] == "Z006"]  # Repairs of parts
Z010 = df[df["Ordretype"] == "Z010"]  # ?

# Calculating costs
Z001_sum = Z001.groupby("Teknisk plass").sum()
Z002_sum = Z002.groupby("Teknisk plass").sum()
Z003_sum = Z003.groupby("Teknisk plass").sum()
Z004_sum = Z004.groupby("Teknisk plass").sum()
Z005_sum = Z005.groupby("Teknisk plass").sum()
Z006_sum = Z006.groupby("Teknisk plass").sum()
Z010_sum = Z010.groupby("Teknisk plass").sum()

# Counting maintence orders
Z001_count = Z001.groupby("Teknisk plass").count()
Z002_count = Z002.groupby("Teknisk plass").count()
Z003_count = Z003.groupby("Teknisk plass").count()
Z004_count = Z004.groupby("Teknisk plass").count()
Z005_count = Z005.groupby("Teknisk plass").count()
Z006_count = Z006.groupby("Teknisk plass").count()
Z010_count = Z010.groupby("Teknisk plass").count()

# Lists of same shape for plotting
def list_for_plot(liste, index, count, lables):
        for i in range(len(lables)):
            for j in range(len(index)):
                if lables[i] == index[j]:
                    liste.append(count[j])
                    break
            if i == len(liste):
                liste.append(0)
```

```
        return liste

# Function for plotting of distribution of maintenance categories
def plot_barplot_maintenance_categories(Z001_x, Z002_x, Z003_x, Z004_x, Z005_x,
↪   Z006_x, Z010_x, Z001_y, Z002_y, Z003_y, Z004_y, Z005_y, Z006_y, Z010_y,
↪   x_label, y_label):
    lables = Z002_x

    Z001_plot = list_for_plot([], Z001_x, Z001_y, lables)
    Z002_plot = list_for_plot([], Z002_x, Z002_y, lables)
    Z003_plot = list_for_plot([], Z003_x, Z003_y, lables)
    Z004_plot = list_for_plot([], Z004_x, Z004_y, lables)
    Z005_plot = list_for_plot([], Z005_x, Z005_y, lables)
    Z006_plot = list_for_plot([], Z006_x, Z006_y, lables)
    Z010_plot = list_for_plot([], Z010_x, Z010_y, lables)

    width = 0.5
    plt.rcdefaults()
    sns.set_style("whitegrid")
    sns.set_context("poster")
    fig, ax = plt.subplots(figsize=(30,15))

    fields = [Z001_plot, Z002_plot, Z003_plot, Z004_plot, Z005_plot, Z006_plot,
    ↪   Z010_plot]
    labels_name = ["Z001", "Z002", "Z003", "Z004", "Z005", "Z006", "Z010"]
    bottom = np.zeros(len(lables))

    for i in range(len(fields)):
        ax.bar(lables, fields[i], width, bottom=bottom, label=labels_name[i])
        bottom = bottom + np.array(fields[i])

    ax.set_xlabel(x_label)
    ax.set_ylabel(y_label)
    plt.xticks(rotation=90)
    ax.legend()

    plt.show()

# Plot: number of maintenance orders
plot_barplot_maintenance_categories(Z001_count.index, Z002_count.index,
↪   Z003_count.index, Z004_count.index, Z005_count.index, Z006_count.index,
↪   Z010_count.index, Z001_count["Ordretype"], Z002_count["Ordretype"],
↪   Z003_count["Ordretype"], Z004_count["Ordretype"], Z005_count["Ordretype"],
↪   Z006_count["Ordretype"], Z010_count["Ordretype"], "Location", "Number of
↪   maintenance orders")

# Plot: duration
plot_barplot_maintenance_categories(Z001_sum.index, Z002_sum.index,
↪   Z003_sum.index, Z004_sum.index, Z005_sum.index, Z006_sum.index,
↪   Z010_sum.index, Z001_sum["Varigheit"], Z002_sum["Varigheit"],
↪   Z003_sum["Varigheit"], Z004_sum["Varigheit"], Z005_sum["Varigheit"],
↪   Z006_sum["Varigheit"], Z010_sum["Varigheit"], "Location", "Duration [min]")

# Plot: cost
```

```
plot_barplot_maintenance_categories(Z001_sum.index, Z002_sum.index,
↪  Z003_sum.index, Z004_sum.index, Z005_sum.index, Z006_sum.index,
↪  Z010_sum.index, Z001_sum["Kostnad"], Z002_sum["Kostnad"],
↪  Z003_sum["Kostnad"], Z004_sum["Kostnad"], Z005_sum["Kostnad"],
↪  Z006_sum["Kostnad"], Z010_sum["Kostnad"], "Location", "Cost [NOK]")

# Dividing system in three
del_hengebane = [0, 9, 10, 11, 36, 37, 38, 39]
del_rullebane = [2, 3, 4, 5, 6, 7, 8, 13, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26,
↪  27, 28, 29, 30, 31, 32, 33, 34, 35]
del_automatlager = [1, 12, 14, 15, 16]

# Changing colors to match the correct part of the system
def change_color(barplot, bars, color):
    for i in range(len(bars)):
        barplot[bars[i]].set_color(color)

# Printing barplot
def print_barplot(x, y, x_label, y_label, color=True):
    plt.rcdefaults()
    sns.set_style("whitegrid")
    sns.set_context("poster")
    fig, ax = plt.subplots(figsize=(30,15))
    barplot = ax.bar(x, y)  # barh dersom horistonal

    if color:
        change_color(barplot, del_hengebane, "tab:blue")
        change_color(barplot, del_rullebane, "tab:grey")
        change_color(barplot, del_automatlager, "tab:orange")

    ax.set_xlabel(x_label)
    ax.set_ylabel(y_label)
    plt.xticks(rotation=90)

    plt.show()

# Plot: number of maintenance orders
print_barplot(Z002_count.index, Z002_count["Ordretype"], "Location", "Number of
↪  maintenance orders")

# Plot: duration
print_barplot(Z002_sum.index, Z002_sum["Varigheit"], "Location", "Duration
↪  [min]")

# Plot: cost
print_barplot(Z002_sum.index, Z002_sum["Kostnad"], "Location", "Cost [NOK]")

# Examination of problem area
def check_problem_area(name):
    area = Z002[Z002["Teknisk plass"] == (name)]
    area_count = area.groupby(area["Dato"].dt.year).count()
    print_barplot(area_count.index, area_count["Teknisk plass"], "Date", "Number
    ↪  of maintenance orders", color=False)

# Example
problem_area = "PUSHROD OVN 3 POS 27"
check_problem_area(problem_area)
```

C.2 Analysis of extracted data from SAP using IW69

```
import pandas as pd
import datetime
import matplotlib.pyplot as plt
import numpy as np
import seaborn as sns

del1 = pd.read_excel("transport_til_anodefabrikk_kodetekst.xlsx")
del2 = pd.read_excel("traverskran_grontlager_kodetekst.xlsx")
del3 = pd.read_excel("transport_gronne_anodar_kodetekst.xlsx")
del4 = pd.read_excel("pushrod_kodetekst.xlsx")
frames = [del1, del2, del3, del4]
df = pd.concat(frames, ignore_index=True, sort=False)

# 10 year duration: 1.1.2022 to 31.12.2020
df = df[df["Meldingsdato"] >= "2011-01-01"]
df = df[df["Meldingsdato"] <= "2020-12-31"]
df = df.reset_index(drop=True)

# Removing compontent
df = df[df["Teknisk plass"] != "80151712"]  # del1
df = df[df["Teknisk plass"] != "80151074"]  # del2
df = df[df["Teknisk plass"] != "80151408"]  # del3

#  Selecting columns
viktig = ["Teknisk plass", "Beskrivelse", "Meldingsdato", "Kodetekst", "Kodetekst
↪  prob.", "Kodetekst årsak", "Prioritet", "Brukerdef. st."]
df = df[viktig]

df["Total kodetekst"] = df["Kodetekst"] + " " + df["Kodetekst prob."] + " " +
↪  df["Kodetekst årsak"]
df = df[df["Meldingstype"] == "Z2"]

# Lists of same shape for plotting
def list_for_plot(liste, index, count, lables):
    for i in range(len(lables)):
        for j in range(len(index)):
            if lables[i] == index[j]:
                liste.append(count[j])
                break
        if i == len(liste):
            liste.append(0)
    return liste

# Printing barplot
def print_barplot(x, y, x_kritisk, y_kritisk, x_vakt, y_vakt, x_label, y_label):
    lables = x

    x = list_for_plot([],x, y, lables)
    x_kritisk = list_for_plot([], x_kritisk, y_kritisk, lables)
    x_vakt = list_for_plot([], x_vakt, y_vakt, lables)

    width = 0.5
    plt.rcdefaults()
    sns.set_style("whitegrid")
    sns.set_context("poster")
    fig, ax = plt.subplots(figsize=(30,15))
```

```
    fields = [x, x_kritisk, x_vakt]
    labels_name = ["All notifications", "Priority: 1.0 og 2.0", "Definition:
    ↪  VAKT"]
    bottom = np.zeros(len(lables))

    for i in range(len(fields)):
        ax.bar(lables, fields[i], width, bottom=bottom, label=labels_name[i])

    ax.set_xlabel(x_label)
    ax.set_ylabel(y_label)
    plt.xticks(rotation=90)
    ax.legend()

    plt.show()

# Function for checking an area
def check_area(df, df_kritisk, df_vakt, plass):
    df = df[df["Beskrivelse"] == (plass)]
    df_kritisk = df_kritisk[df_kritisk["Beskrivelse"] == (plass)]
    df_vakt = df_vakt[df_vakt["Beskrivelse"] == (plass)]

    count = df.groupby("Kodetekst").count()
    count_kritisk = df_kritisk.groupby("Kodetekst").count()
    count_vakt = df_vakt.groupby("Kodetekst").count()
    count_problem = df.groupby("Kodetekst prob.").count()
    count_problem_kritisk = df_kritisk.groupby("Kodetekst prob.").count()
    count_problem_vakt = df_vakt.groupby("Kodetekst prob.").count()
    count_årsak = df.groupby("Kodetekst årsak").count()
    count_årsak_kritisk = df_kritisk.groupby("Kodetekst årsak").count()
    count_årsak_vakt = df_vakt.groupby("Kodetekst årsak").count()
    alt = df.groupby("Total kodetekst").count()

    print_barplot(count.index, count["Teknisk plass"], count_kritisk.index,
    ↪  count_kritisk["Teknisk plass"], count_vakt.index, count_vakt["Teknisk
    ↪  plass"], "Component", "Number of messages")
    print_barplot(count_problem.index, count_problem["Teknisk plass"],
    ↪  count_problem_kritisk.index, count_problem_kritisk["Teknisk plass"],
    ↪  count_problem_vakt.index, count_problem_vakt["Teknisk plass"], "Problem",
    ↪  "Number of messages")
    print_barplot(count_årsak.index, count_årsak["Teknisk plass"],
    ↪  count_årsak_kritisk.index, count_årsak_kritisk["Teknisk plass"],
    ↪  count_årsak_vakt.index, count_årsak_vakt["Teknisk plass"], "Cause",
    ↪  "Number of messages")
    print_barplot_enkel(alt.index, alt["Teknisk plass"], "Component + Problem +
    ↪  Cause", "Number of messages")

