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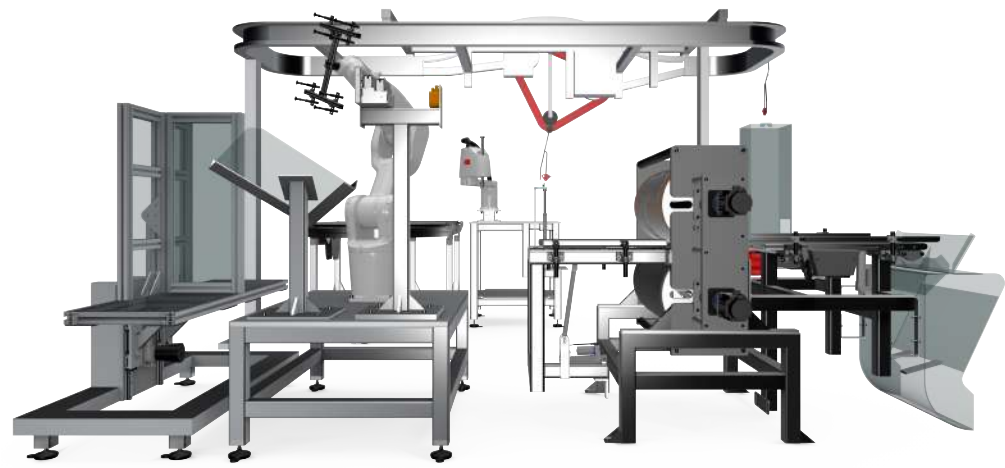

Maintenance Solutions for Smart Factories

Master's thesis in Production Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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Cover: Picture of the virtual factory

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Abstract

The 4th industrial revolution has begun and the Swedish government has recently developed a new industrialization strategy called “Smart Industry”. The goal is to help the Swedish industry to remain competitive and to contribute to a more sustainable society.

The project Smart Factories was founded by Gothenburg’s Technical College and is a contribution to the Smart Industry. The project Smart Factories was founded in central Gothenburg with partners in the region that financed the project with time, money and knowledge. Together they formed the idea to manufacture a demonstration factory. The factory will consist of a production line manufacturing cardboard VR glasses and it will be located at Universeum, there it will be used as a learning tool. Teaching people from all ages about technology and innovation, in order to make technology and employment within industrial companies more attractive.

This thesis work consists of implementing maintenance solutions to the project Smart Factories. Three research questions were formulated in the initialization of the thesis and were answered through a collection of research methods: interviews, literature studies, observations and company visits. All of which were performed alongside four different Virtual Commissioning meetings, where key persons from all the involved companies met up and analyzed important activities in the early design phase. The project Smart Factories production line was then Design for Maintenance and changes in the design phase reduced maintenance requirements. Vibration sensors were used to implement Predictive Maintenance (PdM), where the machine’s health is monitored and analyzed, future scenarios are predicted by comparing new and historical data that verifies if the measurements fall within known thresholds. A maintenance software was installed to support decision making for the maintenance employees. The software was connected to the vibration sensors to enable real-time online monitoring and remote inspection.

Keywords: maintenance, digitalisation, Design for Maintenance, Smart Factories.

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Anton Alveflo & Christoffer Hildebrand, Gothenburg, June 2017

Abbrevations

CIM Computer Integrated Manufacturing
CPS Cyber Physical Systems
CMMS Computerized Maintenance Management System
IoT Internet of Things
PM Preventive Maintenance
CBM Condition Based Maintenance
PdM Predictive Maintenance

Contents

1 Introduction

The introduction chapter describes the background of Smart Factories and the initiative of the project and why it is important to develop the maintenance within Smart Factories. Information about the project will be presented and the associated research questions that have been the guidelines for the project will be described. The purpose of the project, delimitations and case background is described further down in the chapter.

1.1 Background

The new industrial revolution has begun. Manufacturing industries are focusing on digitization, production and development of manufacturing technologies [Kagermann et al., 2013]. "Industry 4.0" is a well-used expression, explaining how the future of the industry can evolve by utilizing new technologies and concepts. "Smart Industry" is the Swedish term of Industry 4.0. It is used to describes the future of the production systems, including state of the art technology, smart ways of working, virtual tools, connection between different databases etc. [Bengtsson, 2017].

The industry is of great importance to Sweden's prosperity and their common welfare [Ministry of Innovation and Enterprise, 2016]. The Swedish industry is currently struggling against the competition from low-wage countries. A need for improved and more efficient production facilities is necessary to keep the industry and the jobs in Sweden. The Swedish government has recently developed a new industrialization strategy called “Smart Industry” [Ministry of Innovation and Enterprise, 2016], the goal is to help the Swedish industry to become world leading in modern and sustainable production. The main focus is on digitalisation, with hopes that it will create important opportunities and conditions, contributing to more jobs and a more sustainable society.

The project Smart Factories is a contribution to the Smart Industry and its potential outcome. The project Smart Factories is a collaboration between many different stakeholders, such as Gothenburg's Technical College, SKF, Prevas and Universeum. Together they will construct a production line which will be used as a learning tool, see Figure 1.1. Teaching people from all ages about technology and innovation, making technology and employment within industrial companies more attractive. The project Smart Factories consists of several groups where Maintenance Solutions is one of the areas that will be covered. Maintenance is a crucial aspect of preventing breakdowns that can lead to decreased productivity and increased financial losses. The importance of maintenance increases as the production evolves and becomes more advanced, in parallel with the demanding cost-reduction that minimizes machine parks and makes production systems more vulnerable to breakdowns [Monostori et al., 2016]. Industry 4.0 provides the opportunity that maintenance might need to catch up on the evolving production: to collect and then analyze more real-time data about machines current health [Roy et al., 2016]. Real-time information can be used in knowledge-driven optimization and management operations [Westkämper, 2014;2013;], optimizing Maintenance Planning, allowing multiple machines to be maintained simultaneously, contributing to a higher plant availability and reduce maintenance costs. Industries have to be able to know when and where to maintain the production lines in order to correct problems before any critical damage occurs and to cut down expenses. Downtime in a production line can contribute to huge costs and maintenance can help to prevent this.

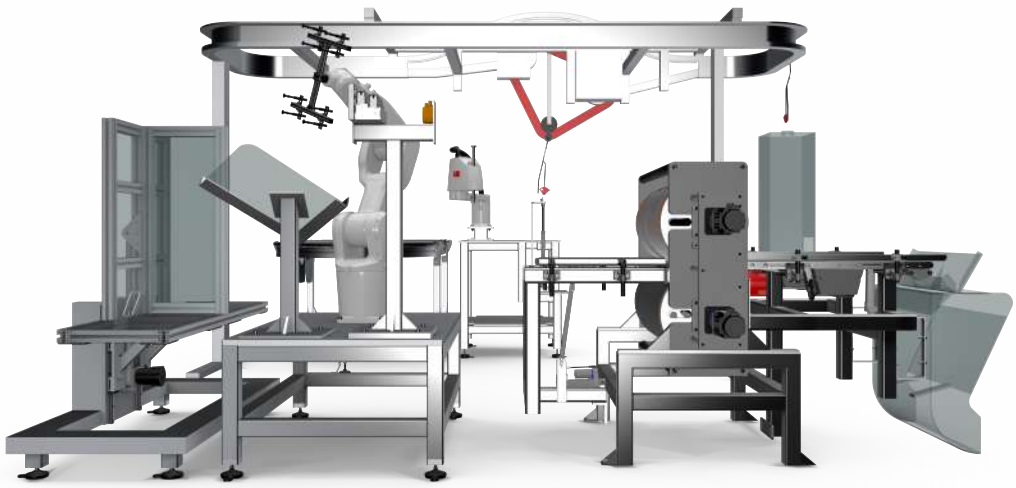

Figure 1.1: Illustration of the production line

The goal of this thesis is to introduce Maintenance Solutions for the project Smart Factories before the building phase of the project begins and to utilize digitalisation from a maintenance perspective. The purpose of implementing maintenance in the design phase is to lower the maintenance requirements by eliminating factors that can lead to future problems. The production line in the project Smart Factories will be available for 8 hours a day, 365 days a year, manufacturing cardboard VR glasses. All maintenance should preferably be performed during closed hours. Information gathered through real-time data from machines can contribute to the production line by optimizing scheduled maintenance event and thereby reducing unplanned failures [Roy et al., 2016], maintenance can then be performed when suited. The condition of machines, tools and equipment can be monitored with sensors such as vibration detectors, tachometers, temperature sensors etc. these measurements are performed continuously (online) or periodically. The key is to get the right information at the right time, allowing the system to schedule maintenance at the most cost effective point: to prevent unexpected equipment failures and only maintaining equipment when needed. The equipment will then be maintained as few times as possible in order to keep costs down.

The project including all the partners will be referred to as "the project Smart Factories" in further reading to avoid misunderstanding between the project and the general term Smart Factory that is described in section 2.1, and "the production line" referees to the physical production line being built within the project Smart Factories.

1.2 Purpose

The purpose of this thesis is to deliver maintenance solutions for the project Smart Factories. Specifically, the thesis will deliver design improvements that will reduce maintenance requirements for the project Smart Factories, components that will monitor the production line and a digital interface to support decision-making.

1.3 Objective

To fulfill the purpose of the project three research question has been developed and used during the project to make sure that right parts of the project have been investigated. The questions have been guidelines during the whole project and have been used to work towards the set goals.

Research Questions
RQ1. How can the maintenance requirements in the project Smart Factories be reduced when Design for Maintenance is implemented early in the design phase?
RQ2. Where should vibration sensors be installed to monitor the state of vital bearings in the project Smart Factories production line?
RQ3. How can maintenance data be presented to support the maintenance employees decision making?

The first research question will be investigated through literature studies, interviews, company visits and meetings with the project managers along with involved companies. The aim here is to solve maintenance issues before the production line in the project Smart Factories has been built.

Various sensors are helpful when monitoring industrial machines, the majority of failures in the production line can be monitored through vibrations, where vibrations are vital indicators of the machine's health. The second research question investigates where vibrations sensors should be installed. Analyzed vibration signals can be used to determine the condition of the machinery and help to predicted problems before serious damage occurs.

It is common for industries to collect data and save information that can be used for maintenance. The third research question investigates how this information can give guidance and support maintenance employees in decision making.

1.4 Scope

The authors are a part of the project Smart Factories, where their task is to implement maintenance solutions for the project Smart Factories production line. The focus of the maintenance solutions will be on the rotating parts within the project Smart Factories though these are key components of the production line. Knowledge about the conditions of the parts will be measured by using vibration sensors. Section 1.6, Case background, describes the project further.

1.5 Delimitations

The project is active from 16 of January until 30 June of 2017. The main work should be finished 30 of May 2017. All components, sensors etc. must be ordered before week 17 in 2017.

This project will not consider the background that the project Smart Factories will be used as a learning platform for people in all ages.

This project will not consider economic differences between various maintenance solutions, but since this is of great importance for the industry, future research therefore suggests to investigate this aspect.

Smart Factories is entirely new so no data from the equipment have yet been measured or collected. Meaning that there are no data to use when implementing the PdM system. The project, therefore, relies on that the companies providing the equipment can contribute with collected data that the project can use in order to implement PdM from the start.

Components and other hardware that will be used will not be compared to other companies that are not partners in the project.

The vibration sensors of the maintenance solutions will be limited to the most critical parts of the production line.

1.6 Case background

Sweden has created the new strategy “Smart Industry” and its main purpose is to keep the jobs and the industry in Sweden in order to make the country competitive. The project Smart Factories is initiated by Gothenburg’s Technical College, its a collaboration between students and the Swedish industry to jointly disseminate knowledge about technology and the industry. The project Smart Factories was founded in central Gothenburg with partners in the region that financed the project with time, components, knowledge and money. The finished project will result in a production line that will be installed in "Universeum", a science center located in Gothenburg. Daily there are around 2000 visitors at Universeum [E. Edblad, personal communication, April 04, 2017] and it is calculated that the project Smart Factories production line should be able to produce 1000 VR-glasses a day. Visitors has to be able to see and understand the meaning of the project Smart Factories during the short period of time they are visiting, availability of the production line is therefore of high importance. Universeum is not an industrial environment, there is a lack of maintenance personnel with the competence to fix urgent problems that may occur in the project Smart Factories production line, making it even more important to plan and predict maintenance requirements. The space is limited and a place for a workshop or spare-part storage is not possible. With this in consideration, it is very important for the project Smart Factories that the production line is functional, and this is where the maintenance case begins.

After the launch of the Smart Factories, a similar project will also take place in Skövde, Balthazar Science Center. Balthazar will observe the development of the project and get access to all the information regarding its result. This will make the start-up process easier for Balthazar and it will be a good comparison if the project Smart Factories can be applied in other locations with the same results.

2
Theory

This chapter will give a clarification of what a Smart Factory is and what characterize it. The chapter also explains maintenance in a Smart Factory and general information about maintenance theory and information regarding different strategies on how to maintain a factory.

2.1 Smart Factory

Smart Factory has been a term since the 70s, were the focus was on the Computer Integrated Manufacturing (CIM) [Diederik et al., 2014]. Smart Factory was more of a concept during the 70s and it could not live up to its full potential, partially because the internet was not developed yet. Back then, proprietary networks (fieldbuses) was used to make the connection between machines but these could not deliver the right conditions to achieve the improvements mentioned in Industry 4.0. Sweden has like other countries created a strategy [Ministry of Innovation and Enterprise, 2016], "Smart Industry", where Sweden wants to be the flagship for the digitalisation. A specific definition of what a Smart Factory consist of does not exist [Adnan and Zen, 2016], but a number of different researcher groups are talking about the implementation of Internet of Things (IoT) in Smart Factories. The utilization of IoT is growing, but not only in Sweden. Germany, USA and Asia are putting in efforts to the new industrialization [Kagermann et al., 2013]. The vision of the Smart Factory is to have computers that are monitoring the physical processes and also creating a digital twin (virtual copy of the factory) that will be used to make decisions within the Smart Factory [Harrison et al., 2016]. The digital twin can be used in Cyber Physical Systems (CPS), which is a relation between the digital system and the machine where they changing data and controlling each other[Kagermann et al., 2013].

