On the development of a maintenance approach for factory of the future implementing Industry 4.0

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Licentiate Thesis

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Acknowledgement

The work of this thesis is conducted at the Mechanical Engineering Department, Linnaeus University in Växjö, Sweden.

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Abstract

The objective of this thesis is to develop a maintenance approach that fulfills the requirements of Industry 4.0. It explores the role and importance of maintenance activities in today’s industry. Then, it develops the features and tasks required to be performed by maintenance to fulfill the demands of Industry 4.0. Finally, it develops a reference model to be used in designing maintenance system for Industry 4.0. To perform these studies, real data were collected and applied as well as a typical scenario was implemented.

The results achieved in the papers of this thesis are 1) a mathematical representation and application of a model that identifies, analyses and prioritizes economic weakness in working areas related to production, 2) a model that analyses, identifies and prioritizes failures that impact the competitive advantages and profitability of companies, 3) characterization of a suitable maintenance technique for Industry 4.0 and 4) a reference model i.e. a framework, that could be utilized to develop a maintenance approach for Industry 4.0.

The conclusion of this thesis confirms that maintenance has a significant impact on companies’ competitive advantages, other working areas and profitability.

To achieve a suitable maintenance technique for Industry 4.0, this technique must be able to monitor, diagnose, prognosis, schedule, assist in execution and present the relevant information. In order to perform these tasks several features must be acquired, the most important features are to be: digitized, automated, intelligent, able to communicate with other systems for data gathering and monitoring, openness, detect deviation in the condition at an early stage, cost-effective, flexible for adding new CM techniques, provide accurate decisions and scalable. The developed framework could be used as a base to design a maintenance system for Industry 4.0. This study contributes to our understanding of the maintenance importance in today’s industry and how to develop a maintenance approach for Industry 4.0.

Keywords: cost-effective maintenance, failure impact, Maintenance 4.0, maintenance for Industry 4.0, maintenance framework, prioritize failures
List of papers

**Paper I**  

Author’s contribution: Participated in initiating the idea, conducted literature survey and data collection, participated in analysis of the results, and participated in paper writing.

**Paper II**  

Author’s contribution: initiated the idea, conducted literature survey and data collection, participated in analysis of the results, paper writing.

**Paper III**  

Author’s contribution: Participated in initiating the idea, conducted literature survey and data collection, participated in analysis of the results, and participated in paper writing.

**Paper IV**  

Author’s contribution: initiated the idea, conducted literature survey and data collection, participated in analysis of the results, paper writing.
Explanation of terms

**Condition based maintenance**: Maintenance carried out to need as indicated by condition monitoring. (BS 3811:1993)

**Condition monitoring**: The continuous or periodic measurement and interpretation of data to indicate the condition of an item to determine the need for maintenance. (BS 3811:1993)

**Cost-effective maintenance**: A measure of how much the considered maintenance policy is economically beneficial in the long run. A dimensionless ratio is used to compare two situations before and after maintenance improvement. (Al-Najjar, 1997)

**Cyber-physical systems**: smart systems that encompass computational components (i.e. hardware and software) and physical components seamlessly integrated and closely interacting to sense the changing state of the real world. (IEC, 2015)

**Efficient maintenance**: Maintenance efficiency is assessed using the two quantities of effectiveness, the proportion of the expected number of failures avoided, and accuracy, the proportion of expected number of failures to expected number of removals. (Al-Najjar, 1997)

**Maintenance**: The combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function. (BS 3811:1993)

Alternative description is:

A means for monitoring and controlling deviations in a process condition and product quality, and for detecting failure causes and potential failures in order to interfere when it is possible to arrest or reduce machine deterioration rate before the product characteristics are intolerably affected and to perform the required actions to restore the considered part of a machine to as good as new. All these should be performed at a continuously reducing cost per unit of good quality. (Al-Najjar, 2007).
**Horizontal integration**: refers to the integration of the various IT systems used in the different stages of the manufacturing and business planning processes that involve an exchange of materials, energy and information both within a company (e.g. inbound logistics, production, outbound logistics, marketing) and between several different companies (value networks). The goal of this integration is to deliver an end-to-end solution. (Kagermann et al., 2013)

**Vertical integration**: refers to the integration of the various IT systems at the different hierarchical levels (e.g. the actuator and sensor, control, production management, manufacturing and execution and corporate planning levels) in order to deliver an end-to-end solution. (Kagermann et al., 2013)

**Industry 4.0**: a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industry 4.0, CPS monitor physical processes create a virtual copy of the physical world and make decentralized decisions. Over the IoT, CPS communicate and cooperate with each other and humans in real time. Via the IoS, both internal and cross-organizational services are offered and utilized by participants of the value chain. (Hermann et al., 2016)

**Software architecture**: is concerned with the selection of different abstract elements, as well as defining their interactions and rules to achieve a system’s goals. (Perry & Wolf, 1992)
Abbreviations

CA : Competitive advantages
CBM : Condition based maintenance
CM : Condition monitoring
CPS : Cyber physical system
FBM : Failure based maintenance
HT : How’s importance
IoS : Internet of services
IoT : Internet of things
MAPE-K : Monitor, analyze, plan, execute - Knowledge
MADM : Multiple attribute decision making
MFD : Maintenance function deployment
OEE : Overall equipment effectiveness
OPE : Overall process effectiveness
PL : Priority list
PM : Preventive maintenance
RCM : Reliability centered maintenance
SAW : Simple additive weighting
TAC : Time-action-consequence
TPM : Total productive maintenance
TQMain : Total quality maintenance
WT : What’s importance
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1 Introduction

This chapter aims to explain the purpose of this research. First the background and the research problem are discussed to formulate the research questions. Next, the relevance, delimitations and structure of the thesis are presented.

1.1 Background

In today’s high market competition, industries attempt to adapt new technologies to fulfill customer needs and retain their market share. Industry has experienced earlier three revolutions during the past 200 years, driven by mechanization, electrical power and the electronics & Information technology (Kagermann et al. 2013; Drath & Horch 2014; Deloitte 2015). With the recent technology advance in Cyber Physical Systems (CPS), the Internet of Things (IoT) and the internet of Services (IoS), Germany has announced the term “Industrie 4.0”, i.e. Industry 4.0, as the 4th industrial revolution. This revolution is driven by the need of shorter time to market, customized mass production and increased efficiency (Helmrich 2015). Industry 4.0 is characterized by the vertical integration of systems at different hierarchical levels of the value creation chain and the business process, as well as, by the horizontal integration of several value networks within and across the factory. This is done through end-to-end engineering across the entire value chain (Kagermann et al. 2013; Hermann et al. 2016; Stock & Seliger 2016).