# Selecting parameters
df_kritisk = df[df["Prioritet"] == (1.0 and 2.0)] # High criticality
df_vakt = df_kritisk[df_kritisk["Brukerdef. st."] == "VAKT"] # On-call duty

# Example
check_area(df, "PUSHROD OVN 3 POS 27")
check_area(df_kritisk, "PUSHROD OVN 3 POS 27")
check_area(df_vakt, "PUSHROD OVN 3 POS 27")
```

C.3 Analysis of records of production setbacks *(tilbakesettingar)*

```
import pandas as pd
import datetime
import matplotlib.pyplot as plt
import numpy as np
import seaborn as sns

df = pd.read_excel("tilbakesettingar.xlsx")

# Keeping necassary columns
columns = ["År", "Veke", "Ovn 3 timer", "Ovn 3 kommentar", "Ovn 4 timer", "Ovn 4
↪  kommentar"]
df = df[columns]

# Group by year, calculating resets per year
year = df.groupby("År").sum()

# Plot resets over the last years
plt.rcdefaults()
sns.set_style("whitegrid")
sns.set_context("poster")

fig, ax = plt.subplots(figsize=(30,15))
width = 0.5
ax.bar(year.index, year["Ovn 3 timer"], width, label="Furnace 3", zorder=1)
ax.bar(year.index, year["Ovn 4 timer"], width, label="Furnace 4", zorder=2)
ax.set_xlabel("Years")
ax.set_ylabel("Resets [hours]")
plt.xticks(rotation=90)
ax.legend()
plt.show()

# Comments of resets for furnace 3
comments_3 = np.array(df["Ovn 3 kommentar"].dropna())

# Grouping comments for furnace 3
green_anodes_3 = ["Utfordring med grønt inn på ovnen", "Utfordring med vippe,
↪  fyring på K303", "Logistikk utfordringer + kran nede 26 timer", "Store
↪  utfordringar med kraner, respirentar, automatkran, børste og transport inn
↪  til og ut av ovn", "Ras grønt + sugerør ovn 3. Varme og muring kortsone ovn
↪  4", "Havari pir11, ikkje nok koks på ovnen + Respirent 3", "Heis før vippe
↪  ovn 3, defekte rullar før vippe inn ovn 3 og overfylling av kokstank ovn 3"]
crane_3 = ["Brann i hengekabler kran 3", "Kran ute 16 timer", "Logistikk
↪  utfordringer + kran nede 26 timer", "Utfordringar med respirent 3", "Havari
↪  pir11, ikkje nok koks på ovnen + Respirent 3","Store utfordringar med kraner,
↪  respirentar, automatkran, børste og transport inn til og ut av ovn",
↪  "kranhavari Kran 3 under lokklegging","planlagt utetid sjøvannstasjon og
↪  dermed manglende fyring på ovn + pga kranhavari traverskran 3", "motorhavari
↪  resipient 3"]
process_3 = ["Bytte av hovedspjeld ut kammer 3. Ovn 3 på nødavsug i 18t",
↪  "Undertrykksmåler", "Fakling", "Utfall av renseanlegg, tap av fyring",
↪  "Utfordring med renseanlegg, temperatur inne på ovnen", "LPG-utfall",
↪  "Strømstans", "Nødveg natt til sundag", "Isolasjon RTO78", "Holdtid K316",
↪  "Vakuumturbin havari", "planlagt utetid sjøvannstasjon og dermed manglende
↪  fyring på ovn + pga kranhavari traverskran 3", "Bru K301 ute, ikke restartet
↪  i løpet av skiftet"]
```

```
other_3 = ["Forsinka muring", "Utfordringar med børsterobot og BM2", "Forsinka
↪  loklegging før helg på 6 timar"]

# Comments of resets for furnace 4
comments_4 = np.array(df["Ovn 4 kommentar"].dropna())

# Grouping comments for furnace 4
green_anodes_4 = ["Logistikk utfordringer + kran nede 26 timer", "Havari
↪  automatkran grønt", "Store utfordringar med kraner, respirentar, automatkran,
↪  børste og transport inn til og ut av ovn"]
crane_4 = ["Logistikk utfordringer + kran nede 26 timer", "Utfall av renseanlegg,
↪  tap av fyring + Havari drivhjul kran 4", "Utfordringar med respirent 4",
↪  "Utfordring med kran 4","Store utfordringar med kraner, respirentar,
↪  automatkran, børste og transport inn til og ut av ovn"]
process_4 = ["Strømstans", "Undertrykksmåler", "Utfall av renseanlegg, tap av
↪  fyring + Havari drivhjul kran 4", "Utfall av renseannlegg (RT079), tap av
↪  fyring", "Utfordring med renseanlegg", "Skifte av hovudspjel på RT079,
↪  utfordringar med temperatur inne på ovnen", "LPG-utfall", "Nødveg natt til
↪  laurdag", "Isolasjon RT079", "planlagt utetid sjøvannstasjon og dermed
↪  manglende fyring på ovn"]
other_4 = ["Revisjonsstans", "Forsinka loklegging i helg på 6 timar", "Riving av
↪  gurttopp på K409/K410, utslitte hjul og aksel vendar ut ovn 4", "Utfordringar
↪  med børsterobot og BM2"]

# Dataframe for furnace 3
columns_3 = ["År", "Veke", "Ovn 3 timer", "Ovn 3 kommentar"]
furnace_3 = df[columns_3]

# Dataframe for furnace 4
columns_4 = ["År", "Veke", "Ovn 4 timer", "Ovn 4 kommentar"]
furnace_4 = df[columns_4]

# Filter columns without comment. Dataframe for every group of comments - furnace
↪  3
green_3 = furnace_3[furnace_3["Ovn 3 kommentar"].isin(green_anodes_3)]
cranes_3 = furnace_3[furnace_3["Ovn 3 kommentar"].isin(crane_3)]
baking_process_3 = furnace_3[furnace_3["Ovn 3 kommentar"].isin(process_3)]
others_3 = furnace_3[furnace_3["Ovn 3 kommentar"].isin(other_3)]

# Filter columns without comment. Dataframe for every group of comments - furnace
↪  4
green_4 = furnace_4[furnace_4["Ovn 4 kommentar"].isin(green_anodes_4)]
cranes_4 = furnace_4[furnace_4["Ovn 4 kommentar"].isin(crane_4)]
baking_process_4 = furnace_4[furnace_4["Ovn 4 kommentar"].isin(process_4)]
others_4 = furnace_4[furnace_4["Ovn 4 kommentar"].isin(other_4)]

# Group by year, sum - furnace 3
green_3_year = green_3.groupby("År").sum()
cranes_3_year = cranes_3.groupby("År").sum()
backing_process_3_year = baking_process_3.groupby("År").sum()
others_3_year = others_3.groupby("År").sum()

# Group by year, sum - furnace 4
green_4_year = green_4.groupby("År").sum()
cranes_4_year = cranes_4.groupby("År").sum()
backing_process_4_year = baking_process_4.groupby("År").sum()
others_4_year = others_4.groupby("År").sum()
```

```
# Generating lists for plotting
def list_for_plot(liste, index, count, lables):
    for i in range(len(lables)):
        for j in range(len(index)):
            if lables[i] == index[j]:
                liste.append(count.iloc[j])
                break
        if i == len(liste):
            liste.append(0)
    return liste

green_3_plot = list_for_plot([], green_3_year.index, green_3_year["Ovn 3 timer"],
↪   year.index)
cranes_3_plot = list_for_plot([], cranes_3_year.index, cranes_3_year["Ovn 3
↪   timer"], year.index)
baking_process_3_plot = list_for_plot([], baking_process_3_year.index,
↪   baking_process_3_year["Ovn 3 timer"], year.index)
others_3_plot = list_for_plot([], others_3_year.index, others_3_year["Ovn 3
↪   timer"], year.index)
green_4_plot = list_for_plot([], green_4_year.index, green_4_year["Ovn 4 timer"],
↪   year.index)
cranes_4_plot = list_for_plot([], cranes_4_year.index, cranes_4_year["Ovn 4
↪   timer"], year.index)
baking_process_4_plot = list_for_plot([], baking_process_4_year.index,
↪   baking_process_4_year["Ovn 4 timer"], year.index)
others_4_plot = list_for_plot([], others_4_year.index, others_4_year["Ovn 4
↪   timer"], year.index)

# Plot grouped resets
plt.rcdefaults()
sns.set_style("whitegrid")
sns.set_context("poster")

fields = [green_3_plot, cranes_3_plot, baking_process_3_plot, others_3_plot,
↪   green_4_plot, cranes_4_plot, baking_process_4_plot, others_4_plot]
lables = ["Transport to furnace 3", "Cranes - furnace 3", "Baking process -
↪   furnace 3", "Other - furnace 3", "Transport to furnace 4", "Cranes - furnace
↪   4", "Baking process - furnace 4", "Other - furnace 4"]

fig, ax = plt.subplots(figsize=(30,15))
width = 0.5
bottom = np.zeros(len(year.index))
for i in range(len(fields)):
    plt.bar(year.index, fields[i], width, bottom=bottom, label=lables[i])
    bottom = bottom + np.array(fields[i])

ax.set_xlabel("Years")
ax.set_ylabel("Resets [hours]")
plt.xticks(rotation=90)
ax.legend()