The following sections describes the general term Smart Factory from the authors perspective and interpretations. The distance between the production and the customers is more important in a Smart Factory compared to a traditional factory, the goal is to follow the customers' need and to change the production after the customers' demands [Ministry of Innovation and Enterprise, 2016]. The ambition is to allow the customers to individually customize products and still be profitable [Kagermann et al., 2013]. The focus will be on the customer satisfaction, meaning that instead of having predefined or optional products it will be possible for the consumer to make an order for an individual adapt product. All this is possible because the manufacturing systems are parallel developed, meaning when the product develops the manufacturing processes will adapt after the new requirements [Kagermann et al., 2013].

A Smart Factory differs slightly from a traditional factory. Machines in a regular factory have for several years utilized digital tools to measure and control the production, but new technologies and the Internet allows the whole Smart Factory to be linked together and cooperate in a way that was not possible before [Diederik et al., 2014]. In the Smart Factory, the increased digitization will allow the machines to communicate with products and with each other in order to optimize the capacity and to adjust the production [Diederik et al., 2014]. The delimitations between the virtual world and the real world will be much less. The status of machines and different changes or movements that are made in the reality will be updated in the virtual model. Products delivered from the Smart Factory will then be linked to the Internet and be able to register their own history, their status and different paths to achieve the target state [Kagermann et al., 2013].

The baby boom, which began in 1946 and lasted until 1964 [Morland, 2014;2016;] is retiring, this lost knowledge will have a big impact on the industry [Currin, 2015]. Research have shown that competent workforce for the industry is decreasing [Larter]. This combined with the demographic challenges that the world is facing, it is crucial to find new solutions for the industry in order for it to evolve. Industry 4.0 takes social factors and demographic changes into account by increasing the resource efficiency and allowing workers to extend their working lives and remain productive for a longer time [Kagermann et al., 2013]. Meanwhile, the technology is evolving, getting better and cheaper, enabling new possibilities for Swedish companies to invest in new technologies and increase their productive without outsourcing [Kihlman, 2016]. SKF in Gamlestaden Gothenburg has during the beginning of 2017 followed the Smart Industry and build their own Smart Factory. SKF:s Smart Factory is able to move and lift material autonomously over the plant and feed and fetch products to and from the machines. Heavy lifts and monotonous work tasks are performed by autonomous forklifts and robots, improving the ergonomic environment for the workers. The Smart Factory will adapt to the challenges that the world is facing, for example, the demographic issues, while the regular factory will always be dependent on operators in the factory that are performing a big part of the work tasks.

2.2 Maintenance in a Smart Factory

The importance of maintenance has increased during a long period of time [Bokrantz]. Factories have to be able to produce without unplanned stoppages and with minimum downtimes. To fulfill this responsibility, data can be collected with sensors installed in the Smart Factory, monitoring and analyzing various component and machines. The required maintenance in a Smart Factory can be calculated by computers [Lee et al., 2017], sensors send information using IoT to make calculations and predictions regarding the required maintenance. Some maintenance tasks in the

Smart Factory can be executed by a robot or a machine. Smart maintenance solutions and digitalisation makes it possible to connect multiple machines and sensors to fulfill the data collection, the data can then be monitored and analyzed, aiding maintenance employees. The development goes towards a self-governing production [Ministry of Innovation and Enterprise, 2016], where the factories may be able to adapt the production to the maintenance and develop a continually and steady flow. With knowledge about the health of the components and the functionality of the production, maintenance can make conclusions on when to maintain the system and how, eliminating unnecessary investments and production stops [Basri et al., 2017].

Availability and reliability are two crucial factors that play a central role for manufacturing companies to remain competitive, both factors contribute to better product quality for a lower cost [Muchiri et al., 2011]. The level of automation is often higher in a Smart Factory compared to a traditional one. The importance of availability and reliability increases as autonomous systems becomes more usual and human interaction and intervention decreases. For these systems, maintenance solutions have gained a new meaning and importance, as these systems generally should not experience little to no failures [Okogbaa and Otieno, 2015]. The effectiveness and efficiency of how the maintenance is performed are two of the factors that influence the maintenance cost. Maintenance can be performed effectively by proactively identifying problems and thereby act at the right time, contributing to minimized environmental consequences, reducing chances of secondary damages and at the same time diminishing the maintenance cost [Muchiri et al., 2011]. The maintenance in a Smart Factory should be executed only when needed, PdM can therefore be utilized in order to secure that no unnecessary maintenance actions occur. The problem with PdM solutions is that they often have a high investment cost [Basri et al., 2017]. PM has a lower investment cost [Basri et al., 2017] and can be utilized when it is not economically defensible or possible to use digital monitoring equipment that is necessary for PdM. Maintenance types are therefore often combined.

2.2.1 Scenarios for maintenance in Smart Factories

There are many researchers that are discussing the increasing importance of maintenance in the industries and that digitalisation will contribute with new solutions that can help maintenance in a Smart Factory. The thesis *On the Transformation of Maintenance Organisations in Digitalised Manufacturing*, written by Jon Bokrantz, describes predictions regarding what the future might hold for maintenance requirements and solutions. The thesis developed 34 projections, describing the most possible changes for the maintenance organizations by the year 2030. The projections were evaluated by 25 industrial maintenance experts, resulting in eight probable scenarios with the highest potential for future maintenance organizations:

1. *Data analytics*, collected data from various sources and time intervals are analyzed to detect patterns.
2. *Interoperability*, developed and implemented standards for integration of information systems e.g. CMMS.

3. *Big data management*, being able to filter out and identify the important data from a maintenance perspective and thereby analyze the right data to make decisions after.
4. *Education and training*, continuous education and training, allowing personnel to maintain necessary competence as the technology evolves.
5. *Fact-based Maintenance Planning*, supported with predictive and prescriptive data analytics.
6. *Smart work procedures*, as technology and data analysis methods evolves, smart work procedures enable e.g. remote inspection and real-time online monitoring.
7. *Maintenance Planning with a systems perspective*, the entire manufacturing system can be optimized based on a combination of a system perspective together with individual machines health and condition.
8. *Environmental legislation and standards*, an increase of environmental legislation puts pressure on maintenance as environmental requirements must be fulfilled.

2.3 Fundamental maintenance theory

This section describes maintenance theory in general and important factors like dependability, reliability and availability that affects the functionality of the production. The purpose of this section is to give a view of the importance of maintenance and the definitions of the states that a machine may have.

2.3.1 Maintenance

The purpose of maintenance is to ensure that the operation and the equipment are running as it should. The dictionary describes it as the work a machine needs to stay in good condition. The maintenance definition according to the Swedish Standards Institute is a “combination of all technical, administrative and managerial actions during the lifecycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function” [Swedish Standards Institute, 2010].

A big cost of the production cost is the maintenance, which can be between 15 to 60 percent of the total production cost [Mobley, 2002]. To make sure that the production is running at a high efficiency and with minimum breakdowns, it is important that the machines are in good health and that maintenance is performed fast when required. This can be done by scheduling maintenance to change parts or repair worn out parts in the machines. Maintenance will always be required and it is important to find the right timing to perform maintenance in the factory without disturbing the production. Some parts can be designed for a few thousand hours and some are designed for a specific number of starts and stops [Sullivan et al., 2004]. The failure can be described through different curves such as bathtub curve, wear out failure and constant failure. In cases where the equipment contains many different parts, it is important to keep in mind that various parts have different lifetimes, and bearings or other small components needs to be monitored to ensure that the main piece is running.

2.3.2 Dependability

Dependability is a measurement of availability and its affecting factors: reliability, maintainability and Maintenance Support Performance [Swedish Standards Institute, 2010]. The definition of dependability is "the ability to perform as and when required" [Swedish Standards Institute, 2010].

2.3.3 Availability

The availability of a part or a system describes how likely it is that the item will be up and running during a predetermined time, giving the probability that the item will function correctly during the predetermined time [Fowler, 2015]. The availability will increase if the stoppages can be repaired fast and easily, hence the item will then operate for a higher percentage of the time. The definition according to the Swedish Standards Institute is the "ability to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided" [Swedish Standards Institute, 2010].

The availability will in may cases be higher if the maintainability and the reliability are higher. Comparing two similar operations were one of them is easier to maintain, that one will have a higher availability than the other one [Fowler, 2015].

2.3.4 Reliability

Reliability is the "ability of an item to perform a required function under given conditions for a given time interval" [Swedish Standards Institute, 2010]. It is required that the item is in functional condition before usage. Places, where it is of high interest of calculating the reliability, is where small failures can lead to catastrophic events. For example in military systems, satellites and aircraft where it is crucial that certain component is functioning correctly. The calculations can provide with approximations of how many hours the item will perform as intentioned [Fowler, 2015]. The calculations are not very reliable but provide with indications of where potential errors might appear.

2.3.5 Maintainability

Maintainability is the ability to, under given conditions and performed maintenance, restore or retain an item to perform as required [International Electrotechnical Vocabulary, 2015a]. Maintainability can be affected by various factors, such as: accessibility, maintenance procedures, location and resources [International Electrotechnical Vocabulary, 2015a]. The maintainability can be calculated and give the probability of a maintenance action to succeed within a specified time interval [International Electrotechnical Vocabulary, 2015b].

2.3.6 Maintenance Support Performance

Maintenance Support Performance indicates to the ability of a maintenance organization, under given conditions, to perform the required maintenance, at the necessary time and place by having the correct maintenance support [Swedish Standards Institute, 2010].

2.4 Maintenance types

The following section about various maintenance types is describing different ways of ensuring the functionality of the factory, when to maintain and how to know when maintenance is needed.

2.4.1 Design for Maintenance

This section will focus on maintenance being implemented in a production systems early phase, the design phase, where the production system will be Designed for Maintenance [Nabdi and Herrou, 2016]. It will not include or consider changes on an already existing system, or design changes in a product development perspective so-called Design out Maintenance [Murthy, 2008].

Maintenance is often introduced after production facilities are completely done. Design for Maintenance is used to evaluate maintenance issues in the concept phase and eliminate them if necessary. Maintenance requirements necessary for certain components can be very costly and add up to a great amount of what the component actually cost, this cost is usually not included in the design [Liu and R.A. Issa, 2014]. Reliability and maintainability are two increasingly growing vital factors in maintenance solutions [Okogbaa and Otieno, 2015]. In order to increase the performance and reduce the cost of the systems, the probability of failures has to be minimized and the ability to bring systems back after unavoidable failures increases [Okogbaa and Otieno, 2015]. Machines that are designed for productivity but does not take maintainability into consideration may not be productive or economically defensible in the long run. Machines that are easy to maintain are more likely to get the required standards of maintenance [Desai and Mital, 2006]. Changes in the design can be of significant importance when maintaining the production system, the production system is preferably designed to have a high maintainability so it can be repaid quickly [Vaneker and van Diepen, 2016]. Common sense is often used when designing for maintenance. Changing the design in an early stage is often cheaper than making temporally changes and improvements when the production is running, see Figure 2.1. There are mainly six losses that can be expected from a production system, failure/breakdowns are one of them and are probably the most obvious one that causes down-times [Rizzo, 1999].

When designing or choosing between different machines or equipment, models that can be easily maintained are preferred [Pahl et al., 2007]. Models that requires minimal services or has components that can be easily replaced minimizes the

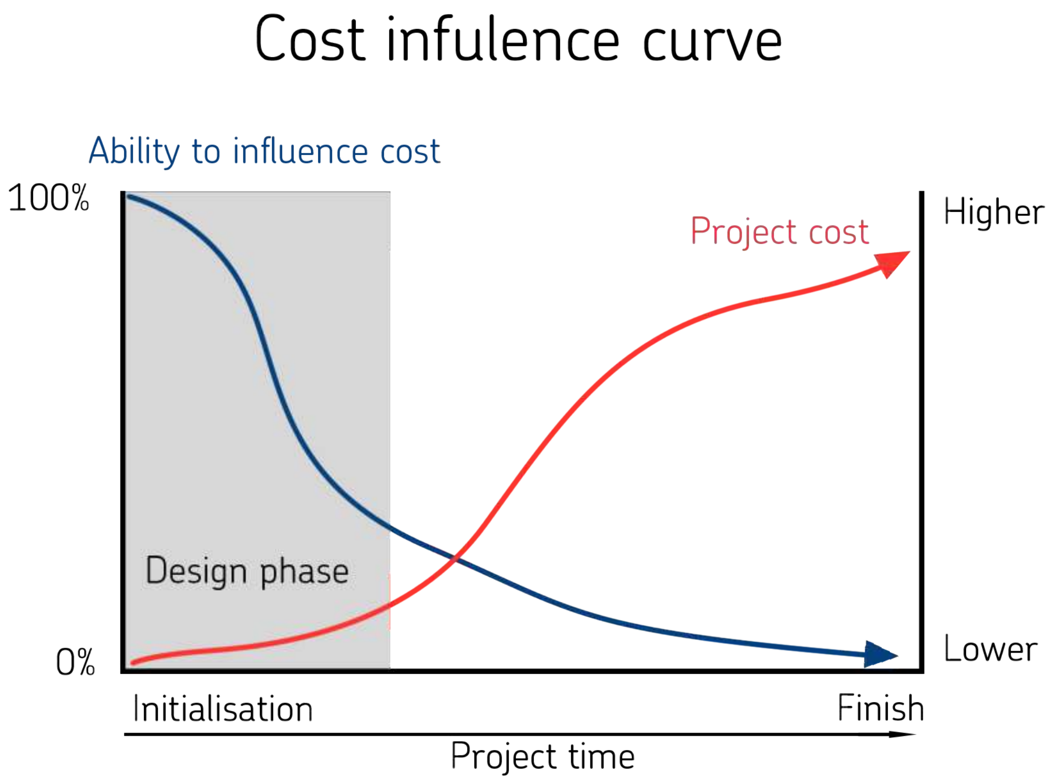

Figure 2.1: Illustration of the ability to affect the cost in the design phase

replacement-time and the maintenance cost. Technical measures that can reduce the service and inspection of an item is according to the book Engineering Design [Pahl et al., 2007]:

- Prefer self-balancing and self-adjusting solutions.
- Aim at simplicity and few parts.
- Use Standard components.
- Allow easy access.
- Provide for easy diassembly.
- Apply modular principles
- Use few and similar service and inspections

Design for Maintenance cannot be implemented in already manufactured machines, tools or other products, other maintenance alternatives must then be considered.

