This exam work has been carried out at the School of Engineering in Jönköping in the subject area of production systems. The work is a part of the Master of Science programme.

The authors take full responsibility for opinions, conclusions and findings presented.

Examiner: Carin Rösiö

Supervisor: Johan Karltun

Scope: 30 credits

Date: 2016-11-11
Abstract

As two emerging terms in industry field, “Industry 4.0” and “Cyber-Physical System” have attracted an increasing amount of attention from both researchers and manufactures. Available advanced technologies brought by these terms, offers possible solutions and improvements for future maintenance.

The purpose of the thesis is to identify how Industry 4.0 integrates with Cyber-Physical Systems regarding maintenance management and the requirements for companies to reach the ideal smart factory. Two researcher questions were studied to fulfill the purpose. Firstly, identifying the integration between Industry 4.0 and CPS regarding maintenance functions. Secondly, to investigate how such integration contribute to maintenance management in an ideal future factory.

Research methods adopted in the thesis include a case study and a literature review. The case study collected empirical data through semi-structured interviews, which offered general understanding of the current status of the case company regarding maintenance management, and focus groups, which produced more detailed and specific information regarding the research questions. Furthermore, the study of related documents at the case company enhanced the overall understanding of current concepts adopted in the maintenance department.

The findings from the case study cover various problems and difficulties exist in maintenance activities. These problems were further analyzed and categorized as part of them cannot be solved directly by technical innovations. A criterion list was proposed regarding the requirements to achieve the ultimate smart factory with a focus on maintenance management. Thereafter, a roadmap for developing a CPS-based maintenance management system is suggested.
Contents

1. Introduction ........................................................................................................................................... 6
   1.1 BACKGROUND ......................................................................................................................................... 6
   1.2 PROBLEM DESCRIPTION ............................................................................................................................. 6
   1.3 PURPOSE AND RESEARCH QUESTIONS ..................................................................................................... 7
   1.4 DELIMITATION ......................................................................................................................................... 7
   1.5 OUTLINE ................................................................................................................................................. 8

2  Theoretical background ................................................................................................................. 9
   2.1 INDUSTRY 4.0-THE FOURTH INDUSTRIAL REVOLUTION .................................................................. 10
       2.1.1 Internet of things & services ........................................................................................................... 11
       2.1.2 Smart manufacturing ....................................................................................................................... 14
       2.1.3 Vertical integration and networked manufacturing system ............................................................. 16
       2.1.4 Horizontal integration through networks ......................................................................................... 17
       2.1.5 End-to-end digital integration of engineering across the entire value chain .................................. 18
   2.2 CYBER-PHYSICAL SYSTEM ................................................................................................................... 19
       2.2.1 Definition of Cyber-Physical System ............................................................................................... 20
   2.3 THE ADOPTION OF CPS IN THE FACTORY ............................................................................................. 20
   2.4 OUTCOMES OF THE APPLICATION OF CPS ............................................................................................ 22
   2.5 MAINTENANCE ...................................................................................................................................... 24
       2.5.1 The Role Of Maintenance .................................................................................................................. 24
       2.5.2 Evolution of Maintenance Approach ............................................................................................... 27
       2.5.3 Comparison among various maintenance concepts ............................................................................. 29
   2.6 HTO MODEL ......................................................................................................................................... 29

3  Method and implementation ......................................................................................................... 31
   3.1 RESEARCH METHOD ............................................................................................................................. 31
       3.1.1 Literature Review ............................................................................................................................... 31
       3.1.2 Case study ....................................................................................................................................... 33
       3.1.3 Choice of methodological instruments .............................................................................................. 34
   3.2 RESEARCH PROCESS .......................................................................................................................... 35
       3.2.1 Orientation Study ............................................................................................................................... 35
       3.2.2 Main study ....................................................................................................................................... 36
   3.3 SUMMARY ............................................................................................................................................ 37
1. Introduction

In this chapter, the background and problem description, the aim of research as well as research questions, and the delimitation of the research are discussed. The introduction closes with an outline to guide the reader through the thesis.

1.1 Background

Globalization enables companies to serve global customers with various demands while facing challenges from foreign competitors at the same time. The increasingly mature and complex market has gradually shifted from sellers’ market to buyers’ market, which in turn creates a tendency that forces a transform on production philosophy from mass production to intelligent production (Brettel et al., 2014). Therefore, customization is regarded as a key strategy and market winner by most companies. Realizing customization comprise mainly two requirements for the company: a thorough understanding of different customers in the market and the ability to fulfill these demands while maintaining the economies of scale at the same time (Brettel et al., 2014). The former requirement can be achieved by segmenting markets through collecting feedback from customer, studying competitors’ actions, predicting demand uncertainty etc. (Johansen et al., 2012). The second requirement focuses more on the production side, for instance, managing trade-offs between different performance objectives as well as achieving the fit between production capability and market demands. Both requirements emphasize companies’ capability of collecting and managing massive information from both inside the company as well as the outside environment.

As one of the means to improve this required capability, the concept “Industry 4.0” was coined in a project of the German government in 2012, and it focuses on information management (Heiner et al., 2014). As the third industrial revolution, which brought computers into production systems, has dramatically changed almost all industries in terms of production, “Industry 4.0” that is called the fourth industrial revolution has unsurprisingly attracted an increasing amount of attention ever since the concept was created in 2012. Industry 4.0 is among other things based on Cyber-Physical Systems (CPS), which refers to the production system where sensors are installed in all physical things in order to connect the physical world with a virtual model (Mosterman et al., 2015). In accordance with this revolution, the use of sensors and networked machines is growing rapidly and has resulted in the continuous generation of high volume data which is known as Big Data (J.Lee, 2015).

1.2 Problem description

As a collective term, understanding “Industry 4.0” is almost impossible in a single case (Heiner et al., 2014). Although the term stems from the rapid development of CPS during last decade, it is crucial to notice that the fourth industrial revolution brings a different way of thinking in terms of the design and application of CPS. Moreover, in spite of overlaps between CPS and Industry 4.0, the term covers more concepts such as Smart Factory, Remote Control, Machine-To-Machine Communication etc. Since this research area is relatively young, knowledge gaps still exist regarding the design and application of CPS (Lee et al., 2014; Yen et al., 2014). Therefore, as the foundation of the fourth industrial revolution, analyzing the integration between CPS and Industry 4.0 is needed for developing a better understanding of the term Industry 4.0.