plt.show()
```

D Analysis of downtime registrations *(stopptidsregistrering)*

The following figures show the reports generated in *APICS*, based on the downtime and stop registrations performed by the operators in production. The different figures show the downtime and number of stops for different locations relevant to the transportation line. The figures are described and analysed in Section 5.3.2.

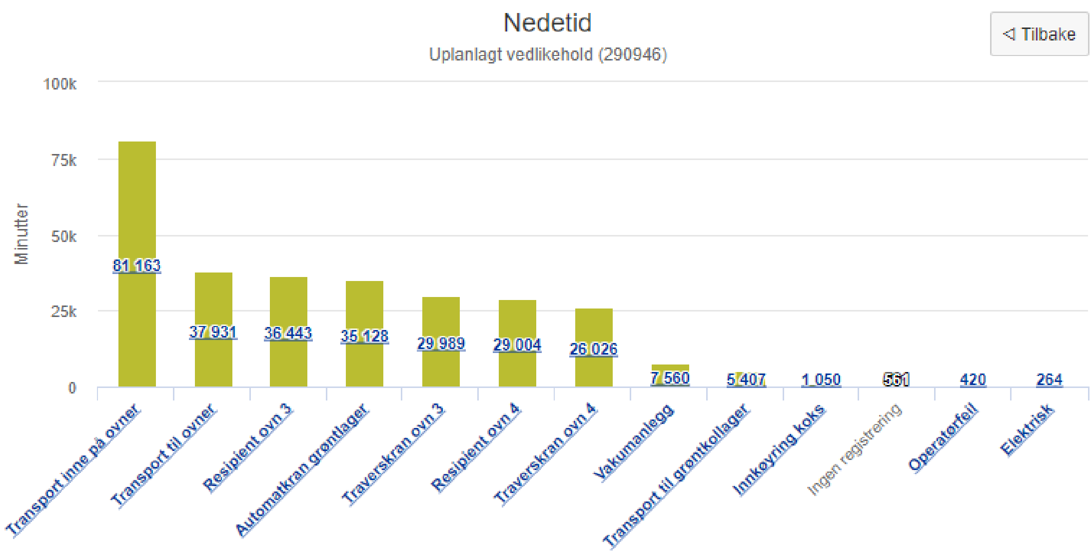

Figure 43: Registration of downtime for *the bakehouse* from 2016 until 2021

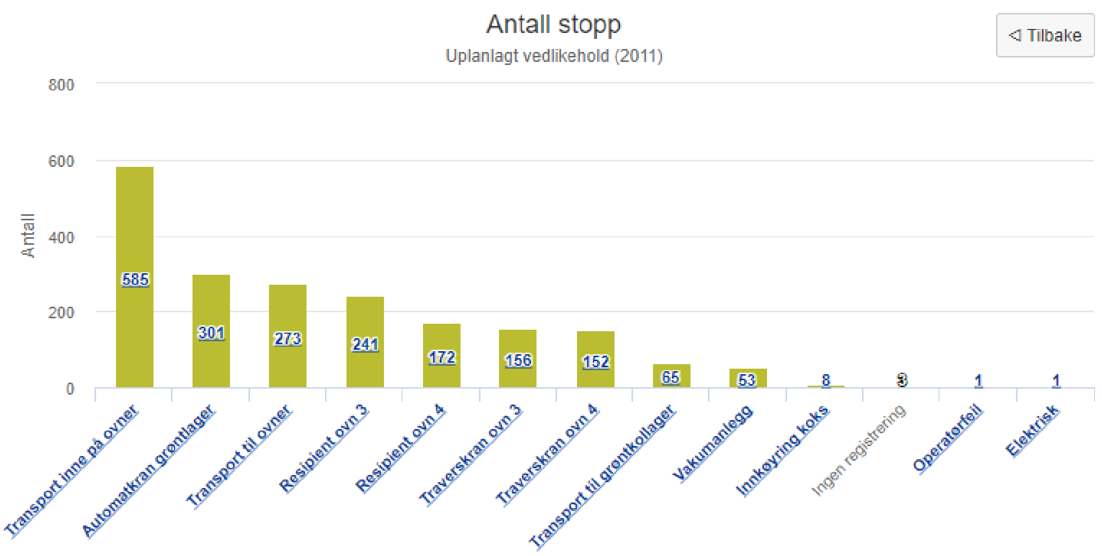

Figure 44: Registration of stops for *the bakehouse* from 2016 until 2021

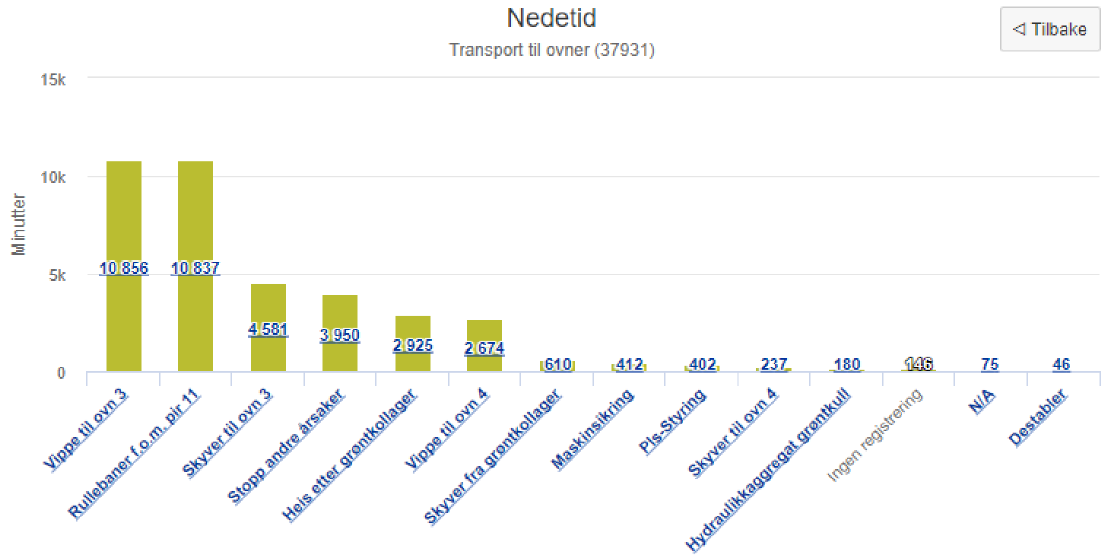

Figure 45: Registration of downtime for *transport to furnaces* from 2016 until 2021

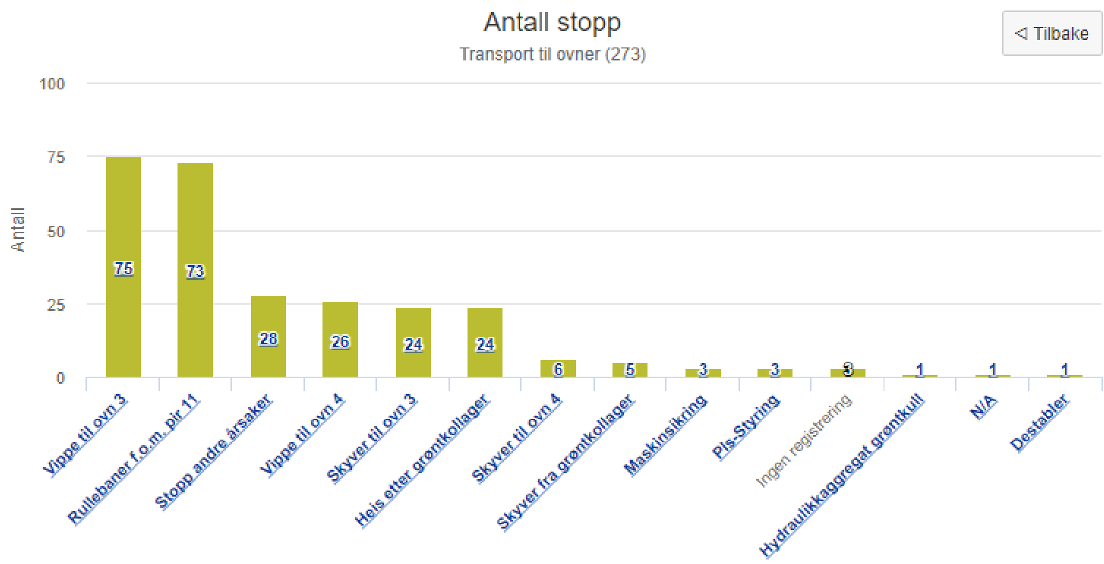

Figure 46: Registration of stops for *transport to furnaces* from 2016 until 2021