Hermann et al. (2016) defined Industry 4.0 as:

*a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industry 4.0, CPS monitor physical processes create a virtual copy of the physical world and make decentralized decisions. Over the IoT, CPS communicate and cooperate with each other and humans in real time. Via the IoS, both internal and cross-organizational services are offered and utilized by participants of the value chain. (p.11)*
Several advantages are expected from Industry 4.0. For example, the technologies of CPS, IoT, IoS and the networking allow the integration of data/information from different working areas/disciplines (e.g. sales, quality, production, production cost and price, risk management, environment, etc.) which facilitates the coordination among them and draw synergies. In addition, the utilization of available data by intelligent systems provides the ability to utilize the resources efficiently as well as the ability to customize even in small production quantities, and yet remains profitable. The different data sources in Industry 4.0 will make factories able to predict and respond rapidly to changes, e.g. in production, in delivery, due to failures, etc. and able to compensate temporary shortages. The flexibility in Industry 4.0 will result in a better working condition for the workers and better life-work balance. In Industry 4.0, new ways of services will be created and therefore, new business models and opportunities will appear (Kagermann et al. 2013). Several researchers proofed that maintenance plays a key role in companies’ sustainability (Al-Najjar 1997; Al-Najjar & Alsyouf 2004; Alsyouf 2004). So, to sustain Industry 4.0 and its expected benefits, maintenance should be considered properly. Maintenance is described traditionally as the combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function, (BS 3811:1993). Also, it has been described as a means for monitoring deviations in a process condition and product quality, in order to interfere when it is possible to arrest or reduce machine deterioration rate before the product characteristics are intolerably affected and to perform the required actions to restore the considered part of a machine to as good as new. All these should be performed at a continuously reducing cost per unit of good quality (Al-Najjar 2007).

1.2 Research Problem

Maintenance activities have an influence on company’s profitability and internal effectiveness, due to its importance and its impact on different working areas, such as quality, safety, production cost, working environment, delivery on time, etc. Thus, a proper and efficient maintenance not only increases the profitability, but it also improves the overall performance of the company (Waeyenbergh & Pintelon 2002; Al-Najjar 2003). In order to sustain the coming industrial technologies i.e. Industry 4.0, maintenance has to fulfill its demands. Therefore, this research investigates the development of a maintenance approach that meets the demands of Industry 4.0 and the factories of the future. The main problem addressed in this study is:

How to develop a suitable maintenance approach that fulfills the demands of factory of the future implementing Industry 4.0?
In this study, several technical aspects have been considered that characterize Industry 4.0, such as, digitalization, integration, automation, intelligence, etc. Maintenance has a considerable impact on profitability (Al-Najjar 1997; Al-Najjar & Alsyouf 2004; Alsyouf 2004). Therefore, beside technical aspects, the economic impact has also been considered in the research as well. That means, all of the maintenance work is performed cost-effectively, and consequently, contributes to the profitability of the company.

1.3 Purpose and research questions

The main purpose of this research is to investigate how to develop a suitable maintenance approach for Industry 4.0. To fulfill the research objective, the three following questions are investigated:

RQ1: What is the current role and importance of maintenance in achieving the competitive advantages and profitability of companies?

RQ2: What are the tasks required to be performed by maintenance to fulfill Industry 4.0 demands?

RQ3: How to design a maintenance approach that is suitable for factory of the future implementing Industry 4.0?

The studies presented in paper I and II attempt to answer the first research question. This question is concerned with the current situation of maintenance; answering this question helps to realize maintenance in its today’s context in maintaining and improving company competitive advantages and profitability. Also, it facilitates identifying maintenance tasks, needs and how to judge the proper maintenance. The second research question is investigated mainly by the paper III. This question is about identifying the features and tasks of maintenance that suit Industry 4.0. The answer to this question is essential in order to investigate the third question, which is studied in paper IV. This study deals with the design of a maintenance framework that suits Industry 4.0. See Figure 1.
1.4 Relevance

The relevance of this research comes from the fact that maintenance plays an important role to enhance production performance and companies’ profitability (Waeyenbergh & Pintelon 2002; Al-Najjar & Alsyouf 2003; Al-Najjar 2007). With the technology advancement in factories and increased complexity in the manufacturing machines, maintenance methods are developed in order to suit the new manufacturers’ demands. Now, with the Industry 4.0, new maintenance paradigm, innovative methods, tools and systems have to be developed to fulfill the new demands.

Industry 4.0 is a relatively new technology (Deloitte 2015; Qin et al. 2016) and therefore a little research is performed in the area of its maintenance, see section 2.2. The investigations presented in this thesis therefore provide knowledge that can be utilized by researchers and developers in both academic and industrial organizations.

1.5 Delimitation

This research includes investigation on the development of a maintenance approach for Industry 4.0 in general and not to a specific domain. However, the major focus in the verifications was limited to the mechanical components in rotating machines.

Figure 1 The relationship between the research questions and the papers
Since the transformation to Industry 4.0 is still under way and not fully realized (Deloitte 2015; Qin et al. 2016), the study is relying on what is achieved in the literature related to Industry 4.0, experience and knowledge. Although, the study deals with maintenance in general; some areas such as, scheduling techniques, mathematical and statistical analysis, etc. are not considered.

1.6 Structure of the thesis

Chapter 1 introduces the research by presenting the background, which illustrates the area of the research and leads to the research problem and questions. Then the relevance, delimitation and thesis structure are presented.

Chapter 2 reflects the methodological choices of the author and his scientific view of the study. Then, the reliability and validity control of the research are presented as well as the studies process.

Chapter 3 reviews and summarizes the related literature, in order to form the basis of this work.

Chapter 4 presents the interpretation and the analysis of the conducted studies and then discusses them in a united form.

In Chapter 5 the results and the contribution of the thesis are presented and then followed by the conclusion, work criticism and future work in Chapter 6. Finally, will be the references and the appended papers.
2 Literature Survey

This chapter reviews and summarizes the relevant literature in order to form the basis of this research.

2.1 Maintenance concepts development

The concept of maintenance has been developed to different levels over the last years due to the changes of the expectations and needs of industries. Different studies divide maintenance concepts developments into different stages (Moubray 1997; Al-Najjar 1997; Arunraj & Maiti 2007; Pintelon & Parodi-herz 2008; Jamshidi et al. 2014; Cooke 2003; Waeyenbergh & Pintelon 2002).

At first, equipment was simple and not highly mechanized, which made them reliable and easy to repair. This made the downtime to be an insignificant issue to the managers, so operation of equipment was kept running until the breakdown. At this stage, maintenance was nothing more than reaction i.e. replacement after failure (Al-Najjar 1997; Arunraj & Maiti 2007; Cooke 2003;). This covers the period up to World War II (Moubray 1997).

A second stage of maintenance concept developing was during the World War II. The high needs of different goods while shortening in the manpower triggered the increase of the mechanizations and complexity of machines. Downtime in this period earned more concern due to its increased cost, (Arunraj & Maiti 2007; Cooke 2003; Moubray 1997). A failure prevention concept has been provoked to reduce losses of downtime. The idea of this concept is to prevent failures, often by equipment service at fixed intervals. This concept leads to maintenance techniques (i.e. policies, strategies, methodologies and philosophies/concepts) such as age based maintenance as one of the policies belonging to preventative maintenance (PM) (Al-Najjar 1997; Arunraj & Maiti 2007). This helped to minimize the failures number. However, it still has some disadvantages such as unnecessary replacement of parts.

In the third stage, a growth of mechanization and the industrial complexity continued and new production concepts, such as Just In Time, were raised which increased the importance of maintenance. This leads to a new concept of detection of potential and hidden failures by the usage of real time data as in the case of using Condition Based Maintenance (Al-Najjar 1997; Arunraj & Maiti 2007).
In this stage the defective part is replaced once the monitored variables exceed the standard values. This method is useful as it reduces the unnecessary intervals and replacements in the PM policies. However, the unplanned but before failure (UPBFR) actions performed to prevent stoppages is still not avoidable (Al-Najjar 1997).