Furthermore, as it was discussed in the background, the shift in production objectives has resulted in the development and implementation of advanced manufacturing
strategies such as Just-In-Time (Suito, 1998). However, unreliable or inflexible equipment often hinders the implementation of these concepts, and limits benefits from these strategies (Tajiri and Gotoh, 1992). Hence, it is critical for companies to maintain a relatively stable production capability in an ever-changing environment. Realization of the stability of production is bound up intimately with a steady overall equipment efficiency (OEE), which relies largely on the execution of effective and efficient maintenance activities on equipment in production facilities (Ahmed, 2013). Therefore, the effectiveness and efficiency of maintenance function significantly contributes towards the overall business performance of a manufacturer (Macaulay, 1988; Teresko, 1992). Consequently, traditional reactive maintenance strategy can no longer satisfy the needs of manufacturers since it has disadvantage of unplanned stoppages, excessive damage and high trouble shooting problems (Telang, 1998). Accordingly, companies started to adapt more advanced maintenance strategies which provided higher level of equipment performance while required greater commitment in terms of resources and integration (Swanson, 2001). Among recent technologies, CPS is an ever-growing tool that provides real-time information and predictive capability for asset management. However, CPS is still in its immature stage and significant amount of effort and research is required to develop and implement CPS based methodologies (Lee & Bagheri, 2015). Taking the increasing emphasis on the success of maintenance process into account, identifying possible applications of CPS on maintenance activities in accordance with Industry 4.0 was interesting as a research subject.

This study was conducted in collaboration with an automotive glass manufacturing company. The unit of analysis was maintenance activity in the factory located in the headquarters of the company. The company had been facing increasing challenges from competitors in recent years. The board of the company believed that starting the fourth industrial revolution ahead of other competitors was the right way to regain market shares. As a part of the whole innovation project, the company aimed to study what advantage CPS brings especially for maintenance activities since problems existed in this area currently. For instance, some maintenance activities had considerably negative effects on the quality of products while several maintenance activities were resource-demanding and may not be necessary at all. Therefore, studying criteria of CPS and how it can contribute to maintenance activities was critical and beneficial for both theoretical knowledge and practical applications.

1.3 Purpose and research questions

The purpose of this thesis is to identify the integration between CPS and the “Industry 4.0” concept. Moreover, to analyze the possibility of applying CPS in maintenance activities in accordance with the fourth industrial revolution. This general purpose will be reflected in two research questions presented below.

RQ1: How do Cyber-Physical System integrate with Industry 4.0 concept regarding maintenance management?

RQ2: How can a CPS-based maintenance system be achieved in a manufacturing company under the Industry 4.0 concept?

1.4 Delimitation

This study was conducted in collaboration with an automotive glass manufacturing company as a part of an innovative project. The data was collected in only one case study in the factory which is located in the headquarter of the company. The study was limited to maintenance activities within Industry 4.0 concept while other areas of production systems was not discussed.
1.5 Outline

Chapter 2 provides the reader with necessary theoretical background for the study including key concepts and research streams in Industry 4.0, CPS and maintenance. Chapter 3 explores the research design of the study in order to make the research process repeatable for the reader, which leads to more convincing results. Chapter 4 presents the case study conducted in an automotive glass manufacturing company. It includes case description and findings from the case study as well as analysis for the findings. Chapter 5 incorporates the discussion and conclusion of the study. Two research questions are answered separately and method and findings are discussed afterwards. At last, the conclusion of the study is presented.
2 Theoretical background

As it was discussed in the background chapter, the study concerns CPS in Industry 4.0 research subject and the connection between CPS and maintenance activities. In the theoretical background, the reader would be acquainted with firstly the definition of Industry 4.0 and what this term actually means for current production. Thereafter, the development of CPS is explored and existing applications of CPS are introduced. Later on, the changing role of maintenance is discussed and the development of maintenance approaches is described. Finally, the integration between CPS and maintenance process is studied and the requirements of latest maintenance approach is related to the functions of CPS in order to answer the second research questions. The relationship among Industry 4.0, CPS and maintenance is illustrated in Figure 1.

![Figure 1. The “Industry 4.0 house”](image-url)
Theoretical background

2.1 Industry 4.0-The Fourth Industrial Revolution

The past three industrial revolutions were all triggered by technical innovation (Brettel et al., 2014). At the end of the 18th century, the first water and steam engine marked the beginning of the first industrial revolution. The late 19 century, the rise of electric energy was the springboard of the second industrial revolution and in 1870, the first assembly belt was used in the production line. In the middle of 20 century, electronics and information technology expanded which created the third industrial revolution. As for the fourth industrial revolution, it was triggered by the use of CPS which enables the information from all perspectives to be closely monitored and synchronized between the physical factory floor and the cyber-computational space. The term ‘Industry 4.0’ was coined by the Germany government after almost 20 years’ practices of utilization of CPS in the manufacturing industry. Nowadays, German industry has to withstand an increasing global competition on product quality and product costs (Brettel et al., 2014). Consequently, Industry 4.0 emerge as the time requires and is believed to be able to strengthen the German economy, intensify international cooperation and create new internet based markets (MacDougall, 2014). According to the further research of professor Kagermann et al. (2013), the strategy of industry 4.0 will allow Germany to stay a globally competitive high-wage country. Although the word “Industry 4.0” is frequently used to describe the changes of the industry, it is still used in different contexts and lacks an explicit definition (Brettel et al., 2014). For instance, several definitions of “Industry 4.0” in existing literature are illustrated as follows:

“Industry 4.0 is a resolution of high-wage countries to relieve the tension between economies of scale and scope as well as a planning and value orientation” (Brettel et al., 2014);

“The core of Industry 4.0 concept is as same as decentralized concept through the intelligent system and CPS to arrive at smart production, green production and urban production.” (Yen et al., 2014);

“The goal of the Industry 4.0 is the emergence of digital factories that are to be characterized by following features: smart networking, mobility, flexibility, integration of customers and new innovative business models.” (Jazdi, 2014).

“The core idea of Industry 4.0 is to use the emerging information technologies to implement IoT and services so that business process and engineering process are deeply integrated making production operate in a flexible, efficient, and green way with constantly high quality and low cost.” (Wang et al., 2016)

This rather chaotic situation was illustrated by the cluster analysis made by Brettel et al. (2014) in his article that presented related research streams of Industry 4.0 (Figure 2). More than 20 research topics were claimed by researchers to be included in the fourth industrial revolution and multiple articles were assigned with each stream.
In this thesis, the term “Industry 4.0” is studied with an emphasis on advanced maintenance strategies within today’s Big Data environment. Therefore, in following sections, two research streams that are directly related to maintenance management will be discussed.