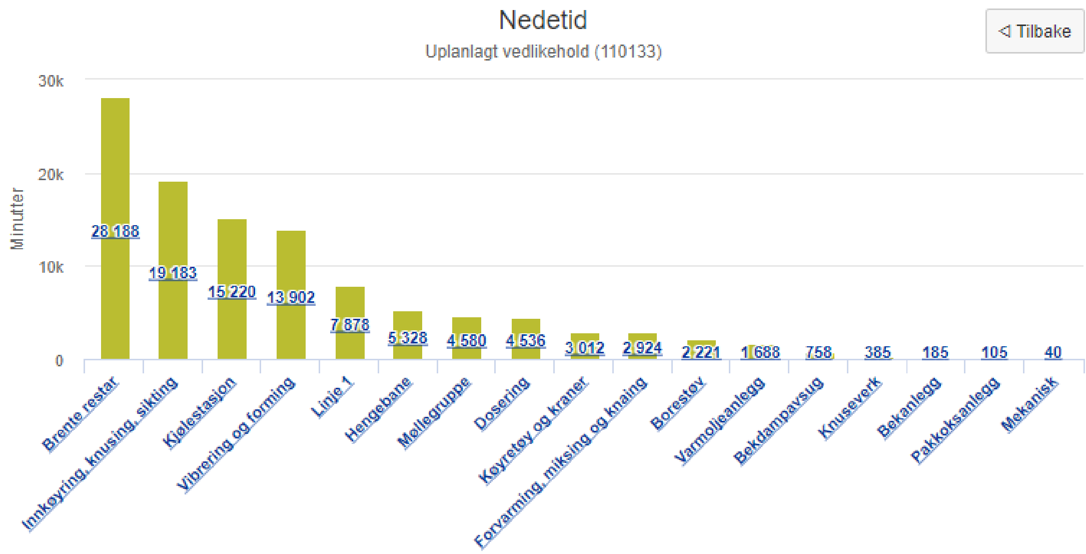

Figure 47: Registration of downtime for *the green mil* from 2016 until 2021

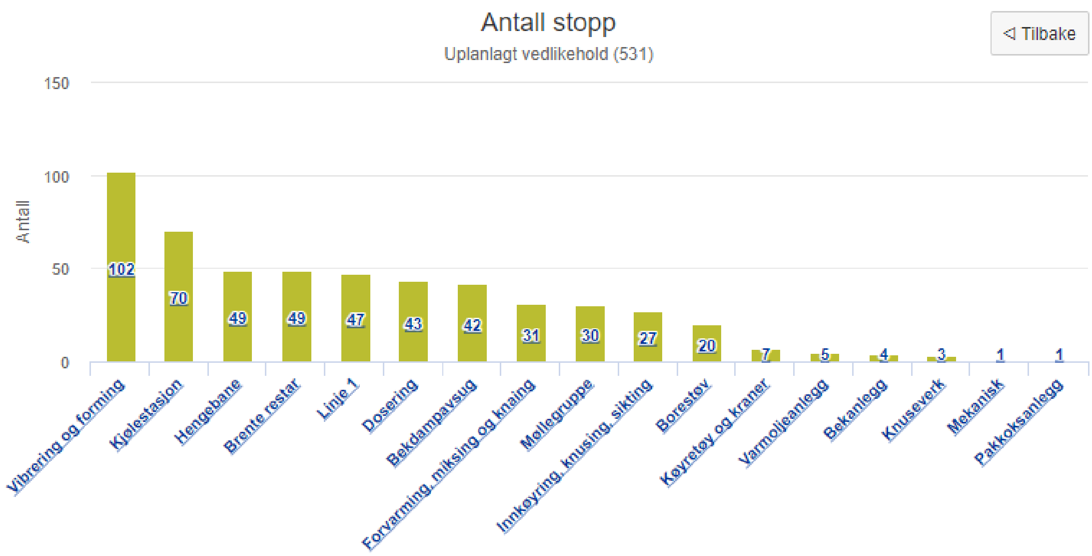

Figure 48: Registration of stops for *the green mil* from 2016 until 2021

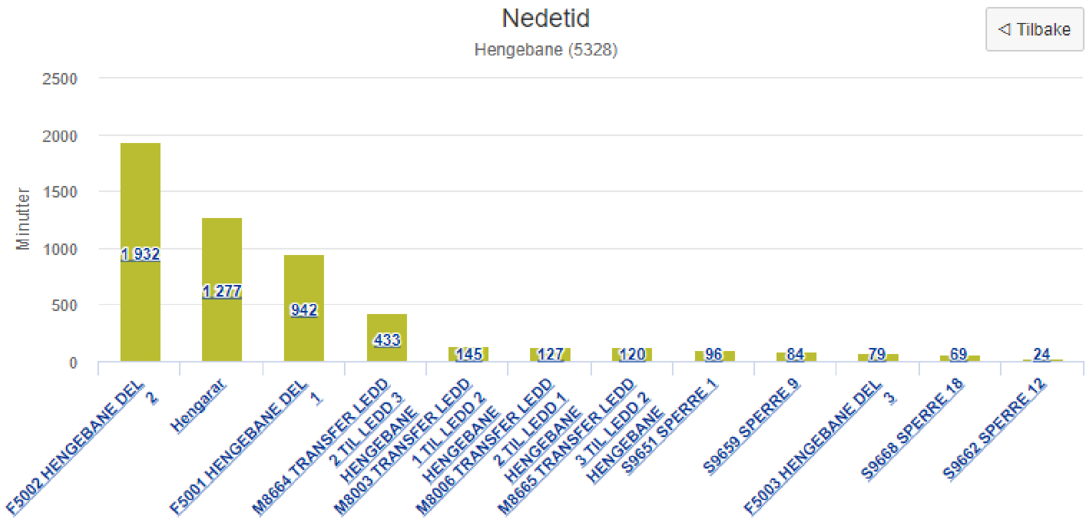

Figure 49: Registration of downtime for *the overhead conveyor* from 2016 until 2021

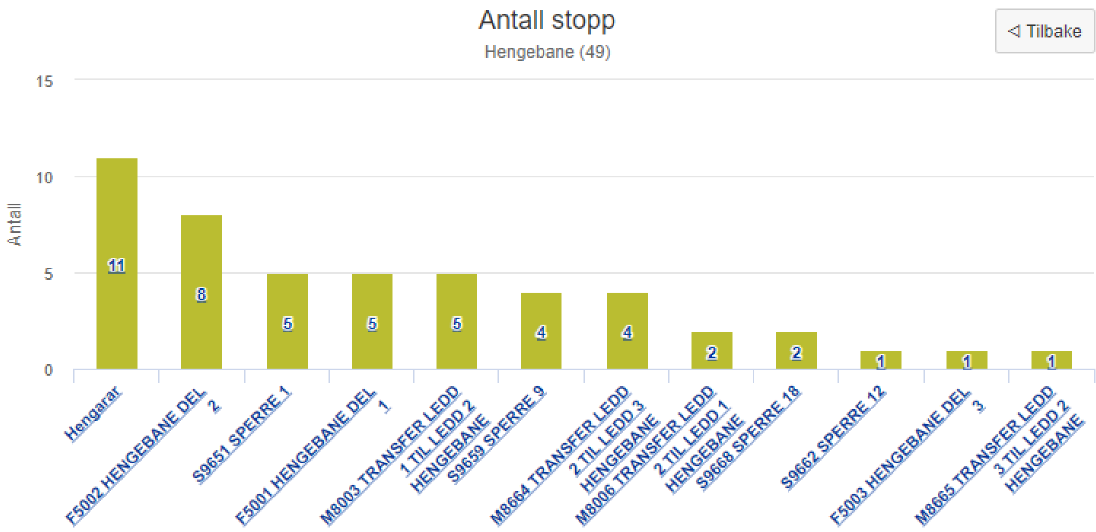

Figure 50: Registration of stops for *the overhead conveyor* from 2016 until 2021

E Analysis of SAP records

The figures in this section are described in Section 5.4, where the maintenance orders and notifications of *S.23*, *R.11*, *R.20*, *P.3* and *P.4* are analysed. Due to the extensive number of figures, the results are discussed in that section, while the figures are found here. These areas are critical for the transportation