This was a major motivation for the fourth stage, which is detecting causes behind failures in order to have a better control on the machine life. With this concept, there is a possibility to eliminate or reduce failure development at an early stage. It has two working levels i.e. proactive and predictive maintenance. Proactive maintenance is defined as those actions that aim to detect and correct the causes of damage initiation such as, misuse, bad quality lubrication, faulty installations, etc. While predictive maintenance is involved in monitoring the symptomatic conditions, when the damage already under the process and could not prevented (Al-Najjar 1997; Al-Najjar 2008).

In addition to the above some researchers also state that another maintenance concept has been developed recently i.e. Risk Based Maintenance (Arunraj & Maiti 2007; Jamshidi et al. 2014). This concept aims to reduce the risk associated with the unexpected failures by planning the maintenance basing on quantified assessed risk. Parts with higher risk impact due to failures are maintained with more frequent inspections and maintenance to reduce the total risk in order to reach tolerable risk criteria.

2.2 On digitized maintenance approaches

Industry 4.0 is characterized by the digital integration of different systems as described in Chapter 1. Several researches discussed digitized maintenance approaches. In Sankavaram et al. (2013) An integrated diagnostic and prognostic framework for Cyber Physical System is proposed. The process involves offline design and online implementation. In the offline design, first the failure modes of the hardware, software, communication and hardware-software interaction are identified. Then fault simulated and compared with the fault-free systems output in different operation states. Subsequently, designing the tests (monitoring mechanism) is performed to distinguish faults from the free fault output. Finally, through fault simulation the fault-test dependency graph model is extracted. In the online implementation phase, the data are captured and transformed for the fault detection then to inference algorithm that infers the health status. This process is applied into two automotive systems using software simulation. In the first system, i.e. Regenerative Braking System, the result showed 97.06% classification accuracy. In the second system, Electric Power Generation and Storage the accuracy were 97.4%.

Singh et al. (2014) discussed the self-maintenance concepts and its need especially in certain industries; where in the event of failure there is no possible economical way to access the site, e.g. offshore wind turbine. Also, elements of
Self Maintenance like data acquisition system, distributed system architecture, smart sensors and wireless networks were discussed. Labib (2006) stated that preventive and predictive maintenance are not sufficient for achieving near-zero breakdown due to the stoppage when performing offline maintenance, where the self-maintenance considers the online adaptive and responsive approaches. Also, features of self-maintenance are presented as well as a model that utilizes an adaptive artificial neuro fuzzy inference system (ANFIS) in order to work in dynamic environment. The availability problem of the offshore wind farm due to the inaccessibility is discussed in Echavarria et al. (2007). Also, a design methodology through function redundancy and reconfiguration of components or sub-systems is introduced, to increase the availability of the offshore windfarms. This methodology is based on Model Based Reasoner (MBR) and Functional Redundancy Designer (FRD) tools which are based on the self-maintenance system. These tools are utilizing the Functional Behavior State (FBS) model. Karray et al. (2011) stated that self-maintenance must ensure high level of knowledge acquisition, elicitation, reasoning, and reuse. Using a method from the software engineering, i.e. Component Based System, maintenance architecture with the respect to the self-maintenance characteristics was designed. The designing approach contains two phases. The first is the pre-analyzing phase, i.e. to find the interesting component that must be in the system, where these components are defined by their functionality and not by their technical specification. In the second phase the relations among the components are defined. The core of the architecture contains four software layers i.e. interface, mediator, components and ontology. The system architecture has been validated by simulating sequential scenario diagram and a multiagent system. Shimomura et al. (1995) stated that Self Maintenance Machine (SMM) should monitor, diagnose and judge its state of health, make a plan that maintain at least some of its required function and then execute the plan. They applied the Self-maintenance concept on a prototype of a photocopier machine. It was designed using sensors and actuators that are controlled to maintain the function even with lower performance.

Lee et al. (2011) summarize the prognostic health management tools for common critical mechanical components along with their possible failure modes. It is stated that the main barriers to predict the reliability of a complex system are:

1) The inability to anticipate the unknown faults in the complex system, where many different subcomponents and subsystems contribute for the overall system function,
2) The difficulties to sustain the system functionality and performance in the presence of anomalies, especially with the multiple operating regimes and varying conditions and
3) The inability of self-adjustment to reduce the internal faults or external disturbances.
Also, a discussion is presented about the concepts of Self-maintenance and Engineering Immune System (EIS). It is stated that Self-maintenance machine can monitor and diagnose itself and in case of failure or degradation, it can maintain its functions for a while by trading off functions. The EIS is robust in diverse and dynamic environment, adaptability to learn and respond to new damages, adaptability to retain memory to assist future responses, and autonomy for Self-controlled ability with no requirement of external control. However, the limitation of the EIS from the author’s viewpoint:

1) EIS assumes the availability of a good health assessment and prognostic system,
2) It requires huge amounts of data and strong data mining tools as well as human skills. This will be challenging and not always feasible.
3) The implementation phase will contain modelling and re-programming of controllers that might not be acceptable by engineers who will apply the system.

So building trust in the system will be a challenge.

The above studies are not specific for Industry 4.0, but they cover some aspects of what might be important for Industry 4.0, such as digitization, autonomous and Self-healing, intelligence, etc. Some studies discussed maintenance approaches for Industry 4.0. In Lee et al. (2014), a framework is proposed for Self-aware and Self-maintained machines that includes the concepts of Cyber-Physical-System (CPS) and decision support system. The framework is applied on a case study to demonstrate its feasibility. Bagheri et al. (2015) presented a framework 5C that integrates CPS in Industry 4.0 environment and analytical methodology using clustering technique to predict the failures in machines. However, all of these studies do not cover all of the steps required to make a complete maintenance action (e.g. data collection, diagnose, prognosis and predict, decision making, scheduling and planning, etc.)

2.3 Failure Impact on the profitability and competitive advantages

Failures in the operative levels have impact on companies’ profitability as well as it is competitive advantages. Several models have been developed to identify, analyze, prioritize and estimate the impact of failures on companies. For example, Al-Najjar (2011) presented a model named Maintenance Function Deployment (MFD). It aims to pinpoint, analyze, and prioritize causes behind losses in the working areas belonging to the competitive advantages, such as losses due to bad quality and delayed deliveries. MFD breaks down these losses in a backwards method to approach the root-causes behind the losses which are usually spread in the operative level of different disciplines in a production process. MFD also provides business based production analysis. This is done
through quantifying losses (in production time and economy), in accordance with the strategic goals of the company, and identifying causes behind them. Then it breaks down the causes and its costs into their root causes. The author used an example to test the model, and the results showed that the model could be used to identify, analyze and quantify losses in order to make cost effective improving decisions.

In Al-Najjar & Jacobsson (2013), a model that demonstrates the interactions between man-machine-maintenance-economy (MMME) was developed, in order to support cost-effective decisions. The model systematically gathers, categorizes, estimates and quantifies the losses in the production time due to failures in order to identify and prioritize the problem areas in the production process. A software program then was built based on the model, and it was tested in a case study at the automaker FIAT, Italy. The results of the case study showed a possibility to identify the problematic areas. Also, as the model compares the time loss in different time periods, it captures the deviations over time for different categories.