2.1.1 Internet of things & services

As a popular concept, it has been almost impossible in last few years not to come across the term “Internet of things (IoT)” in one way or another (Wortmann & Fluchter, 2015). In 2012, the International Telecommunication Union (ITU) defines IoT as “a global infrastructure for the Information Society, enabling advanced services by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies”. The most prominent areas of application for IoT technologies include the smart industry, where the development of intelligent production systems and connected production facilities is often discussed under the heading of Industry 4.0 (Wortmann & Fluchter, 2015). To simplified it, Figure 3 illustrates the value creation of IoT to enhance the primary thing-based physical functions of a thing with additional IT-based digital services which can be accessed at a global level (Fleisch et al., 2014). For instance, the primary physical function of a bulb is to provide light on a local basis. The possible IT-based service of it might serve as a security system that can detect human presence and change the light mode accordingly. In other words, the IT-based digital functions allows a product to be intelligent and remote controlled according to the requirements of owners. Moreover, the functions of individual product may be further enhanced through the connection to
Theoretical background

related products and the whole product system (Wortmann & Fluchter, 2015). Furthermore, as it is claimed by Porter & Heppelmann (2014), through the IoT technologies, the combination of previously disparate product systems may lead to systems of systems which is capable of expanding existing industry boundaries and shake competitive dynamics.

![Figure 3. IoT-product-services logic (Fleisch et al., 2014)](image)

Despite of all the benefits of IoT, the implementation of IoT requires the integration of a range of information and communication technologies in the form of hardware and software (Wortmann & Fluchter, 2015). Such requirements are accordant with the development trend of Industry 4.0 to realize integration between networks through a better information flow. In 2010, Zuehlke proposed the automation pyramid as a part of the approach that is called “factory-of-things” in his paper (Figure 4). The model comprises four different levels: device-level, control-level, MES-level and ERP-level. The system cover the full range of components within the pyramid from sensors/actuators and programmable logic controllers (PLC) through manufacturing execution system to the enterprise resource planning (ERP) level software (Brettel et al., 2014). The information flow goes from signals collected in the device-level to the ERP systems via messages and finally presented through the user interface. This is a classic automation pyramid in most today’s factories, where manufacturers manage the production with the help of data in various ERP systems. However, the one-direction information flow which relies on messages has ignored the need of differentiated information in other levels beside the ERP-level. Therefore, as an important target of Industry 4.0, Figure 5 presents a improved version of the automation pyramid (Brettel et al., 2014).
Theoretical background

The new pyramid comprises the same four levels: sensor level, device level, control level and enterprise level. It differs from the classical automation pyramid in the pattern of communication and information flow. As prices of sensors have decreased significantly over the last years, sufficient data can be collected on the shop-floor level. Such data can be accessible throughout networks via the Internet and can thereby facilitate communication between different hierarchy levels (Brettel et al., 2014). Therefore, comparing to the classic automation pyramid, the communication within the networks is no longer limited to the traditional communication layers. Instead,
accessing and exchanging information in all levels is now possible with the help of IoT solutions.

As it is discussed above, IoT technologies enable products/devices to be accessed at a global level and thereby allow machines to be remote-controllable. Furthermore, by developing better communication systems via the internet, IoT solutions significantly enhance the accessibility and exchange of useful information in the production system, which lays a foundation for maintenance information systems.

2.1.2 Smart manufacturing

Despite of the advanced manufacturing strategies developed during last few decades, the current production paradigm is not sustainable (Alkaya et al., 2015). Furthermore, as the end users continuously require highly customized products in small batches, flexibility has become a key performance indicator of most companies. Therefore, multiple advanced manufacturing schemes such as the flexible manufacturing system (FMS) and the agile manufacturing system (AMS) have been developed by manufacturers in order to achieve high flexibility and efficiency at lower costs (Wang et al., 2016). Among these schemes, the multi-agent system (MAS) is the most representative one (Leitao, 2009), in which all manufacturing resources are defined as intelligent agents that cooperate with each other to achieve dynamic reconfiguration. However, the MAS schemes failed to handle complex production environment in an efficient way due to the lack of global coordination (Shen et al., 2006). Nowadays, with the initiation of Industry 4.0, MAS is enhanced with emerging technologies such as IoT, wireless sensor networks, cloud computing etc. (Wang et al., 2016), and gradually transform into a part of the concept “smart manufacturing”. The term smart manufacturing refers to a data-driven paradigm that facilitates the transmission and sharing of real-time information across networks with the aim of creating manufacturing intelligence in every aspect of the factory (Lee, 2013). To some extent, the objective of smart manufacturing is similar to traditional manufacturing and business intelligence as they both focus on transforming raw data to knowledge (Donovan et al., 2015). However, the smart manufacturing comprises an extreme emphasis on real-time collection, integration, and sharing of information across physical and virtual processes, to achieve a flawless stream of operation. As it is claimed by Donovan et al. (2015), the journey of smart manufacturing adoption can be divided into three sequential phases:

- **Phase 1- data integration and contextualization.** In this stage, factories evaluate all the available data from sensors, actuators, controllers to form a global and contextualized view of data in the factory.

- **Phase 2-simulation, modeling, and analytics.** After the first phase, the data can be processed and analyzed to be further transformed into useful information that can be used for decision making. Simulation models can be developed based on the integrated data in order to reach optimal production status.

- **Phase 3-process and product innovation.** As new insights may emerge from the result of data processing, innovations in production process and products will be inspired.

Although these phases seem achievable in theory, it is generally believed that the realization of smart manufacturing is simply too complex for any individual organization (Davis et al., 2012). In contrast, there are currently a number of government, academic and industry groups dedicated to develop smart manufacturing, such as the Smart Leadership Coalition (SMLC), Industry 4.0 and the Industrial
Internet Consortium (IIC). In spite of diverse terminology used in these initiatives, they share a common vision of real-time, digitized and data-driven smart factories that are based on sophisticated simulation models and data analytics to optimize performance (Donovan et al., 2015). As an important feature of Industry 4.0, smart factory addresses the vertical integration and networked manufacturing systems for smart production. To successfully implement smart factory, the combination of smart devices and big data analytics is vital (Wang et al., 2016). The intelligent devices are capable of dynamically reconfigure whereas the analytics provide global feedback and information management. This enables machines, conveyors, and products to communicate and negotiate with each other to adapt themselves for flexible and efficient production of diverse products (Wang et al., 2016). Consequently, self-optimization is achieved based on distributed self-decision making and self-reconfigure devices. Table 1 represents the differences between a today’s factory and the smart factory (Lee et al., 2014a).

Table 1. Comparison of today’s factory and an Industry factory (Lee et al., 2014a).