line, and the components causing failures, the problems and the causes behind failures are investigated. The yearly development of the number of maintenance orders is also visualised. By critical area, it means the areas behind the most maintenance orders/notifications, maintenance duration, maintenance cost, downtime and stops in production and profit loss due to production setbacks.

The first plot per location shows the yearly development, while the second is of the components needing corrective maintenance. The third figure is of the problems leading to component breakdowns, and the fourth is the cause behind. Regarding the second, third and fourth figure per location, the *blue* part of the bars is relevant for all the notifications. The *orange* is the ratio of these maintenance notifications with high priority *(1.0* or *2.0)*, while the *green* is when there is a need for call up for technicians *(VAKT)*.

E.1 SNUSTASJON OVN 3 POS 23 *(S.23)*

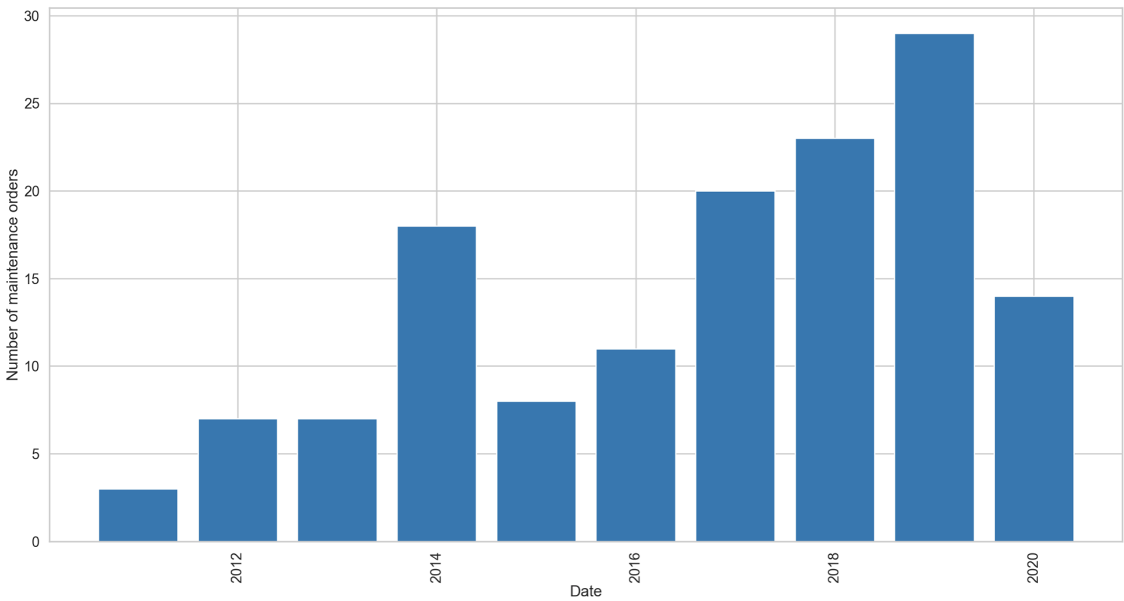

Figure 51: Corrective maintenance orders per year for *(S.23)*

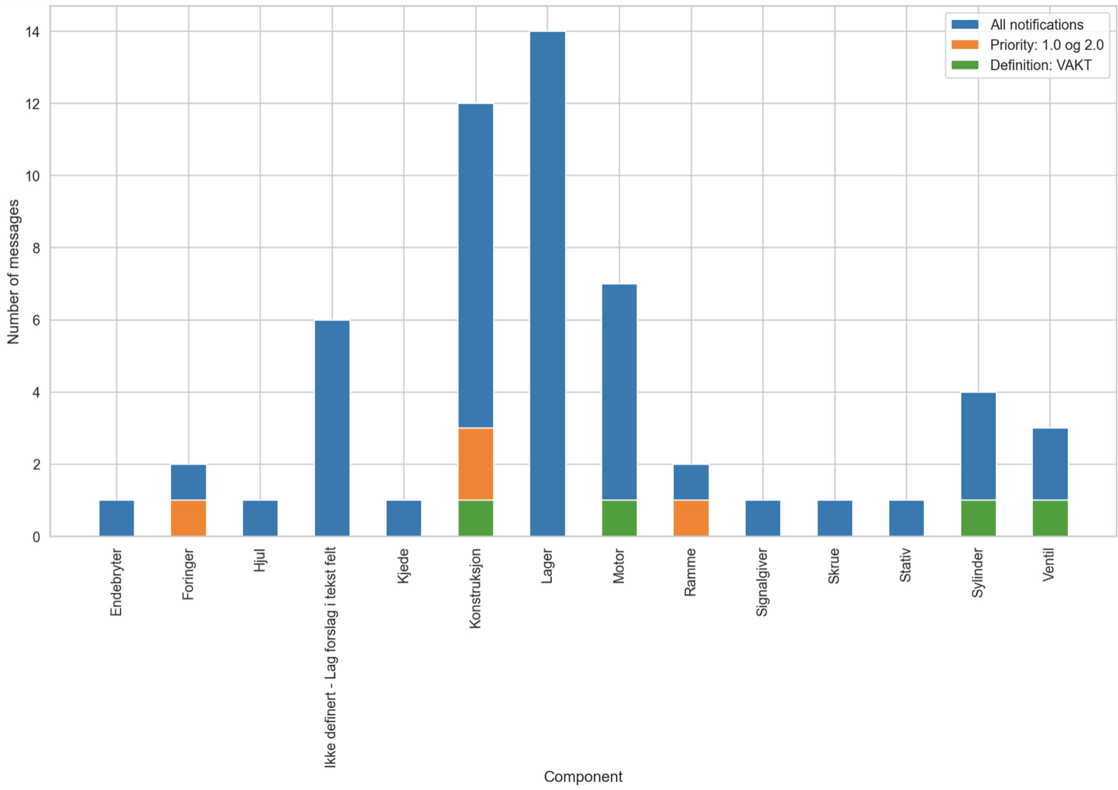

Figure 52: Components in need of corrective maintenance for *(S.23)*

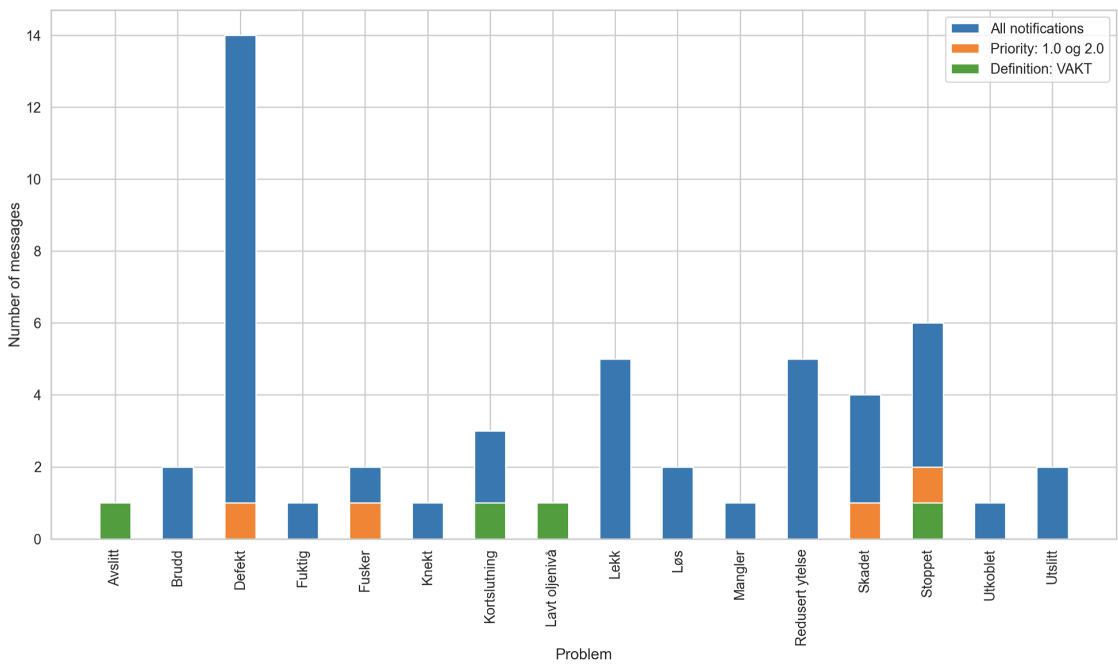

Figure 53: Problems leading to component breakdown for *(S.23)*

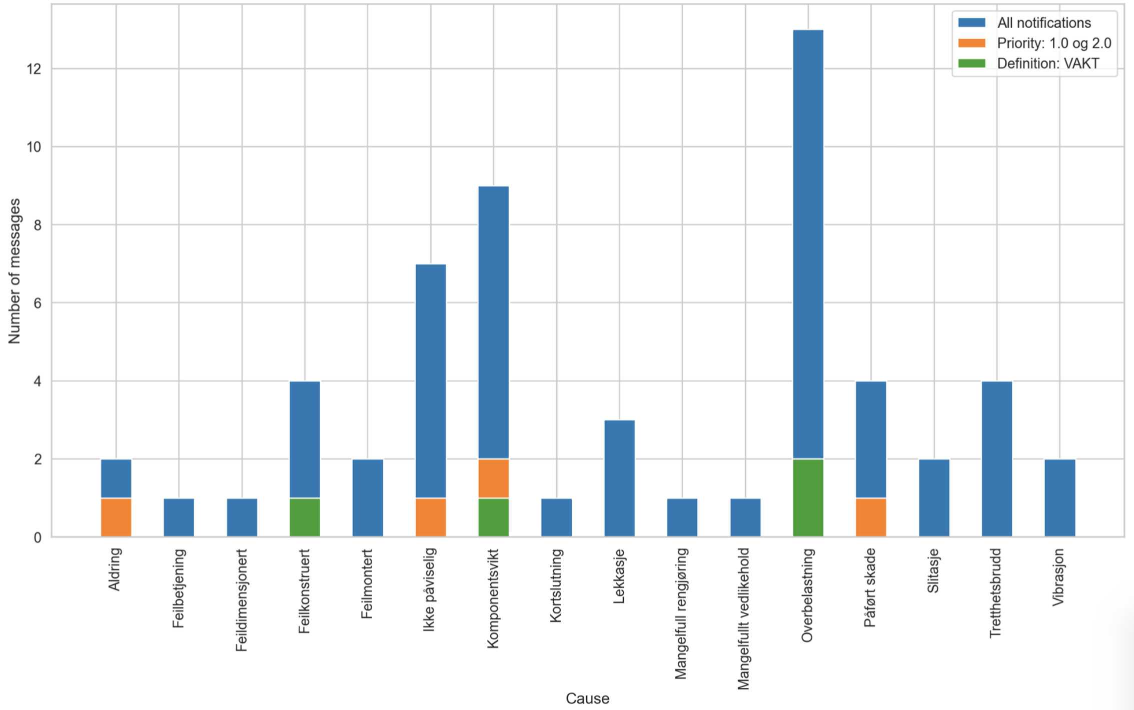

Figure 54: Causes of problems leading to component breakdown for *(S.23)*

E.2 RULLEBANE TIL OVN 2, 3 OG 4 POS 11 *(R.11)*

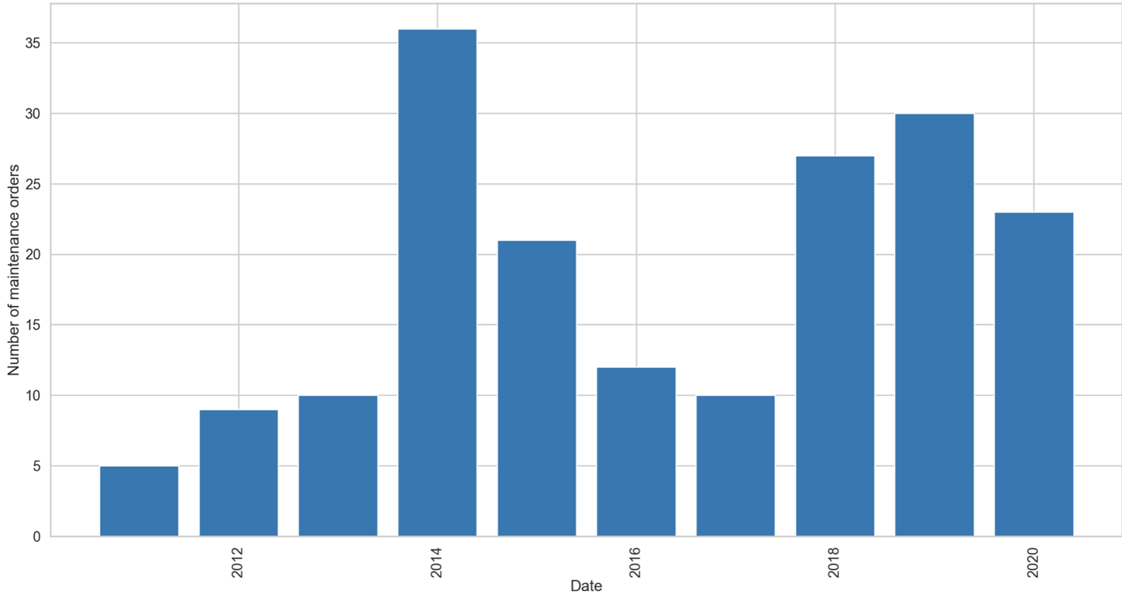

Figure 55: Corrective maintenance orders per year for *(R.11)*

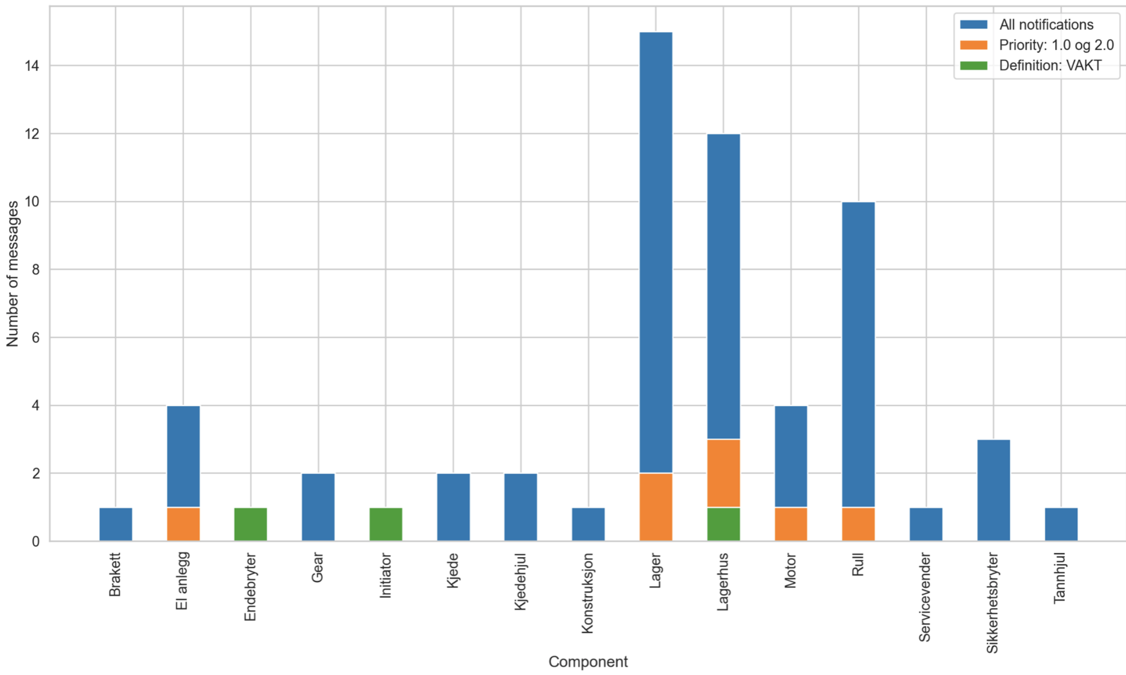

Figure 56: Components in need of corrective maintenance for *(R.11)*

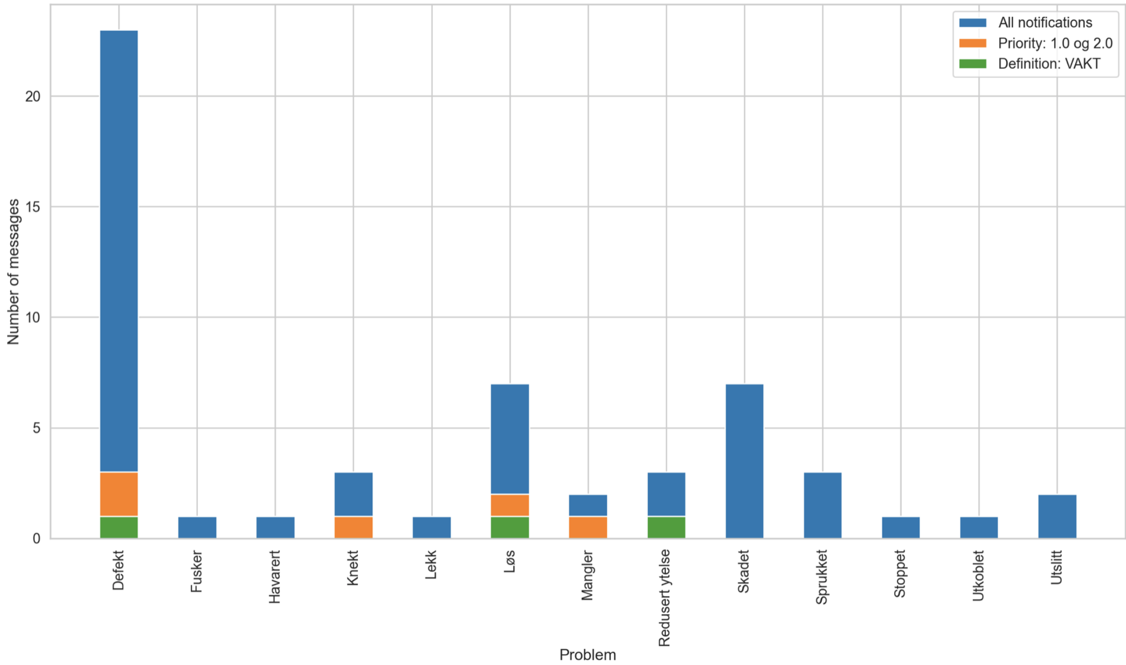