2.4.2 Corrective Maintenance

Corrective Maintenance is according to the Swedish Standards Institute "maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function" [Swedish Standards Institute, 2010]. Corrective Maintenance is the most commonly used maintenance type. In many cases, it is preferred to let the part run to it fails. But it is important that the quality of the production is not affected. There are different types of Corrective Maintenance: deferred Corrective Maintenance and immediate Corrective Maintenance. Deferred Corrective Maintenance is carried out with a delay. The immediate

Corrective Maintenance type relies on that maintenance is performed without any delays. Corrective Maintenance has no initial cost, the downside is that it can contribute to long downtimes [Basri et al., 2017].

2.4.3 Preventive Maintenance

Preventive Maintenance (PM) is a proactive maintenance type that is performed with a predetermined time interval to prevent machine failure [Sullivan et al., 2004]. PM is often used when breakdowns and unplanned products stop leads to high costs, or when it is hard to monitor or see when the equipment is falling apart. The predetermined time intervals are often based on previous failures or the standard lifetime of the component [Basri et al., 2017]. The definition of PM according to the Swedish Standards Institute is "maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item" [Swedish Standards Institute, 2010].

2.4.4 Predetermined Maintenance

Predetermined Maintenance is according to the Swedish Standards Institute [Swedish Standards Institute, 2010] "Preventive Maintenance carried out in accordance with established intervals of time or number of units of use but without previous condition investigation". This method is also called "Time-Based Maintenance". Predetermined Maintenance is useful when it is hard to predict when failure may occur. The Time-Based Maintenance type is less sophisticated [Montgomery et al., 2012;2009;], it does not take into consideration whether to components condition is poor or not. To maintain the component at periodic time intervals, the goal is to maximize the lifetime and to change the part before failure.

2.4.5 Condition Based Maintenance

Condition Based Maintenance (CBM) is according to the Swedish Standards Institute [Swedish Standards Institute, 2010] "preventive maintenance which includes a combination of condition investigation". CBM uses collected data to predict the health of the part [Montgomery et al., 2012;2009;]. Frequently inspections and test of the different parts are executed to make sure that the function of the part is in good condition. Changes or repair of any part is only executed if the prediction of a risk reveals in the system. If the predictions can be trusted, parts will be used as long as they can and then be replaced before failure.

2.4.6 Predictive Maintenance

Predictive Maintenance (PdM) is the maintenance type that is currently in focus among researcher, according to the Swedish Standards Institute it is "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" [Swedish Standards Institute, 2010]. To monitor different components IoT can be utilized [Schmidt and Wang, 2016]. This means that all things are connected to the Internet and are in that way able to communicate and alert each other. Sensors can utilize IoT and monitor production facilities, but even if measurements are collected, the data is often only analyzed at predetermined time intervals and some errors may go undetected.

2.5 Maintenance Planning

Operator's experience is often used in small systems when implementing maintenance. The operator's personal experience and knowledge can then be utilized and maintenance can be performed by the operator during production or planned production stops. Personal experiences are however not enough regarding Maintenance Planning for more complex and larger systems which are more common today [Okogbaa and Otieno, 2015]. Utilizing personal experiences regarding Maintenance Planning for these systems can often lead to significant losses caused by the operators neglecting components until they fail, or the opposite where new components are replaced without reason [Okogbaa and Otieno, 2015]. The losses increase with the complexity and greatness of the systems, meaning that this also increases the importance of Maintenance Planning [Okogbaa and Otieno, 2015]. Digitalisation can aid during the planned maintenance, all the information is connected at the same place which helps the operator to perform the right maintenance actions. Maintenance is forever and will not disappear [Peters, 2015;2014;], this put pressure on the systems and the personnel to develop good solutions to perform maintenance actions at a low cost. The Maintenance Planning system can be connected online since a time back [Raouf et al., 1993], but now it has evolved and can reach much further. The plant can be connected to a different system that is allowing the possibility to monitor and visualize the state of the factory leading to a better-planned maintenance. The management can in that way control the maintenance of the factory and plan the maintenance to achieve the lowest cost. Computerized Maintenance Management System (CMMS) stores information in a database about the organization's maintenance operations. By utilizing this database, company's can control and plan the required maintenance in the factory.

2.6 Vibration Monitoring

The following section gives a brief introduction of what vibration monitoring is and how it works. After that, two different types of sensors are described.

2.6.1 Vibration analysis

Vibration measuring is often used in the industry as a way of collecting data. This data is collected from parts that are hard to inspect because of the encapsulation around the parts. Measuring vibrations can be performed in two ways, online monitoring or off-line monitoring. Usually, it is enough to measure once in a while and use the off-line monitoring technique. When using online measuring, the sensors should be mounted nearby the bearings with a low number of transition materials between the sensor and the bearing. The collected data can vary from root mean square illustrations [Wang and Gao, 2006] to a peak to peak illustrations. When dealing with high frequencies it is preferred to measure the vibrations acceleration. The basics vibration system consist of transducers that measure the acceleration, an amplifier that produces a proportional voltage to the input and a recording unit that can display the data. Accelerometers are used as transducers. All the monitoring devices/sensors should be connected to a central server, where the information is stored and can be analyzed [Okogbaa and Otieno, 2015].

2.6.1.1 Accelerometers

An accelerometer is a transducer that converts mechanical acceleration into an electrical signal, where a mass is mounted on a damper system inside the accelerometer [Wang and Gao, 2006]. A piezoelectric crystal is either sheared or compressed when the mass is accelerating. The acceleration is generating a proportional voltage that can be visualized. The accelerometers are measuring the absolute vibration of the chosen object. It can measure e.g. movement, vibration & rotation [Jain, 2012].

2.6.1.2 Eddy current probe displacement sensors

Eddy current sensors are used to measure the vibration displacement of an object. It is using the Eddy Current electrical definition that describes the relation of a magnitude varying between different scenarios of the vibration. “The eddy currents generated have their own magnetic field which induces a current in the coil in the direction opposite to the supply alternating current and reduces the amplitude of the supply current in the proportion to the gap distance between the probe and the surface” [Wang and Gao, 2006].

2.7 Justify maintenance investments

Implementing PdM is often performed in order to lower downtimes on machines and to increase the efficiency of the production. It can also lead to less extra parts stored in warehouses just in case of breakdowns and companies can save both money and space. Monitoring all tools and machines in the production is still too expensive, it is not economical justified to invest in expensive equipment to monitor a whole factory [Basri et al., 2017]. PdM is therefore often combined with other maintenance strategies. It is often believed that maintenance should be performed as few times as possible to lower costs. The truth is that maintaining a factory can often lead to disturbance when production is stopped in order to repair or replace broken parts. Crucial and cheap parts that are still functional can therefore be replaced during the same maintenance action that is repairing other broken parts, this can lower the downtime and start the production faster again.

3
Methodology

The project Smart Factories has used different methods, this chapter includes the work procedure, literature reviews, Virtual Commissioning meetings, interviews and company visits.

3.1 Project work procedure

Three research questions were formulated in the initialization of the project. The work procedure to answer these questions is described in this section and illustrated in Figure 3.1 below.

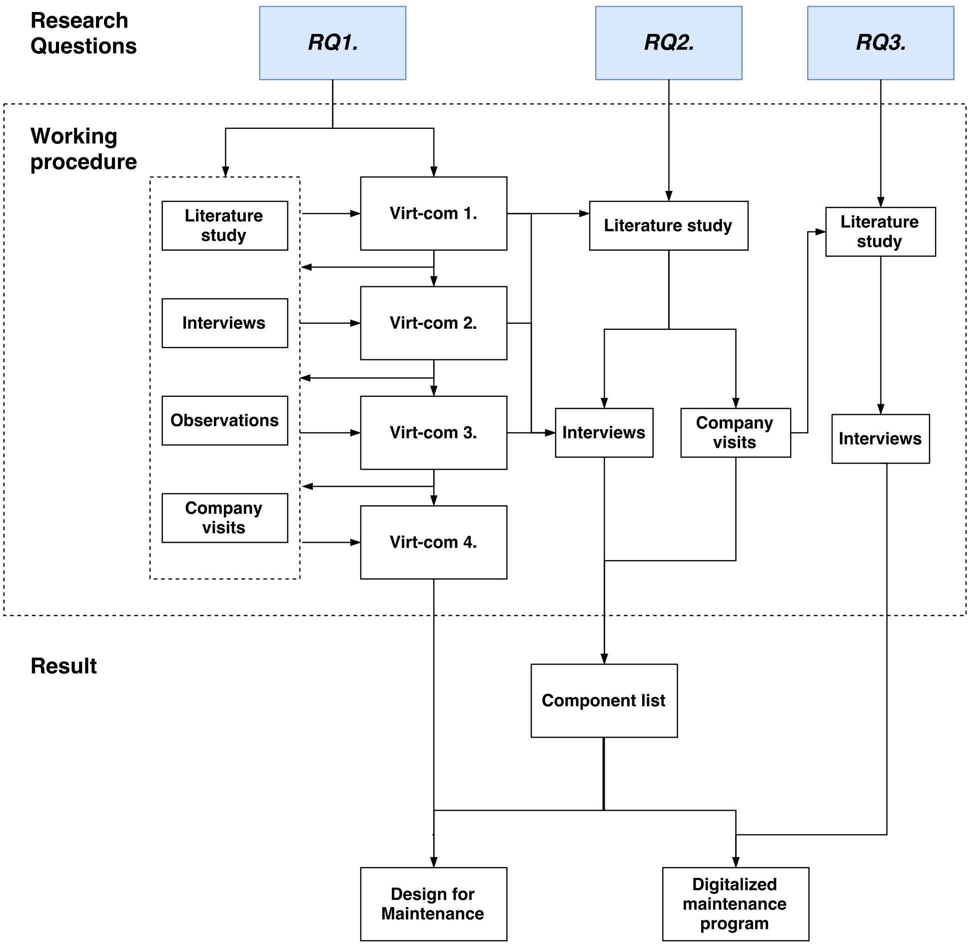

Figure 3.1: Illustration of the work procedure

RQ1. How can the maintenance requirements in the project Smart Factories be reduced when Design for Maintenance is implemented early in the design phase?
The first research question was answered through a collection of research methods: interviews, literature studies, observations and company visits, all of which were performed alongside four different Virtual Commissioning meetings. Literature studies and interviews were first performed before the first Virtual Commissioning meeting to gain knowledge and understanding regarding different maintenance types and how various companies worked with maintenance in their production. The first Virtual Commissioning meeting gave insight into what was important for the involved parties, directing further literature studies, company visits and interviews before the next Virtual Commissioning meeting. Questions that was unanswered or unclear at the meetings was supplemented with the collection of research methods. The knowledge gained from the research methods was later used for upcoming Virtual Commissioning meetings, contributing with thoughts and ideas that could be implemented in the project. The interviews and company visits were also used as sounding boards, aiding in evaluating different thought and ideas. Research questions one was developed with the purpose to reduce potential and future maintenance problems. This was achieved by eliminating problems in the design phase.

RQ2. Where should vibration sensors be installed to monitor the state of vital bearings in the project Smart Factories production line?
Research question number two answered where vibration sensors was to be installed in order to secure the availability of the production line. Data- and information sheets were first used to answer the question. Further investigation was performed through literature studies together with Virtual Commissioning meetings. Interviews and company visits were used as supplements and cleared out any uncertainties. Research question number two lead to a list of components that will aid the maintenance of the project Smart Factories. The components also contributed to the previous result, Design for Maintenance.

RQ3. How can maintenance data be presented to support the maintenance employees decision making?
Research question number three was designed to simplify the maintenance of the project Smart Factories production line on-site. The question was answered through literature studies, interviews and from information found while answering research question number two.

3.2 Literature review

The literature review was the basis for the academic field. Information was collected in order to gather knowledge about maintenance. Wide information was initially targeted and used to gain knowledge about different maintenance types: CBM, PM, PdM etc.

The buzzwords and different keywords that were the basis for finding research articles was collected during different interviews, Virtual Commissioning meetings and during meetings with the project's supervisor Jon Bokrantz. The literature studies were then more focused towards the application and utilization of the maintenance types. Skimming and Scanning were used to facilitate the reading [Freedman, 2012]. Skimming is used when the content of a text is needed and Scanning is used to find a detail in the text. By using this method the reading became more efficient and the right literature were found faster.

Further in the project, the literature studies were more focused towards information about sensors, data analysis tools, visualization tools etc. The databases available at the Chalmers library was the main source of the literature reviews.

3.3 Virtual Commissioning

One of the modern challenges in production industries is the cost-driven demand for fast and secure ramp-up processes [Westkämper, 2014;2013;]. Virtual Commissioning is a method with the aim to include and analyze important activities in the early design process of the production equipment [Reinhart and Wünsch, 2007]. Virtual Commissioning can contribute with a safer and shorter ramp-up process [Reinhart and Wünsch, 2007], see Figure 3.2.