Mohideen et al. (2011) presented a model that aims to reduce the breakdown costs and recovering time in construction plant systems. It starts by categorizing and analyzing the breakdown records in order to identify the main breakdowns and the sub-breakdowns using cause effect analysis, and then ranking them using Pareto analysis. The model was tested by a case study on four types of machines in a construction company using four years’ breakdown records. Major contributing failures and their causes were identified and a strategical plan is proposed accordingly. The survey showed that the impact of failures -in particular- on the companies’ competitive advantages is not payed the proper attention.
3 Methodology

This chapter discusses the scientific view of the research, validity and reliability, and then the process of each study.

3.1 The scientific view of the research

This thesis is composed of four papers that answer three research questions. In Table 1 the scientific design of the papers is shown. The papers arrangement is done according to the logical argument of the thesis.

Table 1: scientific view of the studies

<table>
<thead>
<tr>
<th>Paper No.</th>
<th>Methodological approach</th>
<th>Research design</th>
<th>Methods</th>
<th>Data collection source</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>System approach</td>
<td>Exploratory/</td>
<td>Case study/ Artefact</td>
<td>Interviews, Observations, Documents and related literatures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>explanatory</td>
<td>building</td>
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<tr>
<td>II</td>
<td>System approach</td>
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<td>Artefact building</td>
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<tr>
<td>IV</td>
<td>System approach</td>
<td>Explanatory</td>
<td>Artefact building</td>
<td>Related literatures</td>
</tr>
</tbody>
</table>

According Arbnor & Bjerke (1997), knowledge can be acquired by using three methodological approaches, named analytical approach, actors approach and system approach. The system approach considers the reality to be objective, and that by the arrangement of the system components as well as their
interaction, they acquire new properties. The author of this thesis views maintenance as a subsystem of a system, which is a company. It influences and is influenced by other subsystems of the company such as production, human resources, logistics, etc. Therefore, the dominant methodological approach used in the papers is the system approach.

The research design is the plan of how to link the research question to the conclusion. Based on the type of the research question, the research nature and its method vary. Generally, if the research question is based on “What”, “Where” or “Who” then this is likely to be a new study object that aims for exploration and understanding i.e. exploratory. On the other hand, if the study is based on “How” and “Why” then it is more likely to be an explanation of study object i.e. explanatory, see (Yin 2009). Based on the research question and the researcher’s view, several research methods such as case study, survey, experiments or others could be used. In this thesis, the first and second studies aimed to investigate the applicability of theoretical frameworks in real context in order to explain phenomenon. It also, aimed to increase the knowledge of the author about the field in the real working domain. Therefore, both of the studies were exploratory and explanatory. They mainly used case study method and primary data. The third study was exploratory as well as explanatory and it was part of an artefact building for the forth study i.e. investigating the requirements of a new maintenance technique for a new industrial technology. The forth study was explanatory basing on previous acquired knowledge to design a maintenance framework.

The main data sources used in the studies include interviews, observation during case studies, technical documents and academic literature. All of the collected data was primary data, with exception to some data from technical documents (machines’ operation manuals) in the case studies of paper I and II.

For each study, a literature survey was made in order to investigate whether the problem addressed in each study has been treated before. Generally, a similar process was done through all of the four studies. Four main stages to execute the literature survey have been used: First, basing on each study topic, relevant keywords that represent the entire study aspects were formed. These keywords were utilized in different combinations and thesauruses. The survey was Boolean based and conducted in the One-Search engine, which is linked to different databases, among them: IEEE, Springer Link, Emerald and Science Direct. The inclusion criteria were as follow: full-text available, English language, peer reviewed, academic journals, conference materials and book chapters. Next, the duplication and the unrelated subjects, e.g. public health, social comparison, etc. were removed. Then, the selection from the resultant articles was based on the relation of the abstract and the conclusion contents to the study in concern.
3.2 Validity and reliability

Research should be conducted and designed in a way that answers the research question. Generally, the most common terms to judge a research quality are validity and reliability (Rastegari 2015). Validity describes what variable is measured and if it is suitable to the research question, while, reliability describes how the measurements are conducted and the precision of the analysis. According to Yin (2009), the criteria to evaluate a research quality are the construct validity, internal validity, external validity and reliability.

Construct validity is concerned with the level of conformity between the theory of the research study and the observed results. Internal validity describes to what extent the research findings match results. External validity indicates the extent to which the findings of a study can be generalized. Reliability describes the repeatability of the research findings (Yin 2009).

Several studies suggested possible tactics to increase these criteria (Rowley 2000; Yin 2009). The studies in this thesis followed several tactics to strengthen the quality of research such as multiple data sources and triangulation, analyzing the findings to ensure logical connection to the existing theory, the participation of several people with different background in the studies and describing the steps of the studies’ methodology clearly.

3.3 Studies’ process

Paper I was performed to develop a model to assess the failure impact on company’s competitive advantages (CA) and their profitability, and to test it empirically on a case company to investigate its applicability.

The case company was Auto CNC-Bearbetning i Emmaboda AB. It was selected based on being:
1) an industrial company that produces countable items, and
2) able to provide the required data.

The selected company is located in the Southern part of Sweden and specialized in producing small series of mechanical parts for water pumps and other industrial products. It has about 25 production stations. For simplicity, one production station was selected and one product, “sleeve”, which is a component for water pumps. The product is one of many other products. It was selected based on the criteria of being relatively expensive and produced in a relatively large quantity which makes it important for the company. This was done to enhance the engagement of the company in the study.

The process was as follow: First, we reviewed the related literatures, identified the gap and developed the model. Next, we collected real data from a case company and applied the model. Then, after the analysis of the results we drew conclusion. To strengthen the reliability and the validity, the data were collected from several sources and then compared. The data collection was done through several semi-structured interviews, document analysis, several
discussions with the co-author and company personal, on-site visits and observations. The collected data and conclusions presented in paper II were also used to compare and strengthen the validity and reliability of this study.

Paper II aims to investigate the applicability of the Maintenance Function Deployment model using real industrial data. The model was developed in 2011 at Linnaeus University basing on the concept of Total Quality Maintenance (TQMain). A mathematical representation of the model was developed in this study. Then real data were collected from the same company, production station and product as in paper I. To limit the scope and for data availability reasons, only the working areas of maintenance, operation and quality were considered. To strengthen the reliability and the validity, the data were collected from several different sources as in paper I. These data were analysed and compared to the MFD model output.

In paper III the objective was to identify the tasks and develop the features of a suitable maintenance technique for Industry 4.0; this maintenance technique is called Maintenance 4.0. Also, it aims to investigate the suitability of some of the popular maintenance techniques to the Industry 4.0 demands. The study process was as follow: First, we analyzed, discussed and classified the most popular maintenance techniques (strategies, policies, philosophies and methodologies). Then, we reviewed the Industry 4.0 related literature and developed the tasks required by Maintenance 4.0. Next, we analyzed these tasks to extract the information required for developing the required features of Maintenance 4.0. Finally, we examined and compared the suitability of some of the used maintenance techniques for Industry 4.0 demands. This done by using Multiple Attribute Decision Making (MADM) combined with the Simple Additive Weight (SAW). The maintenance techniques were considered as alternatives and the introduced features were considered as examination criteria. The performance of each alternative against each criterion was assessed using linguistic values. The assessment of the values was performed using Al-Najjar’s long experience in the industry and maintenance technology and the existed literature. Then the potential uncertainty of the results was considered by discussing the possible dramatically variation in the assessed values.