Figure 57: Problems leading to component breakdown for *(R.11)*

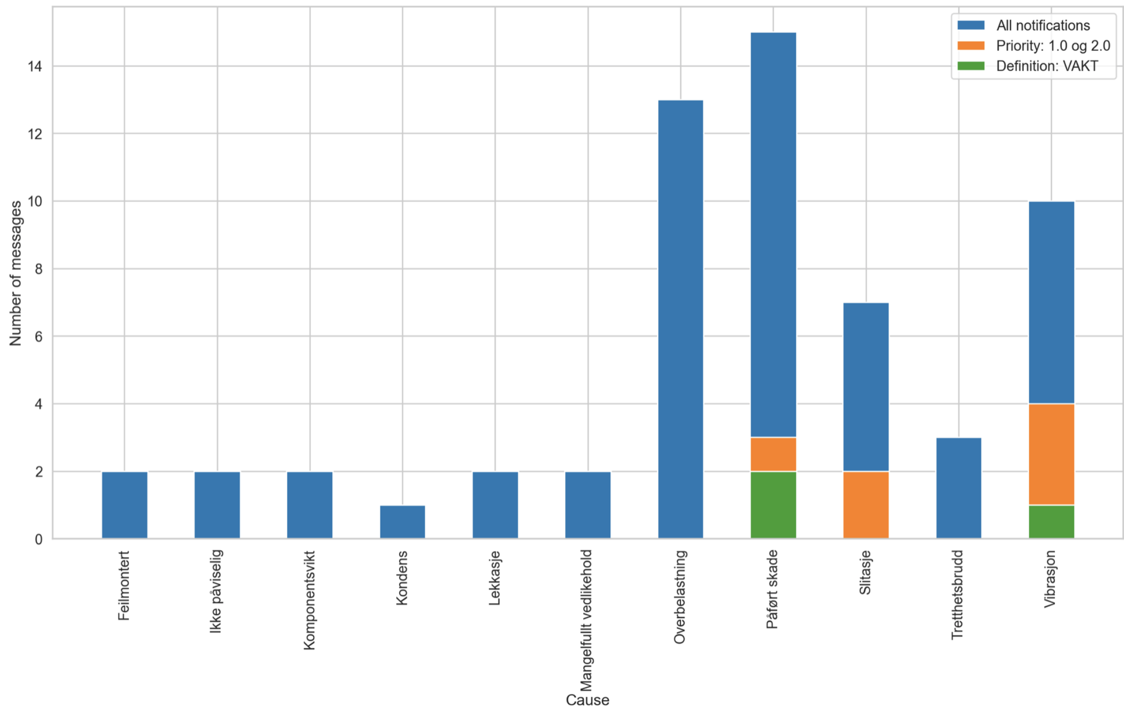

Figure 58: Causes of problems leading to component breakdown for *(R.11)*

E.3 RULLBANE TIL OVN 3 OG 4 POS 20 *(R.20)*

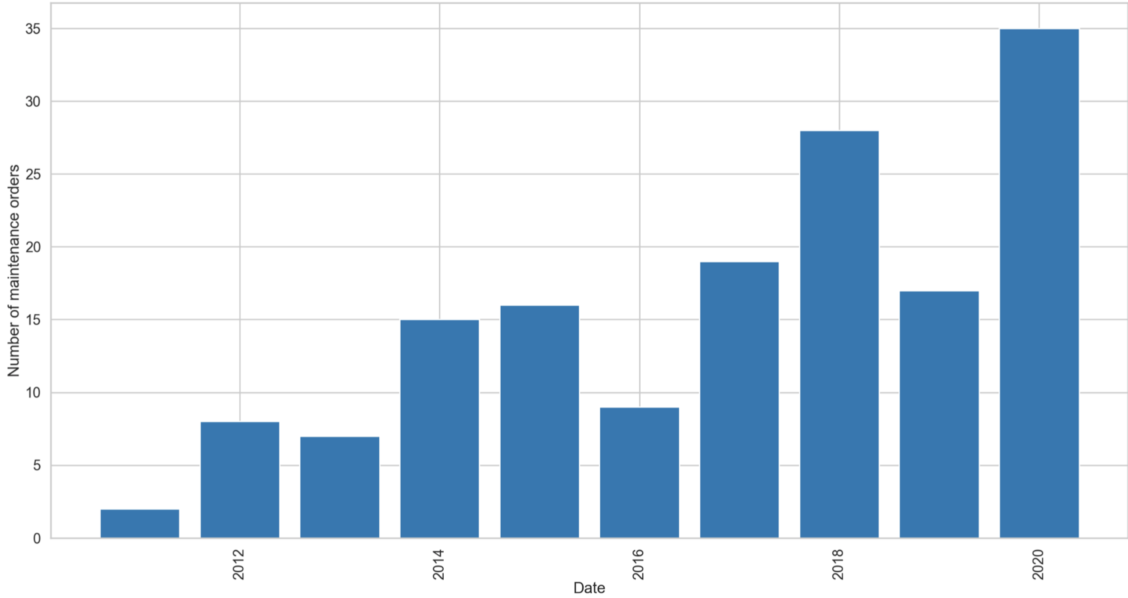

Figure 59: Corrective maintenance orders per year for *(R.20)*

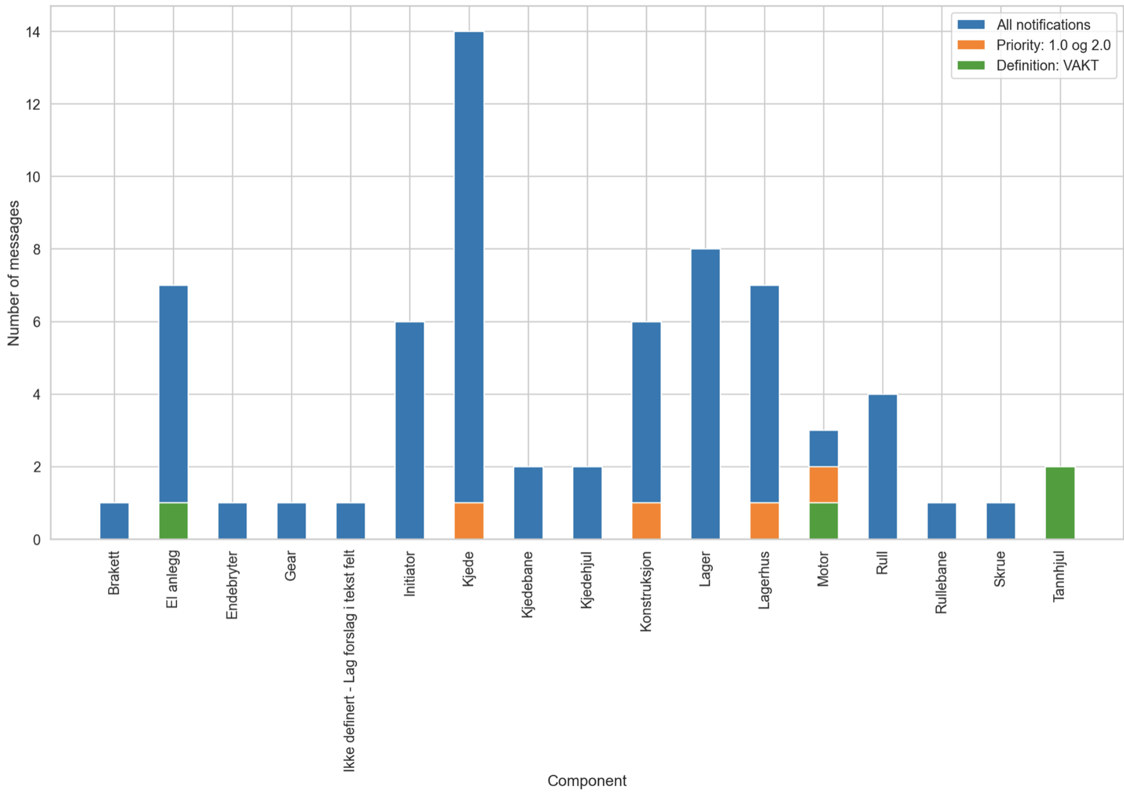

Figure 60: Components in need of corrective maintenance for *(R.20)*

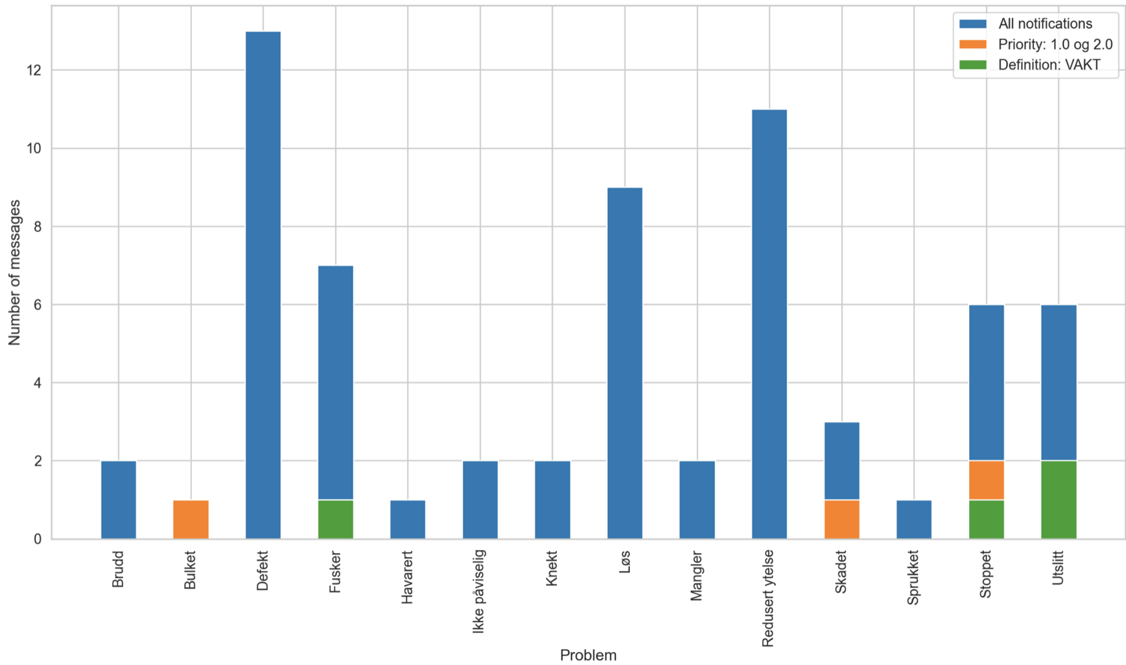

Figure 61: Problems leading to component breakdown for *(R.20)*

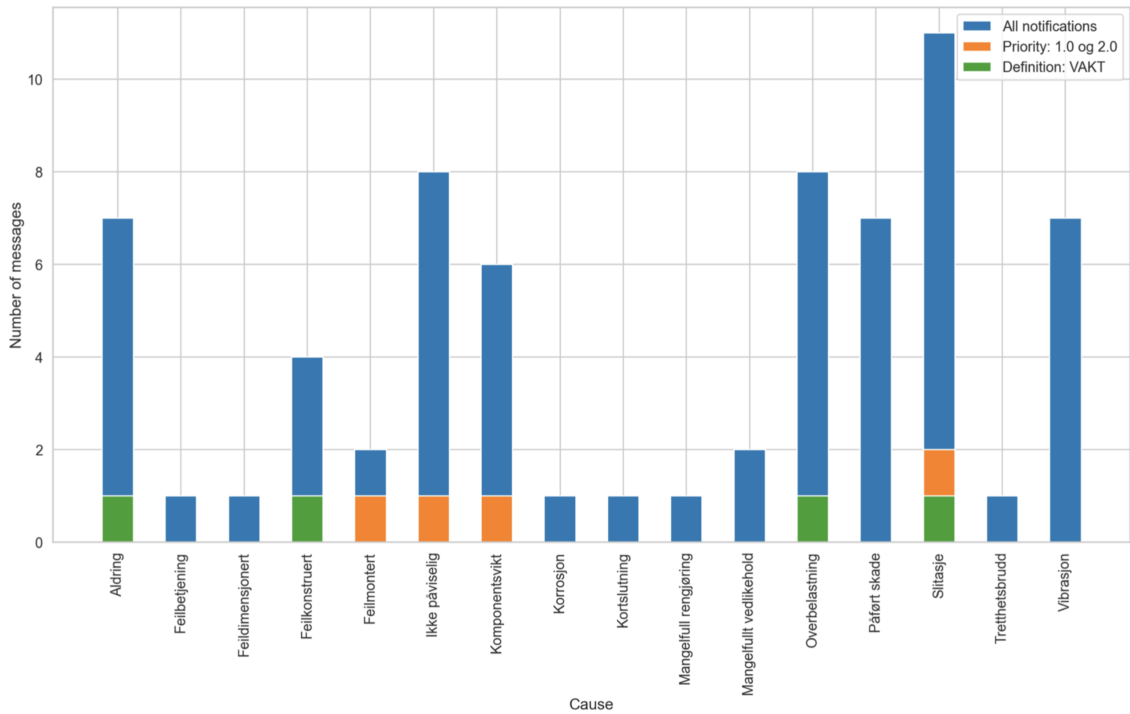

Figure 62: Causes of problems leading to component breakdown for *(R.20)*

E.4 PUSHROD OVN 3 POS 27 *(P.3)*

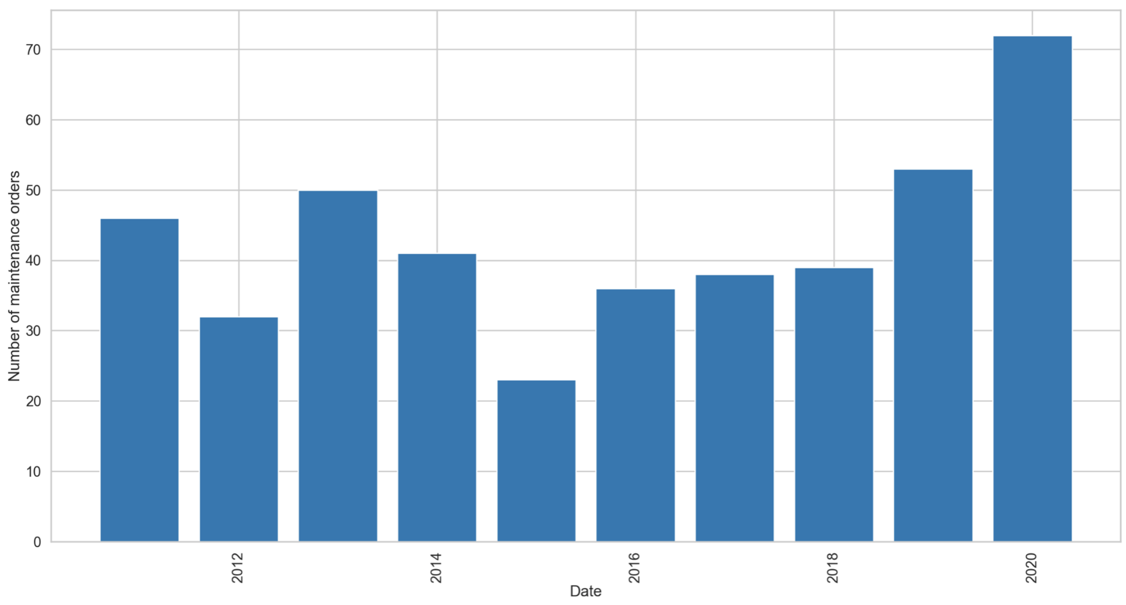

Figure 63: Corrective maintenance orders per year for *(P.3)*

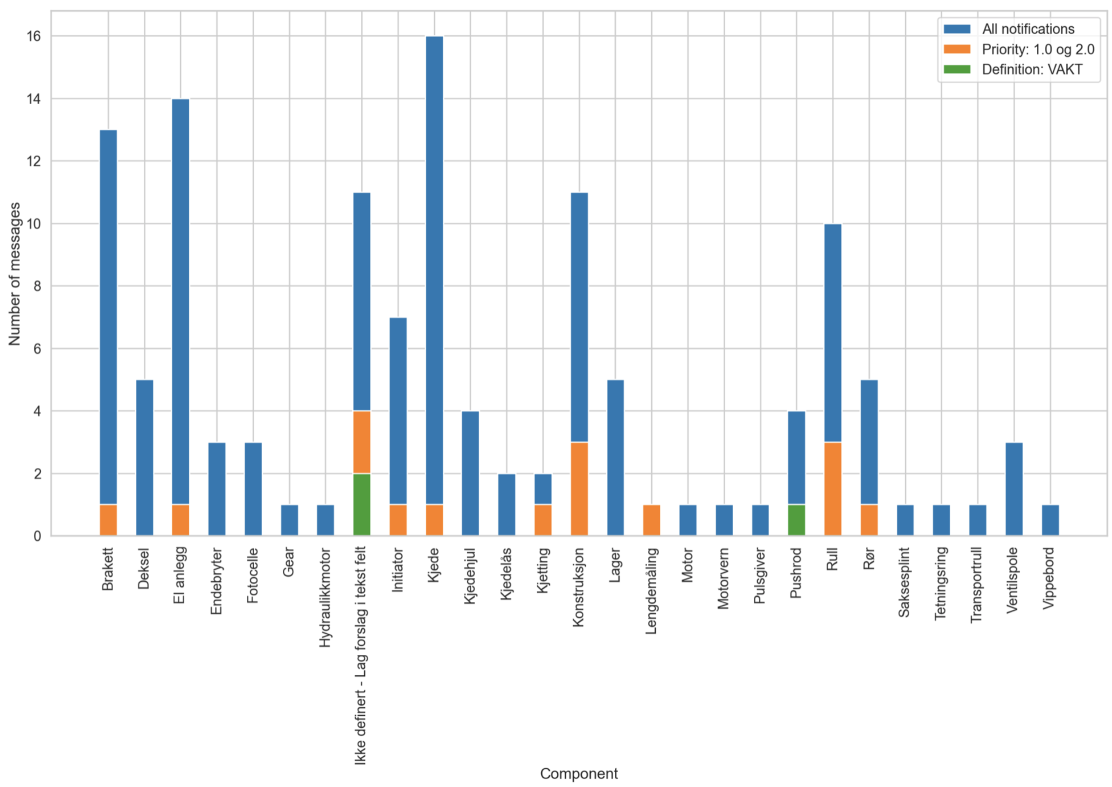