<table>
<thead>
<tr>
<th></th>
<th>Today’s Factory</th>
<th>Industry 4.0 Factory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Data source</td>
<td>Key attributes</td>
</tr>
<tr>
<td></td>
<td>Key technologies</td>
<td>Key attributes</td>
</tr>
<tr>
<td>Component</td>
<td>Sensor</td>
<td>Precision</td>
</tr>
<tr>
<td></td>
<td>Sensors and Fault detection</td>
<td>Self-Aware</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine</td>
<td>Controller</td>
<td>Availability&amp; Performance (Quality and throughput)</td>
</tr>
<tr>
<td></td>
<td>Condition-based monitoring &amp; Diagnostics</td>
<td>Self-Aware</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production System</td>
<td>Networked Manufacturing system</td>
<td>Productivity&amp; OEE</td>
</tr>
<tr>
<td></td>
<td>Lean operations</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In today’s factory, the data is mainly utilized for understanding current condition and detect faults. In system level, various tools are employed to provide overall equipment effectiveness (OEE) information to factory management, which in turn helps to eliminate wastes and achieve lean production. In contrast, “Industry 4.0 factory” enables components and machines to gain self-awareness and self-predictiveness. At system level, an Industry 4.0 factory is able to self-configure, self-maintain, and self-organize so that the whole production system is worry-free and the optimal performance can be reached. For a machine or system, self-awareness refers to the ability of self-assessing its current or past condition at any time, and react to the
assessment result via self-configure (Lee et al., 2014b). Furthermore, as abundant information is provided via the internet, smart devices are able to conduct peer-to-peer comparison among the fleet of similar devices. Such a comparison increase the predictability of potential failures, which in turn support the decision-making for just-in-time maintenance to gain nearly zero downtime (Lee et al., 2014a). Under the concept of Industry 4.0, the companies will be transformed into integrated networks with the capabilities of self-awareness, self-prediction, self-comparison, self-configuration and self-maintenance (Lee et al., 2014a).

2.1.3 Vertical integration and networked manufacturing system

The setting for vertical integration is the factory (Kagermann et al., 2013). A factory owns several physical and informational subsystems, such as actuators and sensors, control and production management, manufacturing, and corporate planning (Wang et al., 2016). Vertical integration refers to the integration of the various IT systems at the different hierarchical levels in order to deliver an end-to-end solution (Kagermann et al., 2013) (see figure 6). It uses CPS to enable plants to react rapidly to changes in demand or stock levels and faults. In turn, the factory has to be designed to allow adoption of CPS. Hence, concrete structures and specification of production processes in the factory are replaced by configuration rules, from which case-specific topologies can be derived automatically (Brettel et al., 2014). As a consequence, with the application of the vertical integration, the concept "smart factory" emerges. A smart factory provides significant real-time quality, time, resource and cost advantages in comparison with classic production systems (MacDougall, 2014). These advantages are achieved through the flexible network of CPS-based production system which, to a large extent, automatically oversee production processes (MacDougall, 2014). With the CPS based vertical integration, the production process can achieve dynamic reallocation of production schedule according to discrepancies in prices, amendments to orders, fluctuations in quality and so on which optimize the process structure and make the production process more flexible (Du & Yang, 2015). As a consequence, the production systems are characterized by a strong needs-oriented, individualized and customer-specific production operation (Schlaefer & Koch, 2014).

In a smart factory, all processing stages are logged, with discrepancies registered automatically (Schlaefer & Koch, 2014). Additionally, CPS as the central hub for data and fleet management provides peer-to-peer health evaluation and components fusion based prediction methods where all of these applications are supposed to increase asset up time and relatively increase productivity and service quality (Lee & Bagheri, 2015). Schlaefer & Koch (2014) explained that the internet of things allows even more predictive maintenance with the condition monitoring, which offers real added value for customers.
2.1.4 Horizontal integration through networks

In the field of production and automation engineering and IT, 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) (see figure 7) (Kagermann et al., 2013). These new value creation networks are real-time optimized networks that enable integrated transparency and offer a high level of flexibility (Schlaefer & Koch, 2014).

To maintain global competitive advantages, companies have to focus on their core competencies while outsourcing other activities to collaborators in the network. (Christopher, 2000). The organization in networks multiplies the capabilities without the need of further investments (Brettel et al., 2014). According to Christopher (2000), being able to leverage competencies of network partners in order to respond to market needs can lead to sustainable advantages. In an increasing complex world, groundbreaking innovations are often only possible by involving a variety of companies (Geisshauer et al., 2015). In the meanwhile, this kind of horizontal integration can generate transparency since comparative information as well as individual machine status is available. Hence, decision on priority of tasks to optimize the maintaining process can be made easier. On the other hand, new business modes and new models for cooperation will emerge due to the reason that new business models can only be developed when several companies contribute their respective complementary competencies (Geisshauer et al., 2015).

To exploit the flexibility potential of collaborations, the supply chain has to be designed to allow adaptation of routes and schedules (Brettel et al., 2014). In the context of supply chain management, agility goes hand in hand with the ability to track commodity flows but also data concerning delivery reliability and customer satisfaction (Moch et al., 2012). Hence, similar to networked production systems, horizontal networks provide networking via CPS which creates transparency and flexibility across the entire process chains from purchasing through production to sales. (Schlaefer & Koch, 2014).
2.1.5 End-to-end digital integration of engineering across the entire value chain

End-to-end digital integration refers to a holistic digital engineering view, and proposes to close the gap between product design and development, through production planning, production engineering, production and associated services (Posada et al., 2015). End-to-end integration focus on the value creation throughout the entire product life cycle. With end-to-end integration, all the participating entities can be supplied with access to real-time information and control is distributed to the shopfloor level (Brettel et al., 2014). Hence, this integrated engineering along the value chain using advanced methods of communication and virtualization promises significant optimization. A central issue of Industry 4.0 is how business processes including engineering workflows and services can be integrated end-to-end using CPS (Kagermann et al., 2013). To implement the end-to-end integration, the entire value creation process should be mapped, from customer requirements, through product architecture to production (Posada et al., 2015). The aim here is full digitization and thus a virtual portrayal of the real-world. The main requirement is to create possibilities of modeling in order to be able to master the increasing complexity of the technical systems (Horvath et al., 2015). Therefore, the appropriate support from CPS should be provided throughout the entire value chain, from product development to manufacturing system engineering, production and service (Schlaefer & Koch, 2014).