Paper IV aimed to design a Maintenance 4.0 framework using Self-Adaptive Software Architecture. To achieve this, first, we analyzed the tasks that should be performed by Maintenance 4.0 in order to identify the necessary subcomponents. Next, we located these subcomponents within a framework of self-adaptive software architecture. Then, we zoomed-in to design and coordinate the mechanisms among the components and sub-components. At the end, the framework was tested in an operational scenario to verify the concept.
4 On the development of Maintenance 4.0

In this chapter, the four studies of this thesis are presented in a unified form that attempts to answer the research questions.

In order to develop a maintenance approach for Industry 4.0, it is important to understand the situation, significance and role of maintenance in today’s industry. Therefore, in this chapter, first, we will discuss the current situation of maintenance and its importance. Next, we will discuss the need of new maintenance for Industry 4.0, its tasks and features. Finally, a framework for Maintenance 4.0 basing on the previous findings is proposed.

4.1 Maintenance situation and its role in today’s industry

Several researchers showed that industries are not using their equipment to the full of their extent (Ljungberg 1998; Ahlmann 2002; Almström & Kinnander 2007; Ylipää et al. 2017). For example, Ylipää et al. (2017) performed a study on Swedish manufacturing companies for the period between the year 2006 and 2012, and the results showed that Overall Equipment Effectiveness (OEE) was about 51.5%. Almström & Kinnander (2007) conducted a study at 11 Swedish companies, the results showed that the average value of OEE is about 66%. Therefore, these results show that it might be possible to improve the production capacity if a proper maintenance is implemented to prevent disturbances instead of purchasing a new machine (Alsyouf 2001), which could be an expensive solution in many cases.

It is unusual that a deteriorated or bad condition machine can produce high quality products at low prices with high overall equipment effectiveness (OEE) (Al-Najjar 1997). This is because failures and other disturbances increase the stoppage time as well as lower the production quality, which consequently leads to increase in the production cost and reduce the profitability (Maletic et al. 2014). As shown in paper I and II, problems in the operative level usually have
several different consequences on the competitive advantages/strategic goals. For example, a failure in a production machine could have different impacts on the company’s competitive advantages, such as lower quality, higher production costs, production delay, etc. This, at the end, will negatively impact the profitability, see Figure 2. Therefore, to enhance the profitability a proper maintenance should be implemented.

![Figure 2 Failures impact on the advantages and profitability](image)

The internal effectiveness in companies is also influenced by the maintenance due to its impact on other working areas such as production, quality, working environment, amount of work in progress and tied up capital (Al-Najjar 2007). Therefore, a proper and efficient maintenance increases the
profitability as well as the overall performance of the company (Waeyenbergh & Pintelon 2002).

To understand the importance of maintenance activities, paper I and II investigate methods that systematically show how the problems and failures occurred in the operative level impact the goals in the strategic level.

The study in paper I presents a model that aims to analyze, identify and prioritize failures according to their significance and impact on the company’s competitive advantages in order to plan and conduct cost-effective maintenance (summarized in next section). Paper II applies MFD which helps in analyzing, identifying and prioritizing problematic working areas in production using an economic parameter as an indicator (summarized in section 4.1.2).

4.1.1 Failure impact on companies’ competitive advantages and profitability

In factories, recorded breakdown data are very useful to enhance the production process. Special management systems and techniques are used to classify failures and losses into predetermined categories (Al-Najjar & Jacobsson 2013; Ahamed Mohideen et al. 2011; Villacourt & Drive 1992; Al-Najjar 2011). The categorization helps engineers and management to determine the breakdown that occurs most often in each category in order to improve the related procedures. This may help eliminating the breakdown of multiple machines in the related category (Villacourt & Govil 1993).

Failures could be defined according to different factors, such as failure impact on: production cost, product quality, operation safety or reason of correction action (Villacourt & Govil 1993). However, these failure classifications are not sufficient to determine the failure impact on the competitive advantages of companies. Therefore, the developed model, named CA-Failures, aims to determine the impact of failures on a company’s competitive advantages using the failure database available in the company.

The competitive advantages that are considered can be summarized as follow:

- High product quality
- On time delivery
- Competitive price
- Low violation of environment
- Maintain good assets condition, i.e. asset value.

In order to determine the impact of each failure in the company’s database, it is crucial to analyze it with respect to the competitive advantages of the company. When a failure is analyzed, it will be possible to realize its impact on the competitive advantages. The prioritization of failures can be done through
summing the impacts of every failure on the competitive advantages and applying Pareto diagram.

A Pareto diagram is a statistical chart that highlights the highest factors that impact a particular effect among other factors by showing the frequent number of occurrence and the accumulative percentage. Its concept is about 20% of the causes produce about 80% of the outcomes. In this study, it is used to identify and prioritize the significant minority out of the insignificant majority of the failures.

The suggestions of the most profitable maintenance actions for the prioritized failures can be done through comparing the economic losses of these failures with their maintenance expenses. This way, it will be possible to conduct cost-effective maintenance through prioritizing the most profitable maintenance actions.

The steps of CA-Failures model are illustrated in Figure 3 and can be summarized as follow:

1. Utilizing the failures’ categories and database, existing in a company, the impact of failures on each competitive advantage is assessed. For example, the impact of the machines’ cutting tools failure could be high on the product quality (due to less accuracy in technical specification), on the delivery on time (due to high rejected items and reproduction), on the competitive price (due to the increased production cost), on the machines condition and could be lower on the environment.

2. Estimating the economic loss -due to each failure- per each competitive advantage. For example, the failure due to the cutting tools could cause 30% of the losses due to bad quality, 15% due to delivery delay, 5% due to lower profit margin, 1% due to worse machine condition and 0% for the environment regulation adaptation. Then, summing the impact of failures category.

3. Prioritizing the failures due to their significance. This can be done through summing the impacts of every failure on the competitive advantages and applying Pareto diagram.

4. Calculating the required maintenance investments to prevent the reoccurrence of failures.

5. Suggesting the most profitable maintenance actions through comparing the economic losses with the maintenance expenses.

This way, it will be possible to conduct cost-effective maintenance through prioritizing the most profitable maintenance action (for more details about the model, see paper I).

The major results of the empirical study in paper I can be summarized as follow:
• The model will support the decision maker to customize a maintenance plan that suits the company’s special situation. This is done by structurally analyzing the failure database to identify and prioritize the failures that affect the company the most.

• The results showed that most of the losses were caused by stoppages and disturbances. These losses were about 71.3%. Failures caused by Gear, Raw material quality and Bearing caused about 27%, 26% and 25% of the losses respectively.

• As in paper II, the results showed agreement with Pareto principal 80/20, that the highest loss is mostly generated by few causes, while the rest of the losses are distributed among the rest of the causes. Therefore, identifying the causes of the highest losses and prioritizing them is important to allocate the resources properly and achieve efficiency in maintenance.