Figure 64: Components in need of corrective maintenance for *(P.3)*

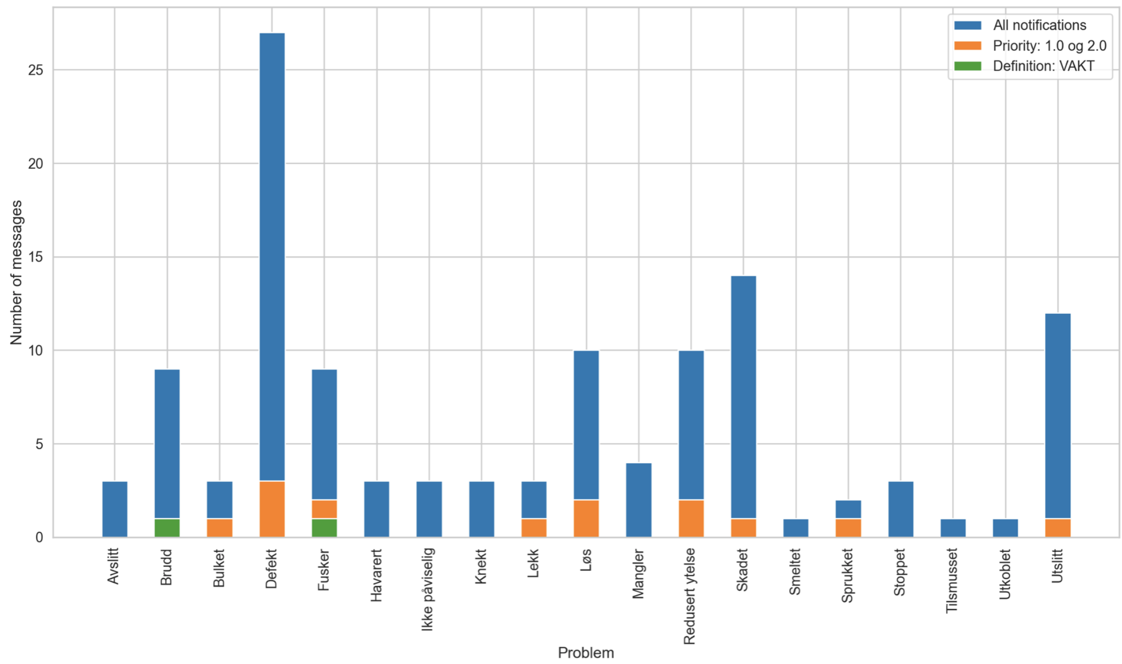

Figure 65: Problems leading to component breakdown for *(P.3)*

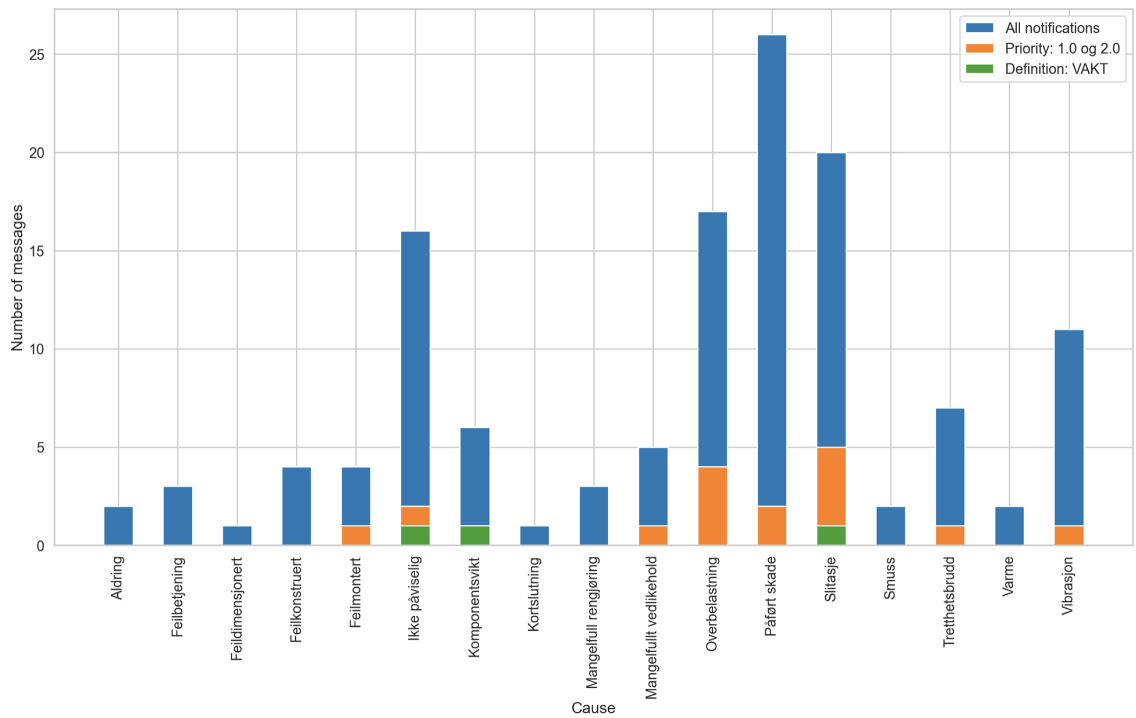

Figure 66: Causes of problems leading to component breakdown for *(P.3)*

E.5 PUSHROD OVN 4 POS 28 *(P.4)*

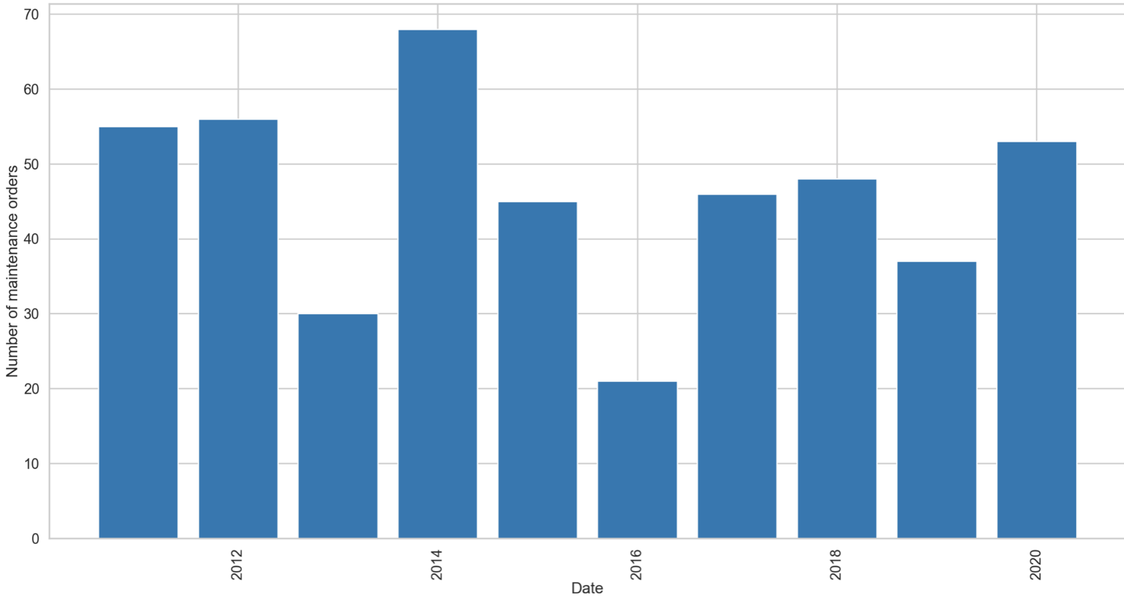

Figure 67: Corrective maintenance orders per year for *(P.4)*

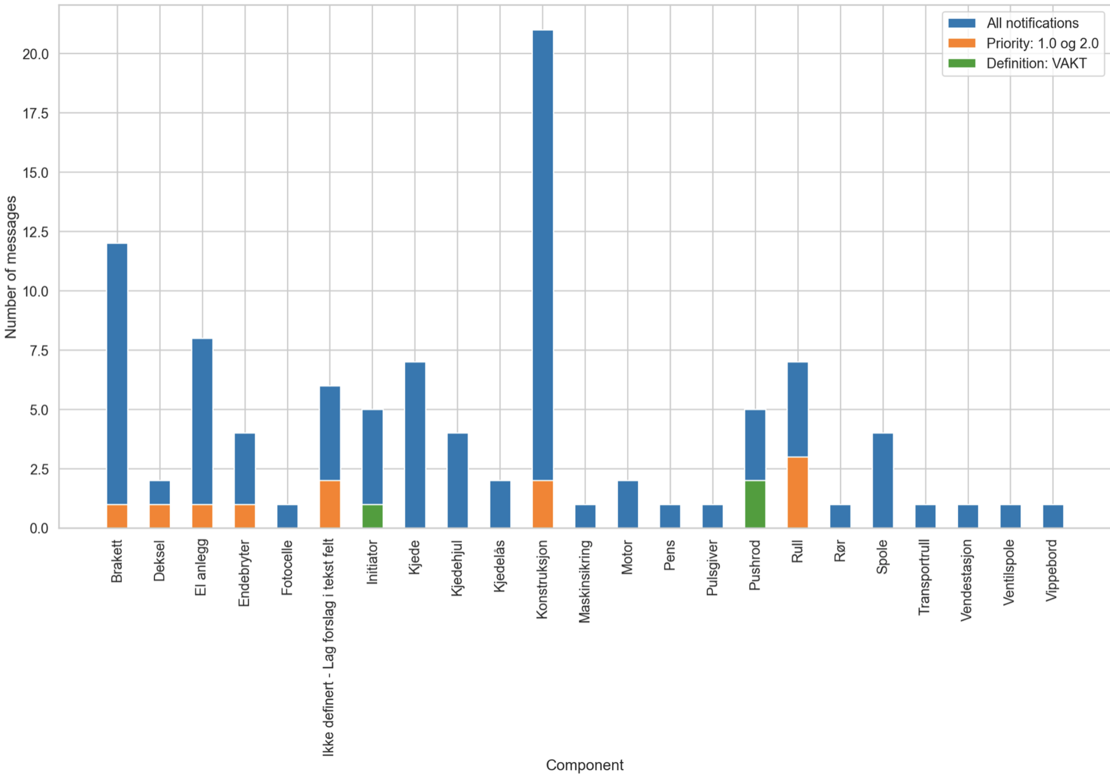

Figure 68: Components in need of corrective maintenance for *(P.4)*

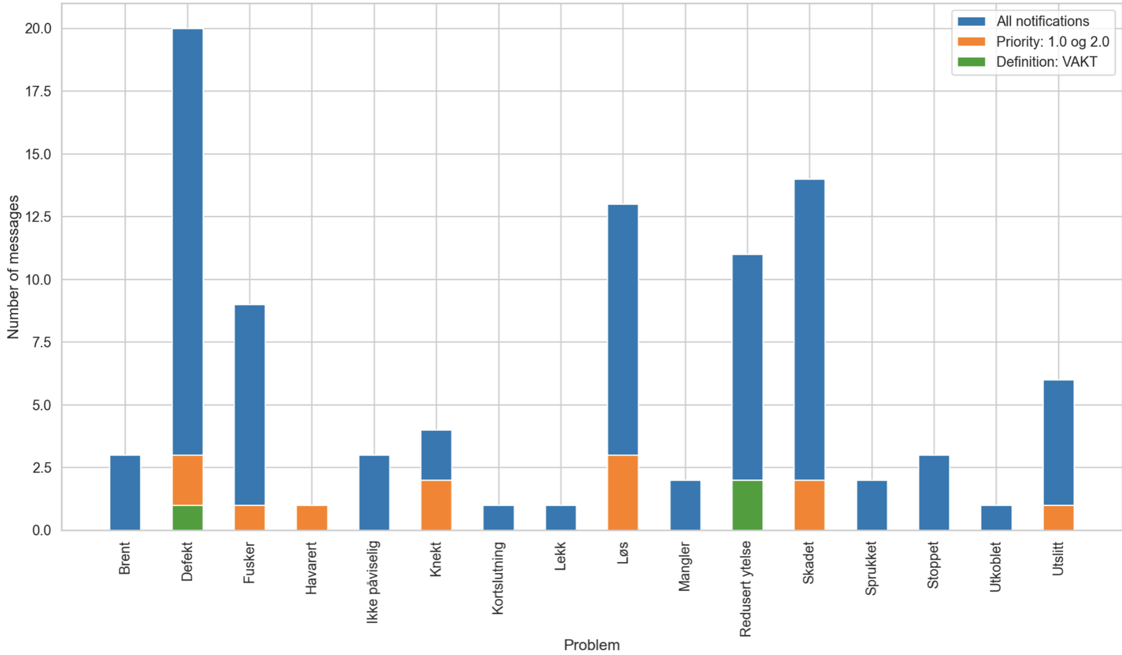

Figure 69: Problems leading to component breakdown for *(P.4)*

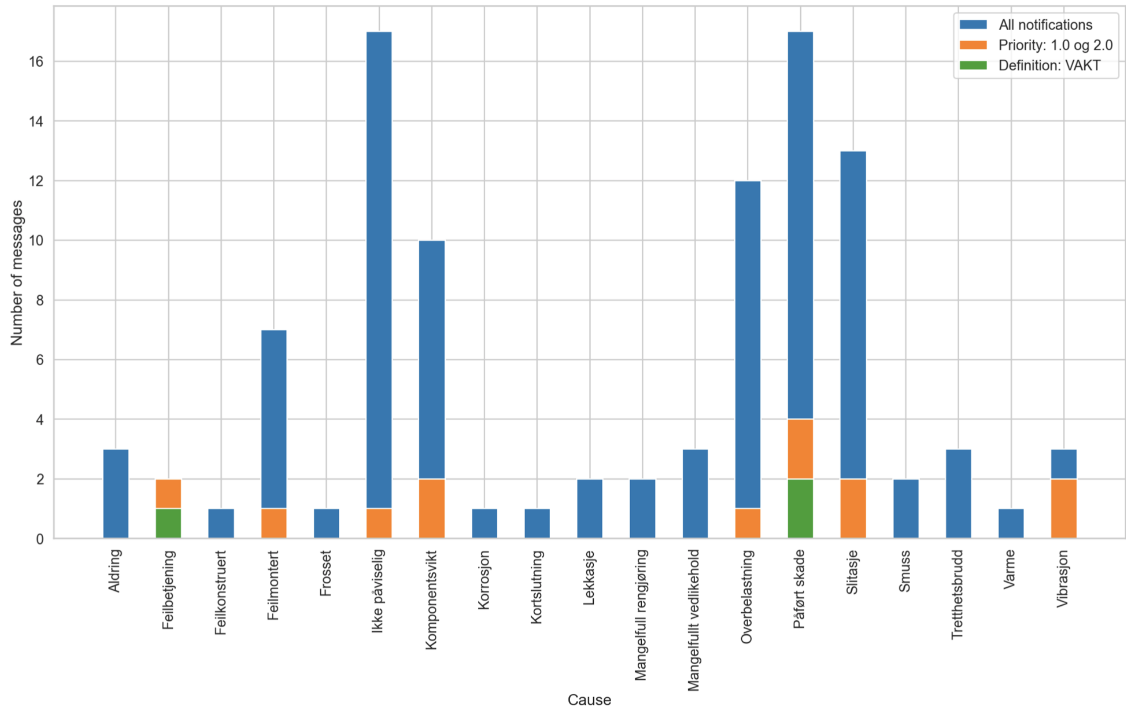

Figure 70: Causes of problems leading to component breakdown for *(P.4)*

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Evaluation of Asset Performance

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