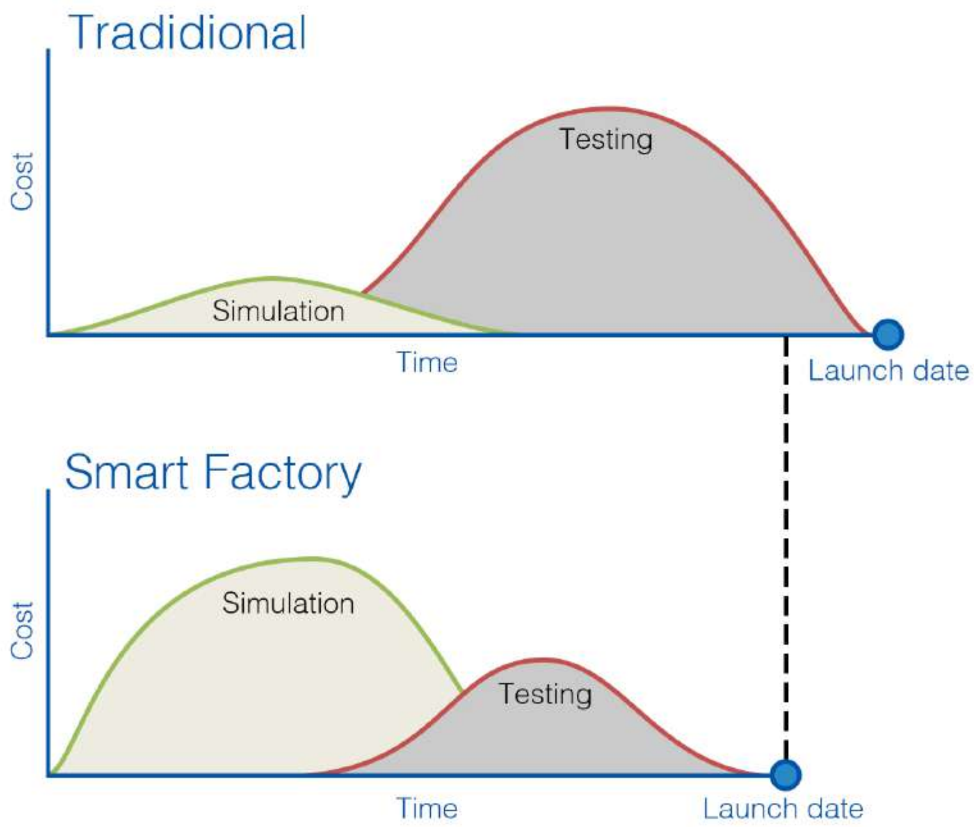

Figure 3.2: Advantage of virtual simulation

Virtual factories are computerized representations of all objects in a factory, collected into one digital twin of the factory. Digital twins can be used as a tactile element between humans and computers and aid in presenting complex technical solutions so that they are easier to understand in a short amount of time [Westkämper, 2014;2013;]. Digital twins can also be used to lower costs since errors are detected earlier and are therefore often less expensive to correct [Kihlman, 2016].

Virtual Commissioning meetings was set up during the design phase of the project Smart Factories. Key persons from each involved company were invited. A digital twin of the production line was presented and virtual reality glasses was used to enhance the experience and give a better understanding of the production line. The "magnifying glass" principle proposed by Zaeh et al. [2003] was used during the meetings. Where an overview of the production line was first presented, the magnifying glass was then moved over key areas of the production line, see Figure 3.3. The areas could then be examined more closely and contributed to a better understanding of the digital twin. Involved partners could then contribute with ideas

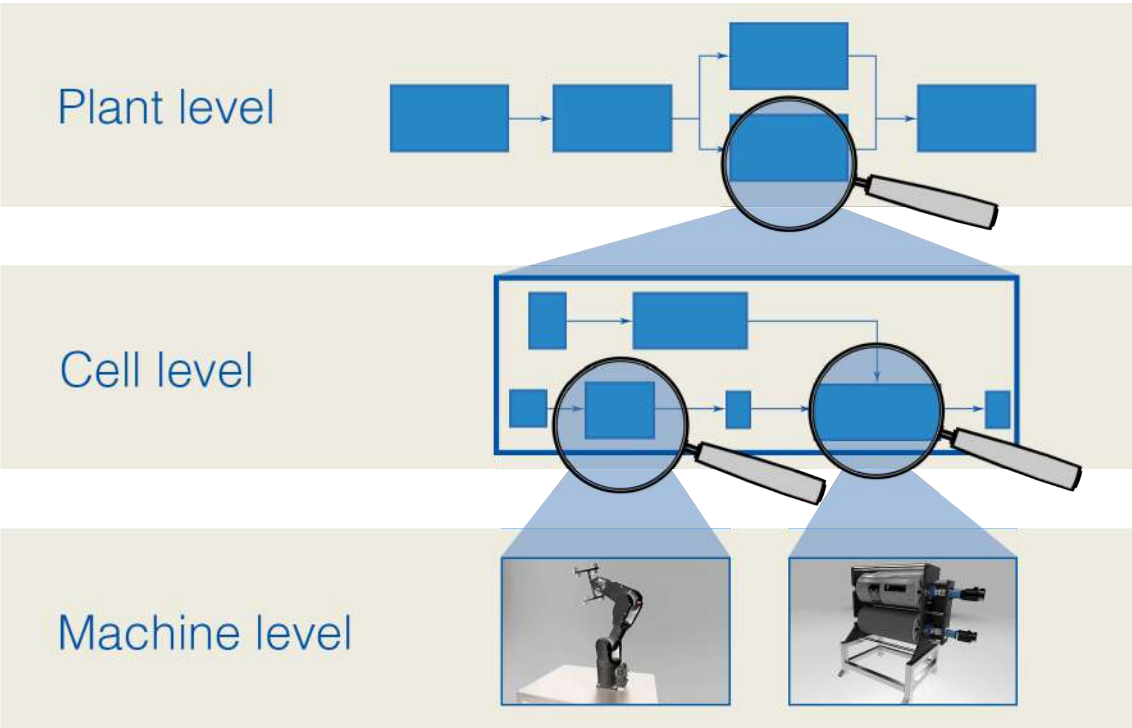

Figure 3.3: Principle of the magnifying glass

that solved mechanical and electrical issues. The author's task was to contribute with questions and ideas regarding maintenance and Design for Maintenance. When the majority of questions and issues were resolved, the magnifying glass moved on to the next key area. The digital twin contributed with easier understanding and helped the communication during the meeting. Different solutions in the production line were displayed. The digital twin allowed the presenter to easily show different manufacturing steps in the production line, and how different parts would move.

Four of these meeting was held during the project. Where all the vital partners were invited for each specific meeting. Since each partner had their own knowledge regarding their own product they could all contribute to the meetings in their own way. Connecting all the partners in the same room also made it easier to collaborate, solve problems and answer questions.

3.4 Interviews

Interviews is a commonly used data collection method, they can be conducted in various ways, and give a good explanation of what is asked for. Interviews can be used when gathering both qualitative and quantitative data [Elliot et al., 2016]. The main purpose of interviews is to understand the respondent's thinking and reasoning to provide knowledge and understanding to the interviewer [Bohgard et al., 2015]. A digital twin of the project Smart Factories was often presented during interviews in the project, the digital twin was used to give an overview of the project Smart Factories and its machines and functions. Two subcategories to interviews were used in this project: semi-structured and unstructured interviews.

3.4.1 Unstructured interview

Unstructured interviews are broad and open, consisting of few and wide questions which are used to guide the interview in the right direction. Unstructured interviews are generally used when gathering qualitative data [Elliot et al., 2016]. The interview method is similar to a guided conversations [Elliot et al., 2016]. In an unstructured interview, open-ended questions allow the respondent to talk freely about their opinions [Bohgard et al., 2015]. The interviewer can then ask supplementary questions and guide the conversation towards different topics that the interviewer is interested in. Unstructured interviews are suitable when the interviewer has little knowledge of the subject.

Unstructured interviews were held at the start of the project in order to gain a better understanding of maintenance and how companies use maintenance in their current production systems. ÅF Consult AB was interviewed to get a broad picture of how some of their customers works with maintenance. Prevas was also interviewed to gain knowledge of what they believed was some of the challenges when working with maintenance in different production lines.

To grasp a better understanding of different technologies on the market, IFM a company working with development and installation of maintenance systems and components, gave us an introduction and answered our questions regarding how their customers usually work with maintenance. IFM showed how their tachometers, temperature gauges and pressure gauges could send live information from different companies around the world directly to IFM:s website, allowing IFM to monitor their customers' different machines and equipment.

3.4.2 Semi-structured interview

The semi-structured interview is the most common type of interview methods to use [Elliot et al., 2016]. A semi-structured interview is usually based on a predetermined broad topic, including some indicative questions [Elliot et al., 2016]. The questions are used as guidance during the interview, but also to give the respondent a chance to present their own thoughts and knowledge. The order of the questions is freely determined by the interviewer. Undetermined questions can also occur during a semi-structured interview, giving the interviewee more freedom to guide the interview [Bohgard et al., 2015]. It is important that the interviewer has some knowledge of the topic and knows what is important within the topic. Allowing the interviewer to ask supplementary questions to issues that arise from the respondent [Bohgard et al., 2015].

Semi-structured interviews were held later on in the project to answer more complex questions which were hard to answer through the literature studies. Semi-structured interviews was also used in order to gain knowledge about how companies utilized technologies and products to improve their maintenance types. Mail was used to supplement semi-structured interviews and to ensure the quality of the answers, the questions were specifically directed towards the project or regarding specific details which were hard to find in the literature studies.

Several interviews were held at SKF to gain knowledge regarding how their products could be implemented in the production line but also to understand how they worked with the development of computerized maintenance programs. SKF also showed how they worked with maintenance, and how digitization could be utilized from a maintenance point of view.

3.5 Company visits

Company visits were performed periodically during the whole project, the goal was to compare the reality with the literature study. Observation is a method used to give insight and knowledge on how various problems and tasks are solved [Bohgard et al., 2015]. Observations are useful when collecting information regarding a situation without affecting the process, the method was used as a complement to interviews.

A company visit at SKF:s new plant in Gamlestaden Gothenburg were set up. They had built a new factory, claimed to be more autonomous than any of their others factories. One of their goals was to take maintenance a step further and improve their PdM. Unfortunately, they had not yet succeeded with a PdM system for their own factory.

U. Person at Volvo cars was visited. He showed how Volvo uses a computerized system to gather all the maintenance information in one spot. U. Persson is a teacher in the subject Design for Maintenance, he pointed out crucial mistakes that are often forgotten in the design phase.

A company visit at Flexlink was arranged when the project decided to use a Flexlink conveyor system in the production line. Flexlink showed how the conveyor system will work and provided with information that was necessary regarding maintenance of the system.

Eton Systems are one of the partners in the project. Their product will be used as a transportation system in the production line. Eton Systems were visited to give a guided tour and to show their product. Eton Systems were then interviewed regard how maintenance should be performed on their products.

3.6 Time plan

This project and the result given in the report is the result of a thesis work performed at the end of a 5 year study period at Chalmers University of Technologies. The thesis was a part of a bigger project where everyone followed the same time plan and schedules, sharing certain deadlines within the project. A tool called Yolean was used to sync all the different project groups. The initialization of the project was on January 16th, 2017. The work consists of 20 weeks, varying from 35 to 50 hours per weeks. One presentation was held by the authors for the examiner and the supervisor at Chalmers on the 31 of May.

4
Results

The result of the thesis will be presented in this chapter. Three results will be presented: "Design for Maintenance", "Component list" and "Enlight".

4.1 Design for Maintenance

The maintenance requirements of the project Smart Factories have been reduced by utilizing Design for Maintenance and answering research question one: *RQ1. How can the maintenance requirements in the project Smart Factories be reduced when Design for Maintenance is implemented early in the design phase?* This section walks through the pros and cons of the design changes performed to increase the maintainability and decrease the maintenance requirements for the project Smart Factories. Following results have been achieved through the use of a collection of research methods: interviews, literature studies, observations and company visits, all of which were performed alongside four different Virtual Commissioning meetings.

Storage table
The project Smart Factories consists of several modules which together creates a production line. The first module in the project Smart Factories is a Storage table containing cardboards. The Storage table is designed to accommodate enough cardboards to supply the production line for one day of manufacturing. The height of the Storage table is designed to allow a industrial robot to pick cardboards from the Storage table. The original design of the Storage table included an actuator and multiple moving parts, their purpose was to continuously adjust the height of the table, allowing the industrial robot that picks cardboards to reach the cardboards in the bottom of the pile. Figure 4.1 illustrates the comparison between the old and the new design, before and after Design for Maintenance was implemented. The need to redesign this module was noticed in the first Virtual Commissioning meeting, B. Magnusson [personal communication, February 03, 2017] brought up several risk factors with the old design, not only maintenance requirements but also problems that might occur if the communication between the Storage table and the next module fails. The actuator was therefore removed in the new design, eliminating one of the risk factors which could have contributed to failure and would have required maintenance. All moving parts, including the linear roller rails, were also removed. Resulting in close to zero maintenance requirements, contributing to a reduced cost and time needed for future maintenance. PdM was no longer considered for this module.