This model will assist users to understand the mechanisms of failure impact on the competitive advantages and to prioritize failures with the highest impact on the company’s competitive advantages. Also, it suggests making a cost effective maintenance plan for the prioritized failures. In general, it may seem difficult to apply this model in today’s companies as the breakdown databases, in many cases, contain a huge number of failures. In this case, representative samples of failures could be collected in order to simplify the process and obtain results that can be generalized on the company under study.
Figure 3 Model (CA-Failures) operative flows
4.1.2 Identifying and prioritizing problematic working areas

In paper II, a mathematical form is developed for the MFD model. The MFD model was developed at Linnaeus University (Al-Najjar 2011) based on TQM. MFD consists of matrices of specific objectives i.e. What’s (W) and attributes i.e. How’s (H) to maintains the What’s. The MFD matrices break down the economic losses in a backwards direction in phases to reach the root-causes of losses.

In the MFD matrixes, see Table 1, the value $V_{mn}$ describes the share value of $H_n$ (How’s) ($n = 1, 2, 3, ... j$) in causing the loses of $W_m$ (What’s) ($m = 1, 2, 3, ... i$).

Then applying a summation of $V_{mn}$ for each What’s and How’s to get a collective value for the What’s importance ($WT_m$) and How’s importance ($HT_n$), see equations (1) and (2).

$$WT_m = \sum_{n=1}^{j} V_{mn}$$ (1)

$$HT_n = \sum_{m=1}^{i} V_{mn}$$ (2)

<table>
<thead>
<tr>
<th>How’s (H) i.e. How to achieve the objectives</th>
<th>Importance of What’s (WT$_m$ %)</th>
<th>Priority list (PL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_1$ ... $H_n$ ... $H_j$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>What’s (W) i.e. What are the objectives to be achieved</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_1$ ... $W_m$</td>
<td>$V_{i1}$ ... $V_{im}$ ... $V_{ij}$</td>
<td></td>
</tr>
<tr>
<td>$W_m$ ... $W_{ijn}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{m1}$ ... $V_{mn}$ ... $V_{mj}$</td>
<td></td>
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<tr>
<td>$V_{ij}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Importance of How’s (HT$_n$ %)</td>
<td></td>
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</tr>
</tbody>
</table>

Priority list (PL) then can be formed by ranking the What’s importance as follow: $P_1st \geq P_2nd \geq P_3rd \geq ... Pi$. Where $P_1st$ is the most important What’s (the highest $WT$) and $Pi$ is the least important (the lowest $WT$). For more details on the MFD steps, see paper II.
The MFD model in paper II is tested using real data and the major results of the MFD empirical study can be summarized as follow:

- The study showed the applicability of the MFD model, and its possible benefits. The MFD model will assist the user to analyze, quantify, pinpoint, and prioritize the economic losses and their causes in the production of the company.
- It shows how different activities affect each other as well as the company’s profitability.
- The results show the importance of maintenance on the company profitability, where the main objective of maintenance is to reduce failures occurrence and their impact. They also indicate the importance of the planning and considering maintenance integration with the rest of the plants activities. This was identified by using MFD model as well as by analyzing the operation process.
- In general, the results of this study showed agreement with the Pareto principal 80/20. The highest loss of sharing is mostly generated by few causes (one or at maximum two How’s), while the rest of the losses are distributed among the rest of the How’s. Therefore, prioritizing failures with higher impacts is required to enhance the efficiency of maintenance, as discussed in paper I and II.

This model will help to realize the impact of problems in the operation level on other working areas. The study in paper II concluded that better maintenance functions can maximize the productivity and enhance the quality, for more details see paper II.

In the models of paper I and II, the accurate assessment of the economic impact on companies might be difficult, as in many cases there is a lack of related data. However, Industry 4.0 is characterized by data accessibility and the integration of different systems. So, there will be mass amounts of data (Lee et al. 2015) and if the required data are properly defined, then by using suitable algorithms, more accurate results could be obtainable.

The models in paper I and II could be used in companies, regardless of the maintenance techniques being used as long as the relevant data are available. In general, relevant data availability is a very important factor for a proper maintenance. An effective maintenance technique should include all of the essential elements of production, since failures may occur due to causes from different working areas (e.g. production machines, operators, maintenance staff, raw materials, etc.). Therefore, the author of this thesis views maintenance as realized by TQMain; TQMain aims to maintain the quality of the elements.
(working areas) constituting the production process (and not only the machines) cost effectively (Sherwin & Al-Najjar 1999; Al-Najjar 2007).

Next section will briefly describe the importance of relevant data for Maintenance 4.0 and then classify some of the current popular maintenance techniques.

### 4.1.3 Maintenance techniques classifications

In Industry 4.0 enormous data mass from different production elements over the network will be generated. This could provide tremendous value to maintenance if the data are utilized properly (Lee et al. 2015). Hence, data coverage as well as its utilization are very important factors for Maintenance 4.0. As the relevant gathered information increases, also the capability of a particular technique increases.

Basing on data coverage and its utilization, maintenance techniques could be classified into three classes (for more details see paper III):

*Class I*, maintenance techniques which are able to utilize relevant real-time data from different relevant working areas e.g. financial, quality, operation and etc. An example of Class 1 is TQMain.

*Class II*, maintenance techniques which are able to utilize only technical data and information related to the producing machine. However, as all of the data gathered in this class are technical, therefore the outcomes that are not technical-related are not expected. Examples of the maintenance techniques under this category are total productive maintenance (TPM), reliability centered maintenance (RCM), condition based maintenance (CBM) and preventive maintenance (PM).

*Class III*, maintenance techniques that are not using any data, for example FBM, i.e. nothing is done before a failure is occurred.

For Maintenance 4.0, there are also other aspects than data coverage and utilization that should be considered. These aspects make the above mentioned maintenance techniques not yet sufficient and require development as shown in paper III. Next section shows these aspects and the requirements of a suitable maintenance for Industry 4.0.

### 4.2 The need of a new maintenance technique for Industry 4.0

It is well known that maintenance plays an important role to enhance production performance (Waeyenbergh & Pintelon 2002; Al-Najjar & Alsyouf 2003; Al-
Therefore, with the recent trend of Industry 4.0 and increased complexity in the manufacturing machines, new maintenance methods are required to be developed in order to suit the new manufacturers’ demands. But to develop a maintenance approach for Industry 4.0, it is essential to identify its tasks and features first, which is the second research question. Therefore, next section discusses these tasks and features (paper II). Then section 4.3 will propose a framework for Maintenance 4.0 (paper IV).