In traditional production systems, IT support systems exchange information via a variety of interfaces, but can only use this information with regard to specific individual cases (figure 8) (Kagermann et al., 2013). The customer can only choose from a predefined range of products specified by the manufacturers. In contrast, with the end-to-end integration, the production systems will cover every aspect from customer requirements to product architecture and manufacture of the finished product (Kagermann et al., 2013). This enables all the interdependencies to be identified and depicted (Kagermann et al., 2013). As the result, it will allow customers to combine their desired product themselves from individual components and functions instead of having to depend on the product portfolio defined by the manufacturer (Horvath et al., 2015).
According to Kagermann et al. (2013), Industry 4.0 can serve to create horizontal value networks at a strategic level, provide end-to-end integration across the entire value chain of the business process level, including engineering, and enable vertically integrated and networked design of manufacturing systems. The horizontal integration of corporations and the vertical integration of factory inside are two bases of for the end-to-end integration of engineering process due to the reasons that product lifecycle comprises several stages that should perform (Wang et al., 2016). The relationship of the three integration can be illustrated as Figure 9.

These features are the key enablers for manufacturers to achieve a stable position in the face of highly volatile markets whilst flexibly adapting their value creation activities in response to changing market requirements (Kagermann et al., 2013).

2.2 Cyber-Physical System

CPS provide the basis for the creation of the Internet of things, which combines with the internet of services to make industry 4.0 possible. In the future, businesses will establish global networks that incorporate their machinery, warehousing systems and production facilities in the shape of CPS (Kagermann et al., 2013). In this section, the authors will introduce the definition of it and due to the reason that this thesis is about the industry 4.0, the application of CPS in the factory will be specified.
2.2.1 Definition of Cyber-Physical System

Cyber-Physical System is defined as transformative technologies for managing interconnected systems between its physical assets and computational capabilities (Baheti & Gill, 2011). Cyber-Physical Systems are enabling technologies which bring the virtual and physical worlds together to create a truly networked world in which intelligent objects communicate and interact with each other (MacDougall, 2014). Such systems that bridge the cyber world of computing and communication with the physical world. (Raj et al., 2010). According to J.Lee (2015), CPS is about the intersection, not the union of the physical and the cyber. It combines engineering model and methods from mechanical, environmental, civil, electrical, bio-medical, chemical, aeronautical, and industrial engineering with models and methods of computer science (Lee et al., 2014a). In a CPS, operations are monitored, coordinated, controlled and integrated by a computing and communication core (Raj et al., 2010). That is, CPS perceive the physical world, process the data by computers and affect and change the physical world (Hu et al., 2012). Just as how internet changes how human interact with each other, CPS change how human interact and control the physical world. Application of CPS include automotive systems, manufacturing, medical devices, military systems, assisted living, traffic control and safety, process control, power generation and distribution, energy conservation, HVAC, aircraft, instrumentation, water management systems, trains, physical security, asset management, and distributed robotics (E. A. Lee, 2015).

According to Yen et al. (2014), the basic components of CPS consist of cloud platforms, embedded systems and sensor networks and no matter how people deal with CPS, they cannot break away from these basic components. In accordance with this theory, Ray et al. (2010) describes CPS as a confluence of embedded systems, real-time systems, distributed sensor systems and controls. According to Sobhrajan et al. (2014), CPS is characterized with some features. These are: 1) cross-domain sensor source and data flows; 2) embedded and mobile sensing Therefore, the promise of CPS is pushed by several recent trends: the proliferation of low-cost and increased-capability sensors of increasingly smaller form factor; the availability of low-cost, low-power, high capacity, small form-factor computing devices; the wireless communication revolution; abundant internet bandwidth; continuing improvements in energy capacity, alternative energy sources and energy harvesting (Raj et al., 2010).

2.3 The adoption of CPS in the factory

In the manufacturing systems, these CPS comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently (Kagermann et al., 2013). However, CPS is still in the initial stage of development. Hence, there is no unified framework or general architecture of CPS can be used in most applications. In the early age, CPS had a two-tier structure inherently, the physical part and computing part (Hu et al., 2012). According to Hu et al. (2012), the physical parts of CPS sense the physical environment, collect data, and execute the decisions made by the computing part and the computing parts analyze and process the data from the physical part, and then make decisions. With the development of CPS, some more specific framework emerged. Here a general framework will be used to illustrate this system first to help understand the system.
According to Wang et al. (2010), the general workflow of CPS can be categorized into four main steps (see Figure 10):

**Monitoring**: Monitoring of physical processes and environment is a fundamental function of CPS. It is also used to give feedback on any past actions which are taken by the CPS and ensure correct operations in the future.

**Networking**: This step deals with the data aggregation, diffusion.

**Computing**: This step is for reasoning and analyzing the data collected during monitoring to check whether the physical process satisfies certain predefined criteria.

**Actuation**: This step executes the actions determined during the computing phase.

In this figure, Y, Z, U, V presents the data acquisition from sensors, the physical data aggregation in-network, the valid computed result of the physical system states which could advise controller to select valid command and the control commands send to the actuators respectively.

With this framework, it is easy to understand that even though the cyber world and physical world are essentially different, they can be connected and affect each other by information. In accordance with Wang’s four-step theory (2010) about CPS which introduced above, the framework of CPS in the factory consists of four tangible layers, namely, physical resource layer, industrial network layer, cloud layer, and supervision and control terminal layer (Figure 11). According to Wang et al. (2016), the four layers can be described as below:

**Physical resource layer**: It comprises various kinds of physical artifacts such as smart products, smart machines, smart products and smart conveyors.

**Industrial layer**: It forms a kind of important infrastructure that not only enables inter-artifact communication but also connects the physical layer with the cloud layer.
Theoretical background

Cloud layer: The term cloud is a vivid expression for a network of servers that provides layered services in the form of Infrastructure-as-a-service, Platform-as-a-service.

Supervision and control terminal layer: With the terminals such as PCs, tablets and mobile phones, people can access the statistics provided by the cloud, apply a different configuration, or perform maintenance and diagnosis, even remotely through the internet.

According to Schuh et al. (2014), the physical resources are implemented as smart things which communicate with each other through the industrial network and various information systems exist in the cloud which can collect massive data from the physical resource layer and interact with people through the terminals.

With these four layers in the framework, the guideline for manufacturing application is needed to coordinate different layers. Lee’s 5C theory can be seen as a guideline which connect the four elements in the four-layer theory. This structure will be further explored and explained in the discussion chapter.