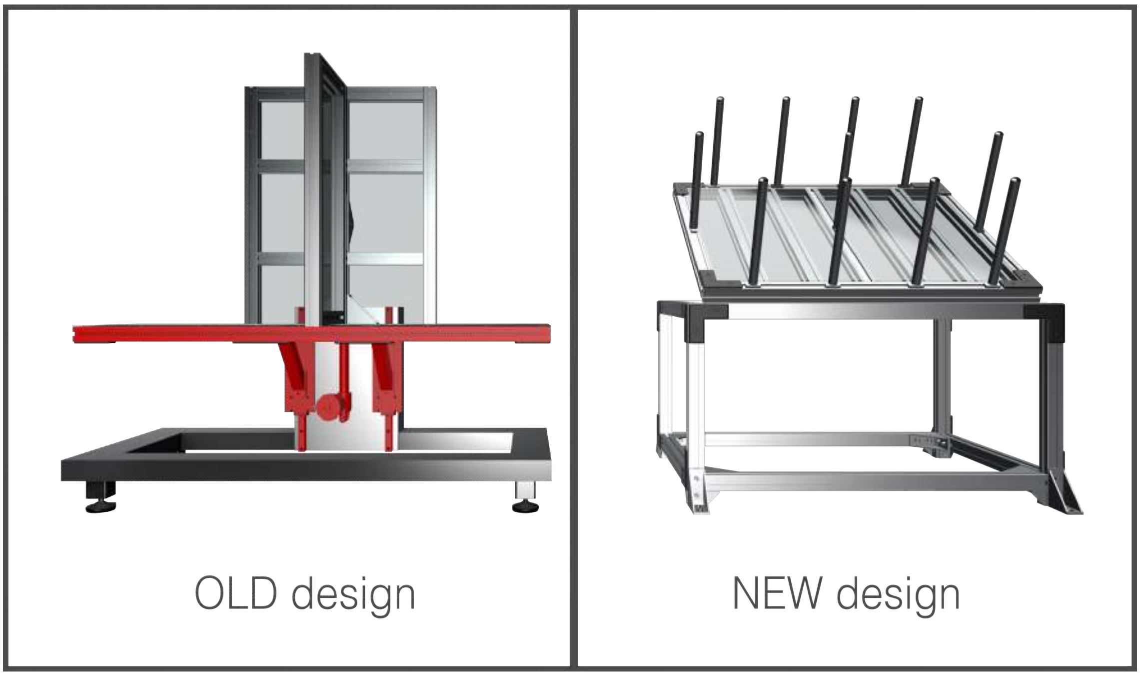

Figure 4.1: Comparison between the old and new design of the Storage table, movable parts that have been removed completely.

Various problems were discussed during the four Virtual Commissioning meetings, one thoroughly discussed subject was the picking of the cardboard laying on the top of the carboard-pile. Chances were quite high in the old design that the cardboard laying underneath the top cardboard would get stuck in the top cardboard during the picking phase due to suction and friction between the two cardboards [B. Magnusson, personal communication, February 03, 2017], tilting the tabletop decreases the risk of cardboards getting stuck in each other. Tilting the tabletop also allows the industrial robot to reach the last cardboard in the bottom of the pile. Other improvements with the new design are: increased space for the operator when refilling the Storage table and providing better access all around the Storage table contributing to increased maintainability and a better ergonomic environment.

Feeding module to the roller die cutter

The feeding module pushes the cardboards into the roller die cutter. The original design consisted of an actuator that moved several parts in order to push the cardboards in the right direction. The design was evaluated by experienced personnel from various companies during the Virtual Commissioning meetings and there was a big concern regarding the design of the moving parts. Design for Maintenance reduced moving parts, resulting in fewer parts affected by sliding wear. Parts that were exposed to leverage forces was removed, eliminating risk factors and reducing maintenance requirements. The new design of the feeding module is more open, resulting in that parts are easier to access and change, leading to an increased maintainability, see Figure 4.2. The new design still includes moving parts and an actuator. To reduce the maintenance requirements on these parts, Design for Main-

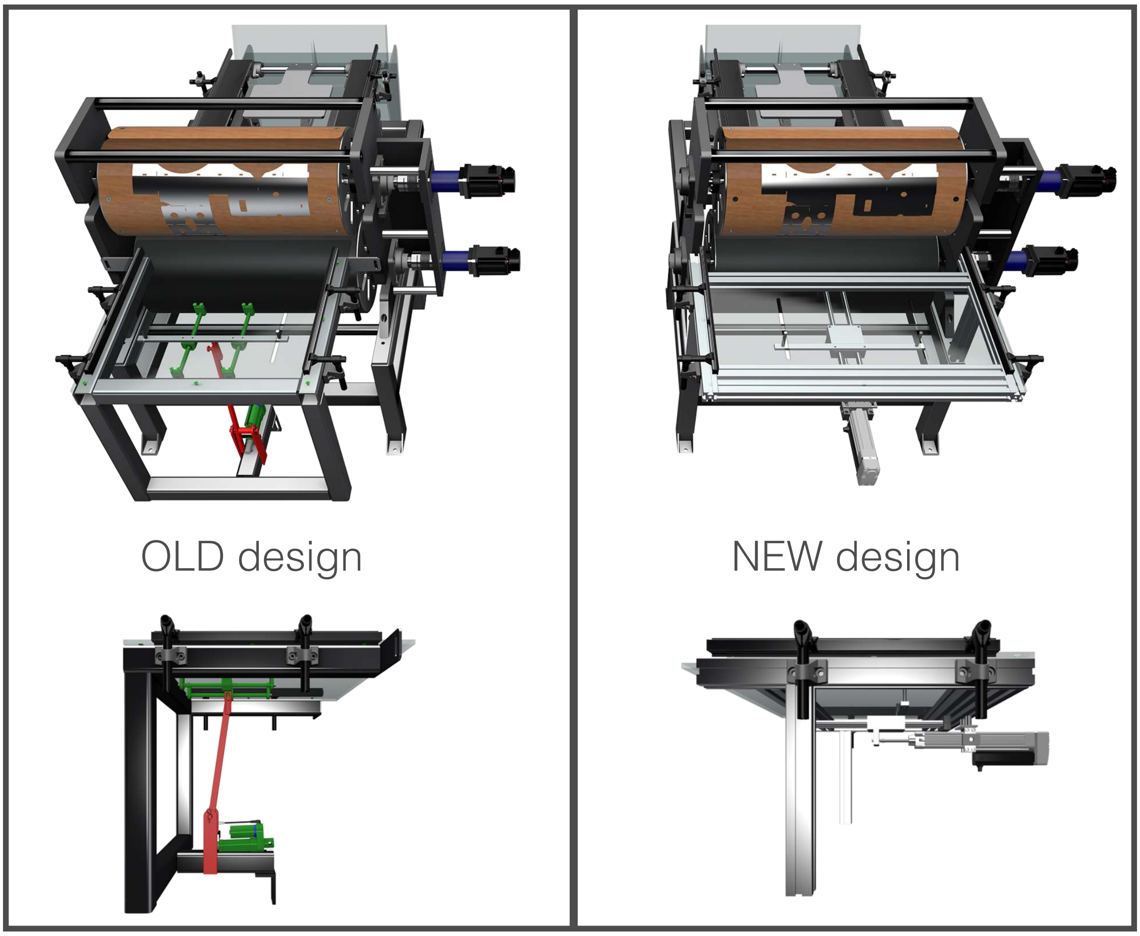

Figure 4.2: Comparison between the old and new design of the Feeding module to the roller die cutter, movable parts that have been reduced or reinforced.

tenance reinforced the moving parts by adding stronger linear roller rails and moved attachment points to more durable locations. During a interview with U. Persson [personal communication, Mars 08, 2017], he argued about the importance of using the same parts or components in multiple locations within the production line, the actuator in the feeding module to the roller die cutter was therefore replaced with a more robust model that is used in other locations within the production line, read more about this in section 4.1 *Lens elevator*.

Lens elevator

The elevator system for the lenses consists of an SCARA robot that delivers the lenses to an actuator, as in turn serves as an elevator, lifting the lenses up to the next module, see Figure 4.3. Design for Maintenance could not remove any unnecessary parts in this case nor eliminate the number of moving parts. U. Persson [personal communication, Mars 08, 2017], working at Volvo cars was interviewed during the project, he is also a teacher in the subject Design for Maintenance. He pointed out one crucial mistake that is often forgotten in the design phase, to use the same parts in multiple places. U. Persson stated that this could help in a maintenance perspective since "The same spare parts can then be applied in many cases, requiring less

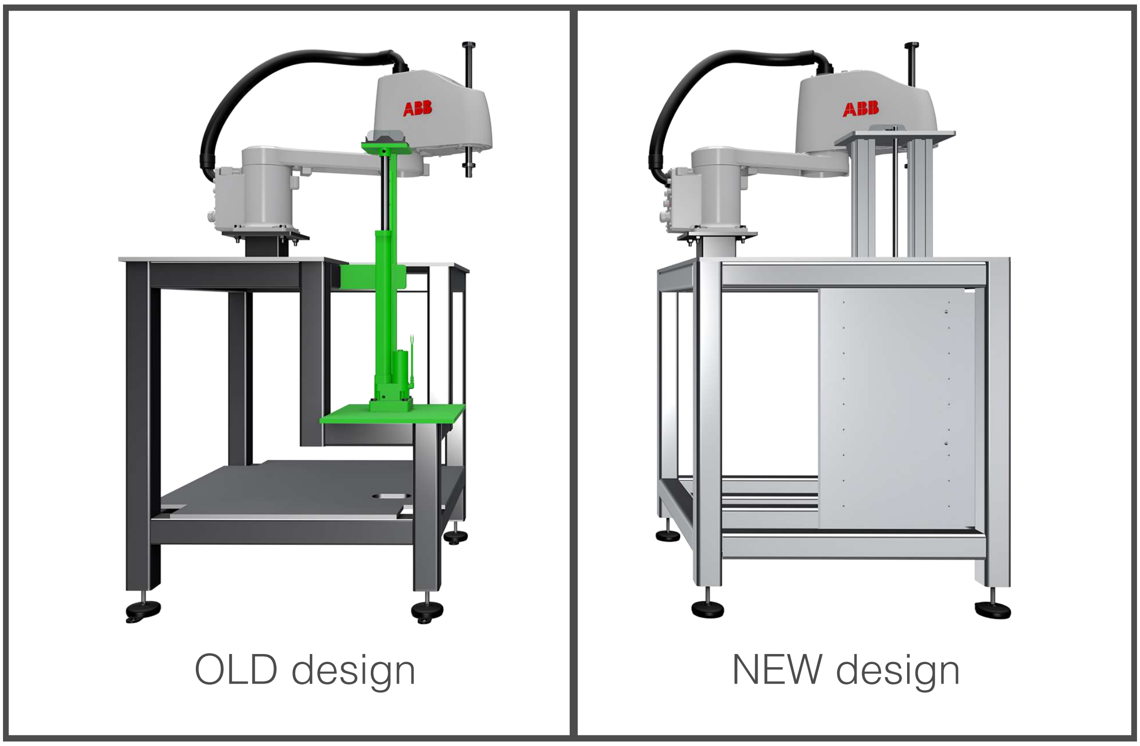

Figure 4.3: Comparison between the old and new design of the Lens elevator, movable parts have been reinforced.

amount of tools and eliminating the variety of spare parts that needs to be stored in the warehouse. It could also lead to lower costs and aid the maintenance team to become better at predicting the failure of the parts and how to solve normal issues." The actuator lifting the lenses in the delivery system was therefore changed between the previous and the new design, to the same actuator-model used in the feeding module of the roller die cutter. The elevator system surrounding the actuator was also improved, making it more robust and stable by adding a second linear roller rail and increasing the number of attachment points from one to four. Maintenance requirements were lowered but the negative side of the new design was the decreased accessibility of the parts that have the highest need for maintenance, resulting in reduced maintainability.

Transportation system for lenses
The transportation system for the lenses consists of a material handling system that operates up in the air. The previous module, described above as "lens elevator", delivers the lenses to the transportation system with an actuator, working as an elevator. The transportation system receives the lenses with the help of a large plastic chain, see Figure 4.4. One of the maintenance requirements of this transportation system is that the plastic chain needs to be tightened. The old design utilized a tension-wheel located at the the bottom of the plastic chain, at the transfer point between the lens elevator and the transportation system for the lenses. The maintenance requirement to tighten the chain was carried out by lowering the tension-wheel, but this would also lead to a relocated transfer point. Meaning that

performing this maintenance action would lead to the necessity of re-calibrating and re-programming the previous module in the production line since the transfer point of the lenses would have been relocated, see Figure 4.4.

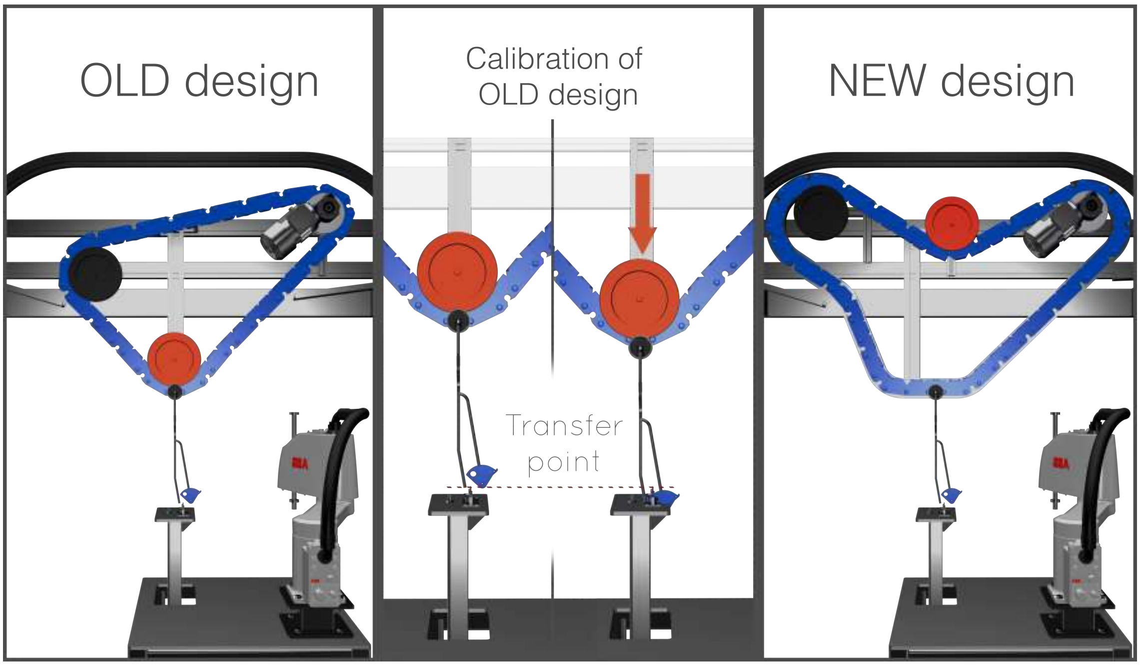

Figure 4.4: Illustration of the calibration of the old design resulting in a relocation of the transfer point.