### 4.2.1 Tasks and Features of Maintenance 4.0

The objectives of Industry 4.0 are driven by the need of shorter time to market, customized mass production and increased efficiency (Helmrich 2015). In order to sustain the success of Industry 4.0; Maintenance 4.0 should have the following objectives (Al-Najjar 2015):

- Rapid responsiveness to meet the dynamic and rapid changes in the operating conditions and surroundings
- Maintain quality of machines at low cost, which makes maintenance and production processes more profitable, and
- Achieve high quality performance of producing machines

In order to achieve a maintenance technique that fulfils the needs of Industry 4.0, this technique should be able to perform several tasks. These tasks are summarized as follow (for more details see paper III):

- It should be able to monitor the asset as well as the elements related to the production process.
- In case of deviations in the condition of assets and production process Maintenance 4.0 should be able to detect it.
- Diagnose, prognosis and prediction abilities are essential in order to identify and localize the causes and damages, estimate damage severity and follow up its development, predict its future development and also assess the asset remaining life.
- The most profitable time to perform maintenance actions should be suggested, with consideration to the resources and competence availabilities.
- Specific maintenance actions should be performed automatically to achieve self-healing assets. In the case that the automatic actions are impossible because of lack of the required technologies, Maintenance 4.0 should be able to assist the maintenance execution, e.g. to provide a detailed report to perform the maintenance action properly.
- It should be able to learn from past data to continuously improve and optimize maintenance decisions and actions.
- Maintenance 4.0 should be able to present relevant information in a meaningful way, for example, maintenance work progress, etc.
To perform the above tasks several features should be existing. The most important features for Maintenance 4.0 are: to be digitalized, automated, intelligent, able to communicate with other systems for data gathering and monitoring, openness, detect deviation in the condition at an early stage, cost-effective, flexible for adding new CM techniques, provide accurate decisions and to be scalable (see paper III). Therefore, applying the study result means that there are well defined developments that are needed in order to achieve Maintenance 4.0. However, as the transformation to Industry 4.0 is still under way (Deloitte 2015; Qin et al. 2016), therefore, to confirm and develop the presented features and tasks, engaging the end-users might be useful to know their expectations.

In the next section, the above findings are utilized to design a Maintenance 4.0 framework.

### 4.3 Framework for Maintenance 4.0

In paper IV we developed a Maintenance 4.0 framework based on 1) previous study in paper III, 2) the experience in maintenance and software architecture and 3) on the concepts found in the related literature (Kramer & Magee 2007; Kephart & Chess 2003; Oreizy et al. 1998; Weyns & Iftikhar 2016; Karray et al. 2011; Garlan et al. 2004; Guillén et al. 2016).

To perform the required tasks of Maintenance 4.0 all of the necessary elements, whether software or hardware, should be considered, such as sensors, actuators, network, processors, middleware, databases, software and applications. The software based architectural approach provides the right level of abstraction and generality to facilitate the designing and the modeling of such a system. Several researches discuss the benefits of this approach (Gil De La Iglesia & Weyns 2015; Garlan et al. 2004; Oreizy et al. 1998; Kramer & Magee 2007).

In paper IV, self-adaptive software architecture is used (Kephart & Chess 2003). This approach is used because of the following advantages:

- It provides a foundation for separation of concerns. This minimizes the components’ interdependency and therefore, simplifies the repair, modification and development.
- The architectural principal covers a wide range of domains. Each domain is associated with its specific architecture.
- It provides a level of abstraction that shifts the developer’s focus from the code-lines and algorithmic level to the important system-level compositions. This facilitates the system understanding and the
use in large complex systems (which might be the case in Industry 4.0).

- It is cost effective as it is based on an external control loop that could be reused by different systems. Developing an internal control system for each new system from scratch would be expensive.
- It is suitable for systems that respond to changes autonomously at run time.
- It is supported by modelling languages and notations to describe and reason about the structure and behavior of the system during the design and at runtime.

4.3.1 The proposed Maintenance 4.0 framework

In paper IV, the proposed framework is developed using the IBM’s self-adaptive based architecture MAPE-K (Monitor, Analyze, Plan, Execute-Knowledge) (Kephart & Chess 2003). This approach consists of a managed system and a managing system. The managing system contains a feedback loop that is concerned with the adaptation of the managed system state, while the managed system is concerned with the working domain (Iftikhar & Weyns 2014; Gil De La Iglesia & Weyns 2015).

In Paper IV we added a Mediator layer that allows several machines to be connected (i.e. Managed Systems) and mapped to the managing system in order to enhance the usability and the scalability. In Figure 4, the architectural layers are illustrated.

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Figure 4 Architectural layers
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The proposed framework, in Figure 4, is realized in the three- architectural-layers of Kramer & Magee (2007), see also Weyns & Iftikhar (2016). These layers are Change Management, Goal Manager and Managed System. The
Change Management layer is concerned with controlling the managed system using the MAPE-K loop according to the strategic goals provided by Goal Manager.

Typically, the adaptation process follows the structure MAPE-K (Kephart & Chess 2003) that represents: Monitor, Analyze, Plan, and Execute, which are all connected to Knowledge repository. The Knowledge stores the gained data and information such as goals and models of the managed system (Gil De La Iglesia & Weyns 2015; Weyns & Iftikhar 2016).

In the MAPE-K loop, Monitor monitors the managed system and other relevant information (e.g. environment, operational parameters, etc.), updates Knowledge accordingly and triggers Analyzer. Analyzer analyzes the collected data and determines whether an adaptation process is required. If so, Plan is triggered to compose a plan with actions that return the managed system to its predefined state. These actions are then performed by Execute (Weyns et al. 2012; Iftikhar & Weyns 2014).

To tailor this generic framework to Maintenance 4.0, it is still required to specify the necessary subcomponents, the interaction among the components/subcomponents and their triggering conditions. To do this, in paper IV, we used a methodology which is based on three different methods used in (Mahmood & Lai 2006; Karray et al. 2011; Weyns & Iftikhar 2016). It consists of three phases as described in section 3.3, for more details, see paper IV. Figure 5 illustrates the final framework after applying the methodology. The subcomponents in the figure are described as follow:

- Update Data: Collects relevant data, e.g. process data, CM (Condition Monitoring) of machines, etc. and update the Knowledge.
- Abnormality Detector: Detects abnormalities in the production process and asset health using relevant current and past data, e.g. CM, process data, performance history, peer machine data, KPI, etc.
- Diagnosis: Identifies abnormality causes using data from the Abnormality Detector and other relevant data e.g. performance history, peer machine data, etc.
- Predictor & Prognosis: Describes the potential deterioration behavior of a component in the near future as well as the abnormality development in time. The inputs are information from Diagnosis, current knowledge and experience concerning the deterioration process as well as relevant current and past data to machine condition e.g. CM, performance history, peer machine data, etc.
- Severity Evaluator: Evaluates and ranks the impact of an abnormality on the Managed System and company goals. Inputs come from Diagnosis, Predictor & Prognosis and other information to assess the impact e.g. safety, cost, etc.

- Health Evaluator: Evaluates the health state of the Managed System when the severity assessed by Severity Evaluator exceeds a predetermined level. The healthy state, i.e. the state when there is no damage/problem, is usually announced as a default state. The evaluation based on the configuration of the system should be visualized for the end-user. The input comes from Severity Evaluator and other relevant data e.g. deterioration rates, CM, performance history, etc.

- Possible TACs (Time-Action-Consequence): To select the most cost-effective/convenient plan (i.e. its consequences are aligned the most with the strategic goals), all the alternative plans with their consequences must be known. Possible TACs generates all the alternatives and their potential consequences, i.e. the alternative times (T) to make the action (A) and estimates their consequences (C). The inputs are relevant data from the Knowledge e.g. schedules of production, maintenance personal and spare parts availability, economic data, etc.