2.4 Outcomes of the application of CPS

According to MacDougall (2014), the deployment of CPS in production systems gives birth to the smart factory which is a significant concept under the industry 4.0 project. As the setting for vertical integration in the context of Industry 4.0, the vertical integration means implementing the smart factory that is highly flexible and re-configurable (Wang et al., 2016). The factory is responsible for actually processing raw materials and semi-finished products to produce finished products. Within the boundary of a factory, various physical or informational subsystems are involved during production and management (Wang et al., 2016). Traditional organizations are often structured into a hierarchy of function units. As the consequence, problems that occur at the interface boundaries are often given less priority than the short-term outcomes of the units (Coorie, 2004). At present, the information flow is often blocked between subsystems and the continuity and consistency are generally difficult to be guaranteed and the material flow is along the fixed production lines that lack flexibility (Wang et al., 2016).
The adoption of smart factory can improve this situation significantly. As the smart factory leverage the web of information from interconnected systems to perform highly efficiently, agilely, and flexible, the overall framework can be divided into three major sections which are components, machines, and production systems (Lee, 2013). Each of these items can bring us different levels of understanding and transparency of the factory (Lee et al., 2014b).

The smart factory exhibits an attractive and promising production paradigm which leads to many advantages which can deal with the global challenges in the sense that customized and small-lot products can be produced effectively, efficiently and profitably. It presents a production revolution in terms of both innovation and cost and time saving and the creation model whose networking capacity creates new and more market opportunities (MacDougall, 2014). Here, the authors list some of the advantages over conventional manufacturing and production (MacDougall, 2014).

1. Transparency

According to Chen et al. (2013), the big data provides real-time, complete, and effective information on every aspect of the smart factory. According to Lee et al. (2014a), due to the reason that in contrast with visible issues, invisible issues might happen due to machine degradation, component wear and etc. while operators and factory managers are not aware of them, factory wide transparency is one of the most important targets of future factory. The adoption of CPS in the factory can bring transparency to the factory which enables us to quantify performance indicators related to machines, products and systems (Wang et al., 2016).

2. Friendly to staff

According to MacDougall (2014), the smart factory can provide tailored adjustments to the human workforce so that the machine adapts to the human work cycle. In addition to this, with the assistance of big data analytics, powerful software tools, and more friendly and flexible interface measures, maintenance and diagnosis become easier (Wang et al., 2016). Mobile devices such as smart phones and tablets have already made inroads in the industrial automation (Jazdi, 2014). This means the workers can overcome the geographical barrier to work together. On the other hand, the working environment of the workers become more flexible.

3. Resource and Energy Efficiency

According to the platform, quite apart from the high costs, manufacturing industry’s consumption of large amounts of raw materials and energy also poses amounts of raw materials and energy also poses a number of threats to the environment and security of supply. In order to solve this problem, smart factory can deliver gains in resource productivity and efficiency. Wang et al. (2016) has summarized two reasons: The smart factory has an accurate knowledge of production process and guarantee system with a stable product quality level and the rate of finished products, which can help determine the needed materials before production so that the production and product redundancy can be minimized. Smart machines operate in more intelligent way that the energy consumption can be reduced. In addition, the platform claims that smart factory also calculate the trade-offs between the additional resources that will be invested in smart factories and the potential savings generated (Kagermann et al., 2013).
4. Integration of customers

The smart factory can conduct optimized individual customer product manufacturing via intelligent compilation of ideal production system which factors account product properties, costs, logistics, security, reliability, time, and sustainability considerations (MacDougall, 2014). It make it possible to customize the products to specific and individual needs of customer (Jazdi, 2014).

2.5  Maintenance

During last decades, the global marketplace has witnessed an increase of pressure from customers and competitors in manufacturers around the world (Basu, 2001; George, 2002). With the globalization progresses, attention has been shifted from realizing economies of scale and increasing production volume to meeting customer demands in terms of various performance objectives, i.e. flexibility, dependability, cost and so on (Yamashina, 1995). This trend has resulted in the development and implementation of advanced manufacturing strategies such as Just-In-Time (Suito, 1998). However, unreliable or inflexible equipment often hinders the implementation of these concepts, and limits benefits from these strategies (Tajiri and Gotoh, 1992). As it is claimed by Gits(1992), maintenance can be defined as “ all activities aimed at keeping an item in, or restoring it to, the physical state considered necessary for the fulfillment of its own production function”. Thus, the impact of maintenance on productivity and profitability, which are two of the most important business performance aspects, has increased considerably (Alsyouf, 2007). Along with such a transition, companies are seeking to facilitate performance of assets and gain safer, more stable and more sustainable environment by using better asset management strategies (J.Lee, 2015). According to Ahuja & Khamba (2008), substantial examples in the past showed that inadequacies of maintenance practices have adversely affected the organizational competitiveness by reducing the reliability of production facilities, leading to fast deterioration, lowering equipment availability etc. Poorly maintained equipment may lead to more frequent equipment failures, poor utilization of equipment and delayed production schedules (Swanson, 2001). Thus, the effectiveness and efficiency of maintenance function significantly contributes towards the overall business performance of a manufacturer (Macaulay, 1988; Teresko, 1992).

2.5.1  The Role Of Maintenance

Although the significance of maintenance process for production is beyond all doubt, it was usually labeled as a “necessary evil” by owners of organizations in the past (Alsyouf, 2007). Maintenance is responsible for controlling overhead costs including the cost of manpower, material, tools etc. (Pintelon and Gelders, 1992; Foster and Van Tran, 1990). Admittedly, as Cross (1988) claims, maintenance expenses accounts for 12 to 23 percent of the total costs in manufacturing industry of UK. Furthermore, it has been found that in refineries, maintenance and operations departments are often the largest and each comprises around one-third of total staffing (Dekker, 1996). Along with these figures, most impacts of maintenance on productivity being indirect has resulted in the confirmed perception that maintenance has a poorer rate of return than any other major budget item (Ahuja and Khamba, 2008). Thus, despite the undeniable contribution of maintenance to the overall performance, it was considered as an inevitable cost center by most manufacturers. Maintenance management, which used to be a separate part of production, has gone through four generations during last few decades (Singh et. al, 2014). Characteristics of all four generations that maintenance management went through are presented in Figure 12.
Theoretical background

In the 1950s, maintenance was simply acknowledged as fixing equipment when it breaks (breakdown maintenance). Scheduled overhaul and maintenance planning was identified as the signature of the second generation. Thereafter, during the third generation, various maintenance concepts such as CBM, PM, RCM were invented and developed. Lastly, the fourth generation of maintenance management started from 2012 as the same time when the term Industry 4.0 was coined. Self-maintenance systems with zero down time, self-maintaining and self-healing features are predicted to be the focus of the fourth generation (Singh et al., 2014). During last decade, reliable production equipment is regarded as the major contributor to overall performance of a company, especially in the growing advanced manufacturing technology application stages (Maggard and Rhyne, 1992). Researchers have highlighted the profound impacts of maintenance function on performance objectives, i.e. productivity and profitability (Al-Najjar, 2000; Al-Najjar et al., 2001; Carter, 2001; Al-Najjar and Alsyouf, 2004). For instance, according to Ahuja and Khamba (2008), implementation of Total Productive Management (TPM) facilitates achieving various organizational goals as illustrated in Table 2.