This problem was noticed during a company visit at Eton Systems, where a operator was interviewed regarding maintenance requirements of the transportation system. The problem was then brought up at the last Virtual Commissioning meeting together with the idea to move the tension-wheel to another location. The tension-wheel is therefore moved in the new design, allowing required maintenance actions to be performed, see Figure 4.4. One negative effect with the new design is the reduced accessibility of reaching the tension-wheel.

Summary
Design for Maintenance also included maintenance solutions that decreased the risks of performing maintenance in a way that could affect the project Smart Factories productivity and efficiency. Virtual Commissioning meetings and company visits made the project aware of risks that could have gone unnoticed otherwise. Design for Maintenance reduced the maintenance requirements in the project Smart Factories by:

- Eliminating risk factors
- Reducing moving parts
- Reinforcing moving parts
- Reinforcing mechanical parts that are exposed to big loads
- Introducing same spare-parts on multiple places
- Increasing maintainability by enabling better accessibility where maintenance actions are required

4.2 Component list

This section walks through the results answering research question two: *RQ2: Where should vibration sensors be installed to monitor the state of vital bearings in the project Smart Factories production line?* The results have been achieved through the use of literature studies, interviews and company visits.

According to the delimitations, different components and sensors that are used in the project will not be compared to non-project related companies. This is decided with respect to the partners of the project Smart Factories and their involvement and engagement for the project. The majority of the components has been chosen from SKF who are sponsoring with time, knowledge and products. The following selection of components explains the opportunities that can be fulfilled by using these devices. Detailed information and location of the various components are shown in Appendix A and Appendix B.

4.2.1 Vibration sensors

Despite the fact that vibration measurement sensors have advanced over the years, placement and selection of sensors are still of great importance in determining the success of any condition monitoring program.

Figure 4.5: Illustration of installed Vibration Sensors

Interviews and company visits have been the basis to secure the right placement and selection of vibration sensors for the project Smart Factories. The placement of the sensors was decided with the help of two interviews performed at SKF, the first interview gave the authors general knowledge regarding placements of the vibration sensors. P. Alverby [personal communication, February 03, 2017] was interviewed during the second visit at SKF, he has years of experience and knowledge in the field of installing and locating where to mount vibration sensors in industrial factories. The digital twin was used during the interview with P. Alverby [personal communication, February 03, 2017] to simplify the explanation of the production line, P. Alverby could also use the digital twin to clarify specific locations on where to install the vibration sensors in the production line. The vibration sensor that has been chosen for the project Smart Factories is the CMSS MT-1, a machine tool industry accelerometer from SKF. The sensor is optimized to use with online monitoring systems in machine tool applications. One big advantage with the CMSS MT-1 is its physical characteristics, the compact design fits the project Smart Factories requirements, see a more detailed specification in Appendix A.1. In the project, the sensors are mounted to measure the vibration of bearings. The goal is to enable PdM, where collected vibration measurements can aid in the determination of wear and potential future risks. The sensor has high resistance to electrical noise and it meets CE and EMC requirements. The simple explanation from P. Alverby [personal communication, February 03, 2017], was that the vibration sensors should in general be mounted as close to the bearings as possible and the lesser material between the sensor and the bearing gives better measurements.

4.2.2 Tachometers

Rotating parts are measured with IFM tachometers that are specially developed to perceive minor deviations. Interviewing specialist in the area and company visits at IFM resulted in the choice of a tachometer with identification number: ifs305. This is a sensor with an M12 attachment and a digital output that can detect a frequency up to 2 kHz, see a more detailed specification in Appendix A.2. Tachometers combined with vibration sensors can help to evaluate and determine which of the bearings internal components has a potential risk of failure.

4.2.3 Datalogger

The vibration sensors and tachometers used in the project Smart Factories do not have the ability to save the measured data. A data-logger is therefore required and can be used to collect data from the different sensors. The sensors are connected to a data-logger that stores the information and distributes it through the Internet, out to the remote diagnostic and overview system where it can be analyzed, see Figure 4.6. The data-logger allows the project Smart Factories to connect various sensors into one system, allowing easier implementation of PdM. The project Smart Factories will be using an IMx-8 Multilog from SKF, see a more detailed specification in Appendix A.3. This is a smart device designed for early fault detection and used to increase the reliability, availability and performance of rotating equipment [SKF, 2017]. The data-logger can connect to mobile devices and laptops. Data can also be transferred through IMx-8 to a central database (cloud), where it is later analyzed and future scenarios are predicted by algorithms that compare new and historical data and verifies that the measurements fall within known thresholds. Limits and rules enable PdM that alarms the maintenance personnel. The central database can be reached from all over the world, allowing specialists to analyze and help the project Smart Factories with predictions.

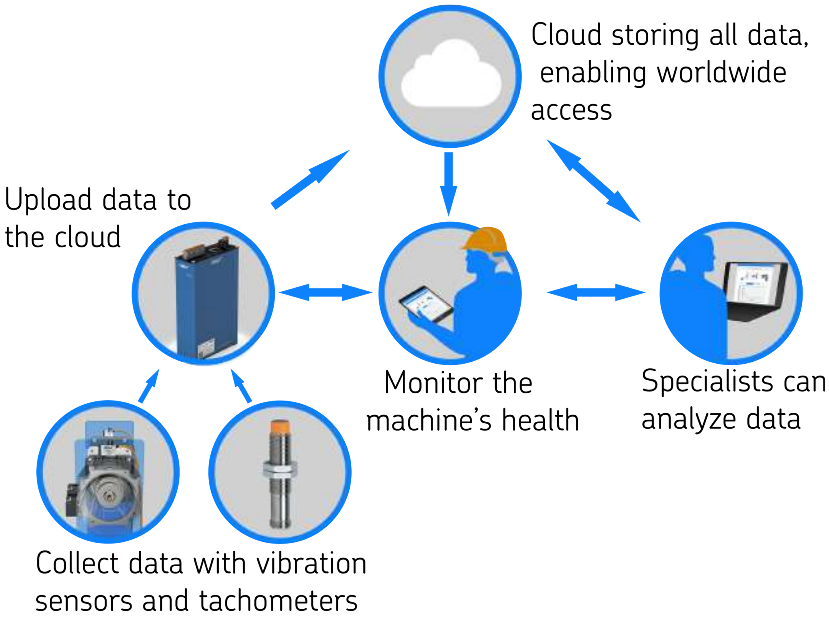

Figure 4.6: Illustration of the information spread

4.3 Enlight

This section respond to research question three: *RQ3. How can maintenance data be presented to support the maintenance employees decision making?* There are multiple maintenance software that can be used to set up and prioritize maintenance, SKF Enlight is presented in this result as a selected software to support and present information for the user. Following result have been accomplished through literature studies and interviews.

Software Engineers developing Enlight were interviewed in order to gain knowledge and understanding of how to utilize the software for our project. The value of using Enlight as a maintenance software in the project Smart Factories is that it is compatible with various sensors and not only SKF:s products, in this case, the vibration sensors, the tachometers and the IMx-8 that are collecting deviations of the rotational parts in the production line, allowing the possibility to implement PdM. Data from the sensors are continually transferred to the program and monitored through a iOS tablet where it can be analyzed, see Figure 4.7. Enlight is connected to the cloud via wireless Internet. Using IoT, all the information and measurements from the sensors are stored in the cloud, enabling maintenance personnel to utilize Enlight in order to evaluate the production from various locations in the world. The software can be used in situations both with and without installed sensors. When sensors are installed, e.g. vibration sensors and tachometers, Enlight can be used to display the readings of the sensors together with notifications and alarms that indicates if the values are good or bad, aiding in PdM.

Traditionally, the maintenance instructions are not linked with the data collection

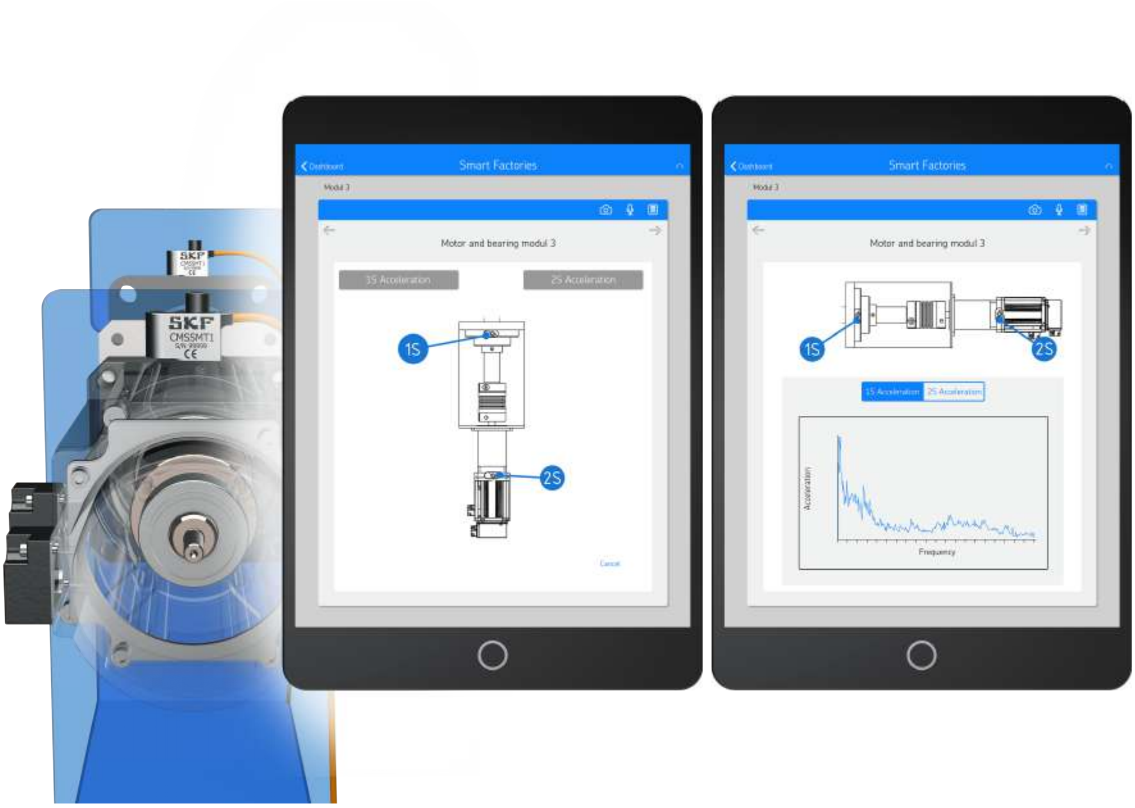

Figure 4.7: Illustration of SKF-Enlight connected to the vibraion sensors

system, this inhibits the maintenance personnel to perform maintenance actions in an efficient way. The data is often stored at one location and then analyzed at another location. Enlight is used as an integrated system for documentation, collecting new and historical data into one location. Enlight is also used to create forms. Forms are used to simplify maintenance rounds where information regarding how maintenance should be performed is displayed on a tablet, thereby aiding in CBM. The maintenance rounds are programmed in advance and a tablet is then used during the maintenance round where Enlight guides the maintenance personnel, instructing what actions to perform by displaying data, drawings or photos. Maintenance personnel can also be guided through a series of questions where different actions or new questions are displayed depending on previously answered questions. Pictures and illustrations can be utilized to enhance the understanding of what the question refers to, see section 4.3.1 for a simplified example. The form can also contain user manuals, locations, corrective actions etc. with the goal to simplify the maintenance rounds for the maintenance personnel. Notes, sound and pictures can be saved during the maintenance round and added in the program, all the information will then be stored in the same place, the cloud. Enlight can collect all the information from the cloud to produce status reports, giving details and summarize maintenance activities.

4.3.1 Maintenance Planning

This section is presenting a simplified example of the Maintenance Planning schedule done in Enlight. To get the most accurate and informative maintenance information and requirements about the machines in the project Smart Factories, instructions on how to maintain the different machines was provided by the machine's manufacturer. Figure 4.8 presents a simplified example where Enlight guides the operator through questions. First, Enlight guides the operator to the right location in the factory, it then shows pictures and informative text, telling the operator what to look for. Enlight asks questions to the operator and follow-up questions will be asked depending on the previous answer by the operator. The questions help the operator to look for known issues and to find problems and eventually, give the operator the correct maintenance action to fix the problem.

The operator is already guided to the right location in Figure 4.8, Enlight then asks "Does the feeding module push the cardboards in a straight line towards the roller die cutter?", the operator can now choose between two answers "yes" or "no". If answer "yes" is chosen, Enlight tells the operator to move on the the next machine in the factory, but if the answer "no" is chosen, Enlight provides the operator with the user manual explaining what maintenance actions to perform in order to fix the problem.