- TAC Selector: Ranks and then selects the best TAC whose consequences are aligned most with the strategic goals. This is done by using data from Possible TACs and the goals set by the Goal Manager.

- Plan Constructor: Construct detailed instructions and adaptation steps that need to be performed by the Executor.

- Update: If the Goal Manager inserts new strategic goals to the system, Update imposes them properly in order to avoid errors and conflict.

- User Interface: Provides the end users access to the Managing System in order to change goals or for other usages.
To validate the framework, a concrete scenario was created. Figure 6 illustrates the scenario using activity diagram. The results of the framework performance in the scenario can be summarized as follow:

- The framework showed a flow that provides all of the necessary information to the users and performs the required task. No conflict or illogical behavior among the components and subcomponents was identified.
The performance, generally, showed a high interdependency, i.e. the majority of the components/subcomponents trigger the next. This could negatively influence the redundancy of the components/subcomponents and therefore it should be considered during the design.

The components and subcomponents in general have a great dependency on knowledge to perform their tasks. This emphasizes the importance of common database and data accessibility as promoted by the maintenance concept of Total Quality Maintenance in Al-Najjar (1996). These results strengthen the findings in paper III which highlight the importance of the data accessibility.

Figure 6 the scenario implementing using activity diagram

As in Industry 4.0 machines will be connected, therefore, peer comparison of machines could be used to forecast and enhance the prediction of a machine’s behavior and damage development. A machine learning approach e.g.
clustering technique (Bagheri et al. 2015) could be used to cluster machines having similar technical parameters in Knowledge. Then, by selecting the closest cluster (in term of technical parameters) to a machine under investigation, it would be possible to expect similar behavior.

Other studies of digitized maintenance approaches do not cover all of the maintenance actions as discussed in section 2.2. The novelty of this study that it develops a framework to design a maintenance approach that considers all of the elements necessary for a complete maintenance action in Industry 4.0. The study in paper IV shows that the proposed framework provides a guideline to start with and simplifies the designing of Maintenance 4.0. For more details, see paper IV.
5 Research results and thesis contribution

In this chapter, the main results and then thesis contribution are presented.

5.1 Research results

- A model (CA-Failures) that structurally analyzes the failure database to identify and prioritize the failures that affect the company’s competitive advantages and its profitability the most. It will support the decision maker to customize a maintenance plan that is cost effective and suits the company’s special situation. Published in paper I.

- A mathematical representation of the Maintenance Function Deployment model is developed. MFD model structurally analyses the working areas related to production in order to identify economic weakness and prioritize them, published in paper II.

- Developing of tasks required to be performed by maintenance in order to fulfill the demands of Industry 4.0. Also developing the features that this maintenance approach should attain. Furthermore, a methodology to compare maintenance approaches or techniques abilities to fulfill the demands of Industry 4.0, introduced and discussed in paper III.

- A framework for Maintenance 4.0 using self-adaptive software architectural approach that facilitates its designing. Published in paper IV.

5.2 Thesis contribution

The findings of this thesis add new knowledge to the area of industrial and maintenance engineering. These findings hold potential usefulness to academic and industrial applications, for example, describing the link between competitive advantages and failures, the tasks and features of maintenance in
order to be suitable for Industry 4.0, as well as, the framework to develop this maintenance technique. Also, this study provides managerial tools to identify and prioritize problems to enhance companies’ performance and profitability.

This thesis also confirms existed knowledge. The results of the case studies showed that proper maintenance activities have an important role in enhancing companies’ performances.
6 Conclusion and future work

This chapter draws the conclusion gained from the results of this thesis, followed by a criticism and then suggestions of future work.

6.1 Conclusions

This research is based on the research problem discussed in Chapter 1. The aim of this thesis was to investigate maintenance approach that suits the Industry 4.0. Three research questions were formed and four studies were performed to answer these questions. The following is the research questions with a brief description on how they were answered in the research thesis.

RQ1: What is the current roles and importance of maintenance in achieving the competitive advantages and profitability of companies?

Two case studies were performed in paper I and II to answer this question. MFD model was applied in a case study to investigate how working areas impact each other, the competitive advantages and profitability. CA-Failures model was developed and then applied in a case study to investigate how failures in particular impact the competitive advantages and profitability. MFD identifies and prioritize problem areas with high economic loss, while CA-Failure identifies failures that impact the competitive advantages and profitability the most. CA- Failures model also considers constructing a cost effective plan in its application. These studies confirm the importance of maintenance in companies and show how a proper maintenance activities influence positively the profitability and performance of companies.

RQ2: What are the tasks required to be performed by maintenance to fulfill Industry 4.0 demands?

This research question was formulated to identify the maintenance needs of Industry 4.0. From paper III, the major conclusions are; that a suitable maintenance technique must be able to monitor, diagnosis, prognosis, schedule, assist in execution and present relevant data. In order to perform these tasks
several features must be acquired, the most important features are to be; digitized, automated, intelligent, able to communicate with other systems for data gathering and monitoring, openness, detect deviation in the condition at an early stage, cost-effective, flexible for adding new CM techniques, provide accurate decisions and scalable.

**RQ3: How to design a maintenance approach that is suitable for Industry 4.0?**

The third research question was formulated to investigate developing a guideline or a structure that could be used to develop a maintenance approach that is suitable for Industry 4.0. In paper IV, a framework was proposed that is developed basing on self-adaptive software architecture. This framework designed using the findings of paper III. The framework was tested in a scenario and the results showed that this framework can be used as a base for further development of Maintenance 4.0.

### 6.2 Thesis criticism

There is always space for improvement in any work and this work is not an exception. The below is pointing some work in the thesis that could be improved:

- In the first research question, the obtained results from paper I and II, which are the losses values for some failure and problems were not available in the company’s database, and therefore after analyzing them they were estimated based on company’s personal experience. This could have some level of subjectivity. However, the observations made at the site, the analysis of the operation process, and the theories in the literature did not show illogical connections.

- To provide a better answer to the second research question, the opinion of the end-users should be considered in the development of Maintenance 4.0 tasks (paper III). This is to validate or improve them; however, this could be a work for a future research.

- In paper III, the values given to the maintenance techniques against the features could have some level of subjectivity as they are based on human assessments although an expert personal. However, we tried to reduce this, by providing a discussion section to reveal the decision; also we tried to support it by some references and scenarios. Furthermore, in the results, we provided sensitivity analysis to strengthen our findings.
• We tested Maintenance 4.0 framework only in one operational scenario and it was not real data. The framework should be validated in several scenarios and with real data. However, this is left for a future work.

6.3 Future work

Several potential areas were identified for further research; these areas were not investigated due to limited time frame. Some of these are as follow:

• The models of the CA-Failures and Maintenance Function Deployment could be computerized and applied in more case studies.

• A tool, method or/and interview structure that reduces the subjectivity in the data collection of the CA-Failures or Maintenance Function Deployment model could be developed.

• A survey study that includes different companies, industries and cultures could be performed to identify the tasks and features of Maintenance 4.0.

• The components/subcomponents of the proposed Maintenance 4.0 framework could be further investigated, to be used in a real system

• The Maintenance 4.0 framework could be tested in a real scenario for further validation.
References