Therefore, equipment maintenance has gradually been considered as an indispensable function in manufacturing enterprise (Ahmed, 2013). The role of maintenance function has been shifted from unpredictable and unavoidable cost center to a profit center which enhances the competitiveness of the company. Moreover, as the production environment become increasingly complex, manufacturers have realized maintenance management needs to be considered at a strategic level (Yoshida et al., 1990). Kumar (2004) goes further and claims that, to maximize the contribution of maintenance to productivity and profitability, it has to be recognized as an integrated part of the
operating strategy. Therefore, an overall maintenance strategy is needed in accordance with business strategy and operating strategy in order to realize strategic fit within the organization. The role of maintenance process has been changed from cost center to a profit center at a higher strategic level. In the following section, the significant evolution of maintenance concepts resulted from such a demand is explored and discussed. Based on the four generations maintenance management has gone through, it is evident that maintenance function has gained high recognition over the last few decades in various industries (Velmurugan & Dhingra, 2015). Consequently, many strategies have been developed to support maintenance management implementation in the industry over the years (Swanson, 2001).

Table 2. Performance objectives and TQM contributions

<table>
<thead>
<tr>
<th>Performance objectives</th>
<th>TPM contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production volume</td>
<td>Reduced unplanned breakdowns</td>
</tr>
<tr>
<td></td>
<td>Improved equipment availability</td>
</tr>
<tr>
<td></td>
<td>Improved actual producing time</td>
</tr>
<tr>
<td>Quality</td>
<td>Reduced issues from unstable production</td>
</tr>
<tr>
<td></td>
<td>Reduced defects due to frequently-inefficient maintenance process</td>
</tr>
<tr>
<td>Cost</td>
<td>Reduced life cycle costing</td>
</tr>
<tr>
<td></td>
<td>Reduced waste in maintenance process</td>
</tr>
<tr>
<td>Safety</td>
<td>Improved workplace environment</td>
</tr>
<tr>
<td></td>
<td>Zero accidents at workplace</td>
</tr>
<tr>
<td>Delivery</td>
<td>Support of Just-In-Time efforts with dependable equipment</td>
</tr>
<tr>
<td></td>
<td>Improve efficiency of delivery by improving reliability</td>
</tr>
</tbody>
</table>
2.5.2 Evolution of Maintenance Approach

As it is discussed above, the role of maintenance has undergone serious changes in both researchers and manufacturers’ point of view. The traditional perception of maintenance process as to fix broken items no longer fits current situation. Accordingly, maintenance approaches have gone through many phases and the scope of maintenance management is increased to cover every stage in the life cycle of equipment (Murray et al., 1996). In this wider context, maintenance function is also known as physical asset management (Ahuja and Khamba, 2008). Reviewing the evolution of maintenance concepts is crucial for understanding the changing need for maintenance management. The progress of such evolution, and differences among these concepts in terms of predictability and possibility of breakdowns, required information as well as cost-efficiency are explored as below in order to identify the pattern of the development of maintenance approaches.

Breakdown maintenance (BM)

This concept was mainly used when maintenance was simply defined as repairing broken items. Maintenance activities are conducted only after failures or breakdowns occur on the equipment (Wireman, 1990). Equipment is allowed to run until failure then the failed equipment is repaired or replaced (Paz and Leigh, 1994). It is also observed that temporary maintenance may be conducted for simply restoring failed equipment to production status, with permanent repair or replacement being postponed (Gallimore and Penlesky, 1988). Reactive maintenance strategy was primarily adopted in the manufacturing organizations prior to 1950 (Ahuja and Khamba, 2008). It allows manufacturers to minimize the amount of manpower and other resources spent on maintenance to keep equipment functioning (Vanzile and Otis, 1992). However, this approach leads to fluctuating production performance, higher levels of out-of-tolerance and scrap output and increased overall maintenance costs to repair serious failures (Bateman, 1995). Moreover, implementation of such maintenance approach offers no predictive capability for equipment breakdowns while the possibility of failures is intimately bound up with the average workload.

Preventive maintenance (PM)

Preventive maintenance is usually referred as use-based or time-based maintenance, which is comprised of maintenance activities that are undertaken after a specified period of time or amount of machine use (Herbaty, 1990). Success of such a strategy relies on the estimated probability that the equipment will fail in the specified time interval (Swanson, 2001). The activities undertaken usually include equipment lubrication, parts replacement, cleaning and adjustment. The production equipment may also be inspected for signs of deterioration during preventive maintenance work (Telang, 1998). This strategy reduces the probability of breakdowns since the equipment is likely to be restored to normal status before failures occur. Furthermore, benefits of preventive maintenance also include the extension of equipment life because catastrophic failures may be avoided (Swanson, 2001). In terms of predictability, preventive strategy relies on accuracy of the estimated time interval that is usually stemmed from previous experiences. Comparing to reactive maintenance, this approach requires more resources on maintenance activities and production may be interrupted at scheduled intervals to perform the work (Swanson, 2001).
Theoretical background

Predictive maintenance (PrM)

Predictive maintenance, often referred to as condition-based maintenance (CBM), is comprised of actions that are initiated in response to a specific equipment condition (Gits, 1992). Real-time assessment of equipment condition is usually obtained from embedded sensors and/or external measurements taken by portable equipment and then processed through software (Velmurugan and Dhingra, 2015). Under this strategy, physical status of equipment such as temperature, vibration, noise, lubrication and corrosion is measured by diagnostic equipment (Brook, 1998). When one or more of these indicators reach a predetermined level, actions are undertaken to restore the equipment to desired condition (Ahuja and Kamba, 2008). In predictive maintenance, activities are based on the actual condition of the equipment, rather than on some predetermined schedule (Velmurugan and Dhingra, 2015). It involves identifying those premonitions of equipment failure and eliminating them before the failure occurs. Therefore, as with preventive maintenance, predictive maintenance reduces the probability of equipment breakdowns and allows maintenance activities to be more cost-effective in the meantime (Swanson, 2001). Information regarding previous experience of failure and real-time status of equipment is essential for the success implementation of predictive maintenance strategy.