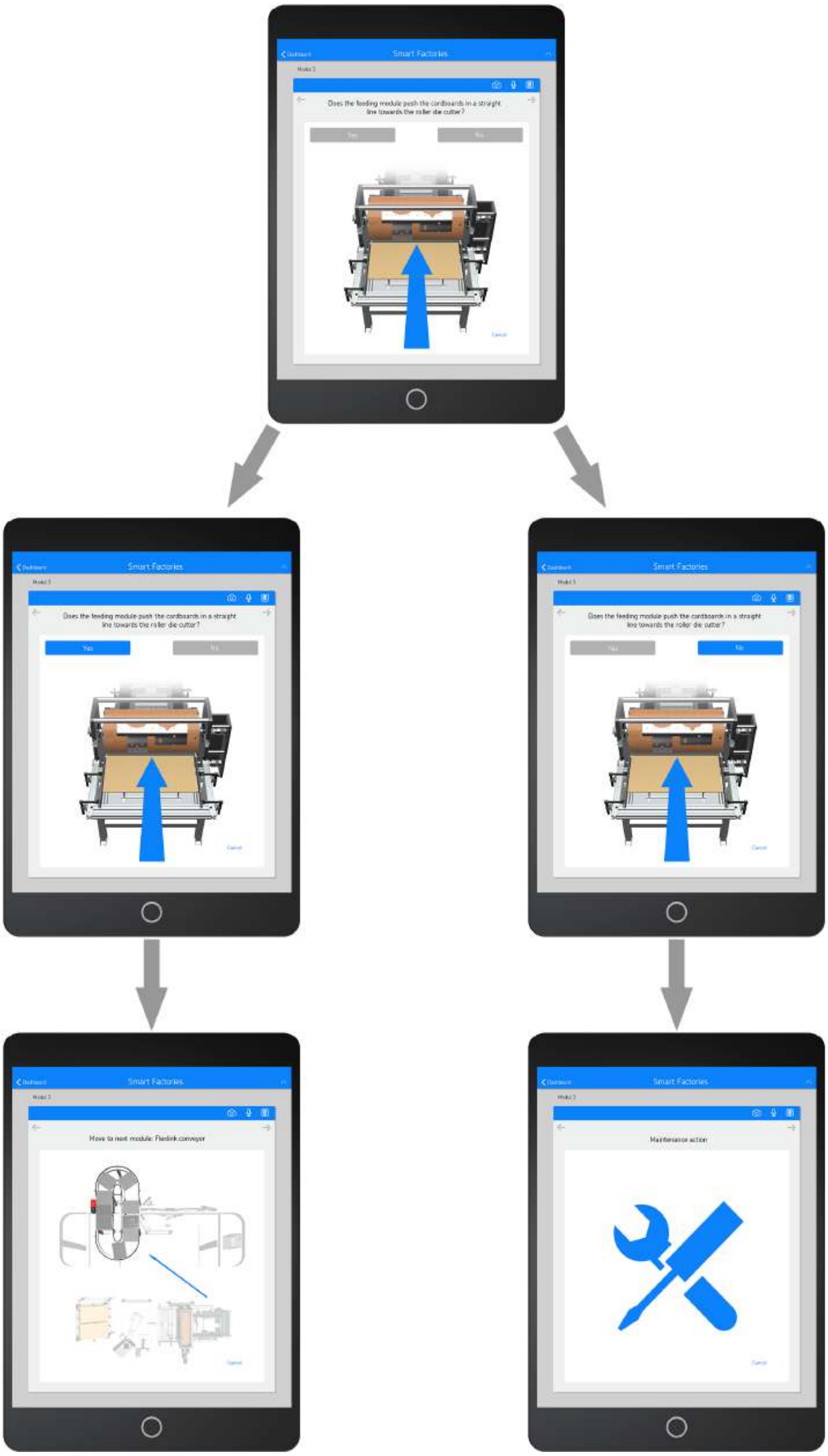

Figure 4.8: Simplified example of Enlight used in Maintenance Planning

5

Discussion

The fifth chapter includes the discussion of the results, theory and the methodologies used throughout the thesis Maintenance Solutions for Smart Factories.

5.1 Results discussion

In this section, the results are discussed and compared with the theory.

5.1.1 Design for Maintenance

Results answering research question one are discussed in this section. Okogbaa and Otieno [2015] argues, that the probability of failures has to be minimized and companies have to increase their ability to bring back systems fast after unavoidable failures in order to reduce the cost of the systems and increase the performance of the system. During the design phase of the project, we focused a lot on minimizing the probability of failures by reducing unnecessary risk-factors in the production line. Vaneker and van Diepen [2016] highlights the significant importance of design changes that can lead to reduced maintenance requirements, arguing that companies should design their production system to have a high maintainability, allowing it to be repaired quickly. This was something that was taken into consideration in the project, but we did not only focus on the designs that allowed the production line to be repaired quickly, but also designs that allows maintenance actions to be performed without affecting the production. Okogbaa and Otieno [2015] means that maintenance solutions have gained a new meaning and importance in autonomous systems since they should, in general, experience little to no failures. Design for Maintenance has been a known term for a long time. Virtual Commissioning meetings was used in the project Smart Factories to apply established practices in a new context that could add value to the smart industry. As Okogbaa and Otieno [2015] cites "To add maintainability into a design, designers need an intensive understanding of the system." to realize Design for Maintenance in the project Smart Factories, key persons from every involved company, that supplied with parts and products, was invited to the Virtual Commissioning meetings. As each individual company had their own knowledge regarding their own product they could all contribute to the meetings in their own way. Parts and components in the project Smart Factories were changed so the involved companies products could work together, including system configuration, topology and component interdependence. Fixtures and transportation lines was designed to fit the project Smart Factories requirements as well as the requirements form the involved companies. Pahl et al. [2007] mentions different factors that can reduce the maintenance requirements of an item: "aim at simplicity and few parts, use standard components, allow easy access, etc." this was utilized in the project Smart Factories, as Design for Maintenance eliminated multiple moving parts, enabled easy access to increase maintainability and reinforced parts and attachment points. U. Persson [personal communication, Mars 08, 2017] highlighted during an interview at Volvo cars, the importance of using similar or related products at multiple places in a factory; this can lead to a shorter learning curve for the maintenance personnel by allowing them to gain knowledge and understanding of fewer parts. Design changes in the project Smart Factories allowed the utilization of identical products at multiple locations in the production line.

5.1.2 Component list

Results answering research question two are discussed in this section. Muchiri et al. [2011] argues about the possibilities and positive effects that proactively identifying problems can lead to: reduced chances of secondary damages, reduced environmental consequences and lowered maintenance costs etc. Basri et al. [2017] goes on about companies that are aware of their machines' health can eliminating unnecessary investments and production stops. By installing vibration sensors together with tachometers and a data logger, we can monitor the state of the machine's health and thereby predict and find problems that are hard to notice otherwise. Vibration sensors can also monitor internal wear of parts that the human eye can not see. Diederik et al. [2014], Roy et al. [2016], Westkämper [2014;2013;] and Kagermann et al. [2013] argues about the new possibilities that the future holds with the new technology that will revolutionize the industry, but what is often left out in the literature is the complexity and uncertainties that companies may face during the installation of these systems. Even though we consulted experts within the field, that helped us with the placement and selection of vibration sensors, there is still a risk that the sensors has to be relocated after installation in order to give the results that we are looking for.

5.1.3 Enlight

Results answering research question three are discussed in this section. Westkämper [2014;2013;] argues that real-time information can be used to optimize maintenance schedules and contribute to a higher plant availability and reduced maintenance cost. This is something that can be utilized in Enlight since the software can collect both real-time information from sensors that monitors the health of the machines, together with information that explains what maintenance actions to perform when something fails. Diederik et al. [2014] indicates that traditional factories have utilized digital tools to measure the production for years, but new technologies now allow the factory to be linked together. This was taken into account in our thesis, were Enlight is utilized to link the information from the sensors to actual maintenance documentation and further on to experts that can analyze the data. Okogbaa and Otieno [2015] mentions the importance of a central station where all the information is stored, Okogbaa and Otieno [2015] clarifies that storing all information in one location enables comparison between new and historical data, aiding to perceive the right maintenance action. Both the industry and the literature is aware of the need to organizing information so it can be utilized in an effective way. Enlight is one of the available software to use in order to link maintenance information, new-, historical- and online-data and store it in one place where it can be reached from all over the world.

5.1.4 Scenarios for maintenance compared with our results

See section 2.2.1 for further reading regarding the thesis *On the Transformation of Maintenance Organisations in Digitalised Manufacturing*, written by Bokrantz. Bokrantz thesis is written on a high level with a larger perspective than our thesis, our results can still be compared but on different levels. Jon mentions the importance of collecting data from various sensors so fact-based Maintenance Planning can be supported and patterns can be detected, this is something that we have taken into consideration in our project and it fits with our result "Component list" where components are utilized to enable PdM and aid in decision making regarding Maintenance Planning. The information from the sensors can be reached by Enlight, enabling smart work procedures such as remote inspections and real-time online monitoring which is also discussed in Bokrantz thesis. Jon discusses smart work procedures at a more general level, our results enable smart work procedures. All eight scenarios in Bokrantz thesis *On the Transformation of Maintenance Organisations in Digitalised Manufacturing* have not been included in our thesis, but our results, Component list and Enlight, goes along and fits some of the scenarios mentioned by Bokrantz. It is therefore possible to say that previous research consents with our results Component list and Enlight. Our result, Design for Maintenance, is not mentioned by Bokrantz, meaning that we have considered the early life cycle phase more important and utilized new technologies to implement Design for Maintenance.

5.1.5 Summarizing result discussion

Design for Maintenance and sensors to monitor the machine's health have been used long before our thesis, we have therefore utilized proven methods, but put them in a new context and utilized them in new ways e.g. through Virtual Commissioning meetings. We have then tied all the information into one location, the importance of which is discussed in the literature. In summary, our results go along of what is expected and supported by previous research as well as added to something further: the utilization of digital twins in the early life cycle phase and thus utilizing digitization to make Design for Maintenance.

5.2 Methodology discussion

Following section discuss the methods: Virtual Commissioning, Design for Maintenance, literature reviews, interviews and company visits.

Virtual Commissioning is a method with the aim to include and analyze important activities in the early design process of the production equipment [Reinhart and Wünsch, 2007]. The first Virtual Commissioning meeting started off with a very clear structure and goal, groups and teams were predetermined in order to form an efficient environment, this made the method quite effective. One problem was that the entire production line was reviewed during the first Virtual Commissioning meeting, leading to a very time-consuming process where it was hard to maintain the focus and efficiency. A more efficient way of utilizing Virtual Commissioning meetings would be to arrange more meetings where only one key area of the production line is discussed during each meeting and not the whole factory at once.

Design for Maintenance excludes potential errors by changing different parameters in the design phase before the production begins [Nabdi and Herrou, 2016]. The emphasis of Design for Maintenance is important and it is crucial that the production management is on the same track. The project Smart Factories included maintenance solutions in the project's early phase. The problem was that it was hard to convince the management regarding design changes for increased maintainability. It was clear that the management had not taken a maintenance perspective in consideration when discussing the project Smart Factories functionality. Therefore we would like to emphasize the importance of discussing the advantages with the management about implementing Design for Maintenance in an early stage of the project, utilize calculations or other convincing arguments to explain the importance and potential outcomes of the design changes.

The project began with a lot of hours spent on reading and evaluating various articles and books that explain previous studies in the field and their results. Reading those articles gave us great knowledge in the field, allowing us to make trustworthy investigations and qualitative interviews. In further investigations is it preferable to make interviews in the beginning of an project to get an impression of what literature to look for. In that case buzzwords and other words that are discussed in the interviews can be used to guide literature search-words.

In interviews and company visits, it was initially difficult for the respondent to understand the level of the project and what we were talking about, this often led to problems, making it difficult to reach the results we wanted. The digital twin showed at the Virtual Commissioning meetings was therefore utilized. The digital twin was used as an introduction at interviews and company visits to facilitate the discussion about the project.

6
Conclusion

This section summarizes the answers of the three research questions. The purpose of this thesis was to deliver maintenance solutions for the project Smart Factories. Specifically, by delivering design improvements that will reduce maintenance requirements for the project Smart Factories, components that will monitor the production line and a digital interface to support decision-making.

RQ1. How can the maintenance requirements in the project Smart Factories be reduced when Design for Maintenance is implemented early in the design phase?
Research question one was answered through Virtual Commissioning meetings along with a collection of research methods: interviews, literature studies, observations and company visits. The construction designers were not always aware of some of the required functions, companies involved in the project participated at the Virtual Commissioning meetings and shared knowledge and guidance to the designers and gave feedback regarding the designs. Big changes of the designs were proposed to prevent failures with high risk. Parts with high maintenance requirements were eliminated, reinforced or relocated etc. The focus was often on moving parts and parts that were exposed to big loads. Design for Maintenance reduced the maintenance requirements in the project Smart Factories by:

- Eliminating risk factors
- Reducing moving parts
- Reinforcing moving parts
- Reinforcing mechanical parts that are exposed to big loads
- Introducing same spare-parts on multiple places
- Increasing maintainability by enabling better accessibility where maintenance actions are required

RQ2. Where should vibration sensors be installed to monitor the state of vital bearings in the project Smart Factories production line?
Despite the fact that vibration measurement sensors have advanced over the years, placement and selection of sensors are still of great importance in determining the success of any condition monitoring program. Research question two was answered by using knowledge gained through literature studies, interviews and company visits. The vibration sensor CMSS MT-1 was chosen for the project Smart Factories, advantages with this sensor are its physical characteristics, high resistance to electrical noise and that it meets CE and EMC requirements. The sensors are mounted as close to the bearings as possible, the lesser material between the sensor and bear-

ing gives better measurements. The signal from the sensor is transferred through a data-logger called IMx-8, to a central database, where it is later analyzed and future scenarios are predicted by algorithms that compare new and historical data and verifies that the measurements fall within known thresholds. Limits and rules enable PdM to alarm the maintenance personnel. The central database can be reached from all over the world and displayed on computers and mobile devices, allowing specialists to analyze and help the project Smart Factories with predictions.

RQ3. How can maintenance data be presented to support the maintenance employees decision making?
SKF Enlight is one of multiple available software designed to simplify maintenance. Enlight is used to store all maintenance information in one location: documentation, corrective actions, history data, user manuals, photos, notes etc. The program can be installed on a iOS tablet and thereby guide the maintenance personnel during maintenance rounds, text or pictures can be used to illustrate what action is needed and where it should be performed to solve various issues, thereby aiding in CBM. Enlight can also display real-time online readings from various sensors, making it easy to verify if the measurements are within the thresholds or if maintenance is required, thereby aiding in PdM.

6.1 Suggested future research

According to the delimitation in the project, the investment cost of the maintenance solutions has not been taken into considerations, but it is still very important and the authors recommend to make investigations in this area. The maintenance type should be selected with respect to models and tools that are used to determine appropriate maintenance investments, that solves the required maintenance at the best cost. There are models [Vaneker and van Diepen, 2007] that is used to make valid investment calculations for replacements and repairs. The importance of quantifying the right maintenance type should be connected to the required cost, but also possible savings, quality improvements, reduced downtimes etc. that is why different maintenance solutions and prices can not be compared without quantified maintenance specifications related to the cost.

Bibliography

Mahmood Adnan and Hushairi Zen. Ict convergence in internet of things - the birth of smart factories (a technical note). *International Journal of Computer Science and Information Security*, 14(4):93, 2016.

Ernnie I. Basri, Izatul Hamimi Abdul Razak, Hasnida Ab-Samat, and Shahrul Kamaruddin. Preventive maintenance (pm) planning: a review. *Journal of Quality in Maintenance Engineering*, 23(2):114, 2017.

Johan Bengtsson. Lyft teknikintresset hos unga med smarta fabriker, 2017. URL `http://www.nyteknik.se/opinion/lyft-teknikintresset-hos-unga-med-smarta-fabriker-6578000`.

Mats Bohgard, Stig Karlsson, Eva Lovén, Lars-Åke Mikaelsson, Lena Mårtensson, Anna-Lisa Osvalder, Linda Rose, and Pernilla Ulfvengren. *Arbete och teknik på människans villkor.* Prevent, Stockholm, 3. uppl. edition, 2015. ISBN 9789173651950;9173651958;.

Jon Bokrantz. *On the Transformation of Maintenance Organisations in Digitalised Manufacturing.* Licentiate thesis, Chalmers University of Technology, 2017.

Darren Currin. *Demographic shifts lead real estate industry issues.* 2015. ISBN 8750-4022.

Anoop Desai and Anil Mital. Design for maintenance: Basic concepts and review of literature. *International Journal of Product Development*, 3(1):77–121, 2006.

Verzijl Diederik, Dervojeda Kristina, Sjauw-Koen-Fa Jorn, and Nagtegaal Fabian. Buisness innovation observatory - smart factories. (Ares(2015)4620702 - 27/10/2015), 2014.

Mark Elliot, Ian Fairweather, Wendy K. Olsen, and Maria Pampaka. *A dictionary of social research methods.* Oxford University Press, Oxford, 2016. ISBN 0191816825;9780191816826;.

Kim R. Fowler. Appendix a - dependability calculations. In Kim R. Fowler, , and Craig L. Silver, editors, *Developing and Managing Embedded Systems and Products*, pages 793 – 800. Newnes, Oxford, 2015. ISBN 978-0-12-405879-8. doi: https://doi.org/10.1016/B978-0-12-405879-8.00034-9. URL `http://www.sciencedirect.com/science/article/pii/B9780124058798000349`.

L Freedman. Reading to write: About skimming and scanning, 2012. URL http://www.artsci.utoronto.ca/current/advising/ell/pdfs/Reading_to_Write_Skim_and_Scan.pdf.

Robert Harrison, Daniel Vera, and Bilal Ahmad. *Engineering the smart factory*, volume 29. 2016. ISBN 1000-9345.

International Electrotechnical Vocabulary. Iec 60050-192:2015, international electrotechnical vocabulary - part 192: Dependability, 2015a.

International Electrotechnical Vocabulary. Iec 60050-192:2015, international electrotechnical vocabulary - part 192: Dependability, 2015b.

Preeti Jain. 6-dof high accuracy orientation sensor for embedded applications, 2012. URL https://www.engineersgarage.com/articles/accelerometer.

Henning Kagermann, Johannes Helbig, Ariane Hellinger, and Wolfgang Wahlster. *Recommendations for implementing the strategic initiative IDUSTRIE 4.0*. Forschungsunion, Berlin, 1 edition, 2013.

Henrik Kihlman. *Virtual Robotics*. lecture notes, MPR213 Robotics and manufacturing automation, Chalmers University of Technology, delivered Mars 24, 2016.

Ebba Larter. Projekt Smarta Fabiker, year = 2017, url = http://www.smartafabriker.se/info/projektet, urldate = 2017-03-15.

Jay Lee, Chao Jin, and Behrad Bagheri. Cyber physical systems for predictive production systems. *Production Engineering*, 11(2):155–165, 2017.

Rui Liu and Raja R.A. Issa. Design for maintenance accessibility using bim tools. *Facilities*, 32(3/4):153–159, 2014.

Ministry of Innovation and Enterprise. Smart industry - a strategy for new industrialization for sweden, 2016. URL http://www.government.se/information-material/2016/04/smart-industry---a-strategy-for-new-industrialisation-for-sweden/.

R. K. Mobley. *An introduction to predictive maintenance*. Butterworth-Heinemann, Amsterdam;New York;, 2nd;2; edition, 2002. ISBN 9780750675314;0750675314;.

L. Monostori, B. Kádár, T. Bauernhansl, S. Kondoh, S. Kumara, G. Reinhart, O. Sauer, G. Schuh, W. Sihn, and K. Ueda. Cyber-physical systems in manufacturing. *CIRP Annals - Manufacturing Technology*, 65(2):621 – 641, 2016. ISSN 0007-8506. doi: http://dx.doi.org/10.1016/j.cirp.2016.06.005. URL http://www.sciencedirect.com/science/article/pii/S0007850616301974.

Neil Montgomery, Dragan Banjevic, and Andrew K. S. Jardine. Minor maintenance actions and their impact on diagnostic and prognostic cbm models. *Journal of Intelligent Manufacturing*, 23(2):303–311, 2012;2009;.

Paul Morland. *Demographic engineering: population strategies in ethnic conflict*. Ashgate Publishing Limited, Farnham, Surrey, England, new edition, 2014;2016;. ISBN 1472441648;9781472441645;.

Peter Muchiri, Liliane Pintelon, Ludo Gelders, and Harry Martin. Development of maintenance function performance measurement framework and indicators. *International Journal of Production Economics*, 131(1):295–302, 2011.

D.N.P. Murthy. *Springer Series in Reliability Engineering: Complex System Maintenance Handbook*. Springer London, 2008. ISBN 1848000103;9781848000100;.

Souad Nabdi and Brahim Herrou. Approach to assessment of maintainability in design. *International Journal of Performability Engineering*, 12(6):551–560, 2016.

Geoffrey Okogbaa and Wilkistar Otieno. *Design for Maintainability*. John Wiley Sons, Inc., 4 edition, 2015. ISBN 1118118995;9781118118993;.

G. Pahl, Ken Wallace, and Luciënne Blessing. *Engineering design: a systematic approach*. Springer, London, 3rd;third; edition, 2007. ISBN 1846283191;9781846283192;9781846283185;1846283183;.

Ralph. Peters. *Reliable maintenance planning, estimating, and scheduling*. Elsevier, Waltham, Maryland;Oxford, England;, 1 edition, 2015;2014;. ISBN 9780123970428;9780123982919;012398291X;0123970423;.

A. Raouf, Zulfiqar Ali, and S. O. Duffuaa. Evaluating a computerized maintenance management system. *International Journal of Operations Production Management*, 13(3):38–48, 1993.

Gunther Reinhart and Georg Wünsch. Economic application of virtual commissioning to mechatronic production systems. *Production Engineering*, 1(4):371–379, 2007.

Kenneth E Rizzo. Total production maintenance: A primer. *Oak Brook*, 46, 1999. ISSN 0895-1608. URL `http://proxy.lib.chalmers.se/login?url=http://search.proquest.com/docview/224362706?accountid=10041`.

R. Roy, R. Stark, K. Tracht, S. Takata, and M. Mori. Continuous maintenance and the future – foundations and technological challenges. *CIRP Annals - Manufacturing Technology*, 65(2):667 – 688, 2016. ISSN 0007-8506. doi: http://dx.doi.org/10.1016/j.cirp.2016.06.006. URL `http://www.sciencedirect.com/science/article/pii/S0007850616301986`.

Bernard Schmidt and Lihui Wang. Cloud-enhanced predictive maintenance. *The International Journal of Advanced Manufacturing Technology*, 2016.

SKF. Skf multilog on-line system imx-8, 2017. URL `http://www.skf.com/group/products/condition-monitoring/surveillance-systems/on-line-systems/skf-multilog-on-line-system-imx-8.html`.

Gregory P. Sullivan, Aldo P. Melendez, and Ray Pugh. Femp's om best practices guide a guide to achievingoperational efficiency. *Strategic Planning for Energy and the Environment*, 23(4):40–52, 2004.

Swedish Standards Institute. Maintenance terminology. (SS-EN 13306:2010), 2010.

Tom Vaneker and Tijmen van Diepen. The maintenance management framework. *Models and Methods for Complex Systems Maintenance*, 2007. ISSN 1614-7839.

Tom Vaneker and Tijmen van Diepen. Design support for maintenance tasks using triz. *Procedia CIRP*, 39:67 – 72, 2016. ISSN 2212-8271. doi: http://dx.doi.org/10.1016/j.procir.2016.01.167. URL `http://www.sciencedirect.com/science/article/pii/S2212827116001827`.

Lihui Wang and Robert X. Gao. *Condition monitoring and control for intelligent manufacturing.* Springer, London, 1. aufl.;1; edition, 2006. ISBN 9781846282683;9781846282690;1846282683;1846282691;.

E. Westkämper. *Towards the re-industrialization of Europe: a concept for manufacturing for 2030.* Springer, New York;Heidelberg;, 1;2014; edition, 2014;2013;. ISBN 9783642385025;3642385028;364238501X;9783642385018;.

MF. Zaeh, G. Wünsch, C. Poernbacher, and M Ehrenstrasse. Emerging virtual machine tools. *29th design automation conference, Chicago, Illinois*, pages p.513–518, 2003.

A

Appendix A

Appendix A is walking throw which comonents that are used in the project.

A.1 SKF Vibration sensor CMSS MT-1

The small size sensor is a low profile, bolt mounted sensor used for ease of location in inaccessible and guarded locations. To exclude noise from electrical transients, it uses a double-shielded integral cable. It can be used for Machine tool drives, Machine tool gearboxes and Machine tool carriages.

The sensor is featured with:

- For use with the SKF on-line system DMx, IMx and TMU
- Meets CE, EMC requirements
- High resistance to electrical noise
- Low profile, side exit, industrial accelerometer with captive bolt (M8 × 1,25, 33 mm (1.3 in.) length) provided
- Compact design ideal for mounting with limited space
- Corrosion resistant and hermetically sealed

A.2 Tachometer - IFS305

The tachometer is used to measure the rotation and the manufacture is IFM Electronics.

Function	Feature
Electrical design	*DC PNP*
Operating voltage [V]	*10...30 DC*
Current consumption [mA]	*< 20*
Protection class	*III*
Reverse polarity protection	*yes*
Outputs	
Output function	*normally open*
Voltage drop [V]	*< 2.5*
Current rating [mA]	*100*
Short-circuit protection	*yes*
Overload protection	*yes*
Switching frequency [Hz]	*2000*
Monitoring range	
Sensing range [mm]	*8*
Real sensing range (Sr) [mm]	*8 ± 10 percent*
Operating distance [mm]	*0...6.48*
Accuracy / deviations	
Hysteresis [Percent of Sr]	*3...15*
Switch-point drift [Percent of Sr]	*-10...10*
Environment	
Ambient temperature [°C]	*-40...85*
Protection	*IP 65 / IP 66 / IP 67 / IP 68 / IP 69K*
Max. electromagnetic field immunity [mT]	*300*

A.3 SKF Multilog On-line System IMx-8

SKF Multilog IMx-8 provides a complete system for early fault detection. Improve the reliability, availability and performance of your rotating equipment with automatic advice for correcting existing or impending conditions.

This compact device offers eight analogue and two digital channels, with connectivity to mobile devices as well as laptops for easy configuration and monitoring. Machine intelligence from IMx-8 data will help you avoid unplanned downtime and schedule maintenance proactively, prolonging machine availability and minimising maintenance and repair costs. IMx-8 integrates easily with other IMx units. It can connect you with the SKF Cloud for storing and sharing data, enabling SKF Remote Diagnostic Services for expert reporting and recommendations.

The IMx-8 is DIN rail mounted, and can be housed in an IP65 cabinet to provide additional protection in demanding industrial environments.

The key features are:

- 8 dynamic or DC inputs and 2 digital or speed inputs
- Simultaneous measurements of all channels, true synchronous measurements programmable up to 8 analogue channels
- PoE (power over ethernet), 24-48Vdc
- 4GB internal memory - capable of storing a year's worth of machine data and numerous event captures
- Adaptive alarm levels
- Data buffering in non-volatile memory when communication is down
- Stand-alone mode or compatible with SKF @ptitude Monitoring Suite
- Crash detection capability (machine tools)
- Improved ModBus capability (TCP/IP RS 485)
- Bluetooth configuration and data access in stand-alone mode via iOS Android device app
- SAT (Site acceptance test), and reports via iOS and Android device app
- DNV GL / ABS / Lloyds Marine type approval (pending approval)
- DNV GL Renewables Certifications (pending approval)

B
Appendix B

This section shows the installation of the vibration sensors in the roller die cutter, and the feeding of the roller die cutter.