Total Productive Maintenance (TPM)

Maintenance has traditionally been viewed as a separate entity while TPM is a maintenance philosophy designed to integrate equipment maintenance into the manufacturing process (Velmurugan and Dhingra, 2015). The goal of TPM program is to eliminate “six major losses” including equipment failure, set-up and adjustment time, idling and minor stoppages, reduced speed, defects in process and reduced yield (Macaulay, 1988). By minimizing rework, slow running equipment and downtime, maximum value is added at the minimum cost (Jain et al., 2014). As an innovative approach to maintenance, TPM optimizes equipment effectiveness, eliminates breakdowns and promotes autonomous maintenance by operators through day-to-day activities involving total workforce (Bhadury, 2000). For fulfilling high involvement of the ordinary workers, team-based activities that involve groups from maintenance, production and engineering are deployed as the core part of TPM (Swanson, 2001). According to Adair-Heeley (1989), these team-based activities contribute to improve equipment performance through communication of current and potential equipment issues among these teams. As it is claimed by Goto (1989), these teams aim to design and install equipment that is easy to maintain and operate (Maintenance prevention), and improve the ways in which maintenance is performed (Maintainability improvement). Advantages of TPM includes reduced probability of breakdowns, reduced maintenance costs, increased maintenance efficiency and increased equipment availability.

Computerized maintenance management systems (CMMS)

As it is claimed by Parida and Uday (2009), maintenance process is concluded as a complex issue as it involves various inputs, outputs and stakeholders. Therefore, tremendous amount of efforts have been devoted to develop computerized maintenance management systems to assist in managing a wide range of information on maintenance workforce, spare-parts inventories, repair schedules and equipment histories (Ahuja and Kamba, 2008). CMMS may be used to plan work orders, determine priorities of different maintenance requests and integrating maintenance activities into the whole production system. According to Raouf et al. (1993),

implementation of CMMS is crucial for effective utilization of manpower and material. Furthermore, the capability of CMMS to manage maintenance information contributes to improved communication and decision-making capabilities within the maintenance function (Higgins et al., 1995). Moreover, it allows production and maintenance departments to improve their communication and coordination in their activities (Swanson, 2001). Along with the development of CMMS and other information technologies, the new maintenance concept e-maintenance has emerged during last decade (Elliot and Tobias, 2005; Karim and Parida, 2010). For instance, Prognostics and health management (PHM), which is dedicated to trace assets condition by analyzing sensory and system level data, has been developed quite aggressively in recent years (J.Lee, 2015).

### 2.5.3 Comparison among various maintenance concepts

Table 3. Differences among several maintenance approaches

<table>
<thead>
<tr>
<th>Maintenance concepts</th>
<th>Possibility of breakdowns</th>
<th>Predictability</th>
<th>Required supportive resources</th>
<th>Information processed</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>PM</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>PrM</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>TPM</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>CMMS</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

### 2.6 HTO Model

The HTO concept identifies Human, Organization, Technology as three key components that have profound impacts on the performance of enterprises. It was firstly developed in the nuclear industry of Sweden for improving the safety of nuclear plant, but has gradually been elaborated by researchers to wider applications and related to other aspects such as system performance and health issues (Ahlin, 1999; Berglund and Karltn, 2007; Karltn, 2011). The HTO concept is committed to analyze and understand the interactions between these three aspects (see Figure 13). In other words, the concept emphasize how the sub-systems influence each other rather than what the sub-systems themselves (Karltn et al, 2017). Such a concept helps both manufacturers and researchers to observe, study and thereafter analyze the whole system in a dynamic way. Within this concept, the ‘H’ factors can be described at different levels including physical, cognitive, psychological and social aspects (Daniellou, 2001). ‘T’ was defined as the means of transformation from input to output using procedures and methods (Porras & Robertson, 1992). Lastly, ‘O’ was defined as formal organizational arrangements and informal social structures (Porras & Roberson, 1992).
Figure 13. The relationship between sub-systems in the HTO conceptual model (Karltun et al., 2017)
3 Method and implementation

This chapter aims to explain the research design and the course of action employed to answer the research questions. To increase reliability of the research, it is crucial to define and present the process of research for the scrutiny of the reader. At first, adopted research methods are presented, which is followed by a discussion of data collection techniques. This chapter closes with the illustration of the research process in detail.

3.1 Research Method

The research method is often referred as the general plan about how to answer research questions (Saunders et al., 2012). As it was claimed by Glazier (1992), "because a satisfactory means of evaluating qualitative research methods has not been found, validity and reliability are often used as the primary means of ensuring integrity". Furthermore, he suggested that reliability can be guaranteed through the application of triangulation. Therefore, multiple research methods are employed in this thesis to achieve method triangulation, which aims to check the consistency of findings by using different research techniques (Williamson, 2002). Research methods adopted in this study are literature review and case study. In following sections, these methods are further explored and the choice is motivated.

3.1.1 Literature Review

Literature review is a desk-based research strategy which is used to critically describe, review, and interpret what is already known about a topic and add new insights on the topic using secondary sources (Jesson et al., 2011). It is frequently used as a data collection method to develop a theoretical background or framework for further exploration of the research problems (Armitage & Keeble-Ramsay, 2009). As it is claimed by Denney & Tewksbury (2013), scientific knowledge accumulates so rapidly that it is not realistic to expect readers to be familiar with all the relevant background and pre-existing knowledge about any topic. Therefore, a literature review is vital for making a research understandable as it shares with the reader the results of other studies that are closely related to the study being reported (Fraenkel & Wallen, 1990). Meanwhile, a literature review relates a study to the larger, ongoing dialog in the literature about a topic, filling gaps and extending prior studies (Marshall & Rossman, 1989). Within this thesis, the research subject is relatively young, acquainting the reader with basic knowledge about the topic is important for allowing the reader follow the thoughts behind the research process. Therefore, literature review is regarded as a strategic choice of research method instead of being a minor part of the case study in this thesis.

One approach to undertaking a review of existing literature is called systematic literature review, which has been used by increasing number of researchers in the past decade (Creswell, 2009). In contrast to other types of literature review, systematic literature review follows a structured approach: Firstly, a body of potentially relevant publications is identified; Thereafter, each publications is evaluated according to clearly defined criteria for inclusion or exclusion set beforehand (Boell and Cezec-Kecmanovic, 2010). The process is structured so that it is potentially reproducible by other researchers (Greenhalgh, 1997). The aim of systematic literature review is therefore to apply more rigorous methods when searching for existing literature, in order to avoid the waste of time and resources on unnecessary studies (Oxman, 1995).
As it is claimed by Boell and Cezec-Kecmanovic (2010), a systematic literature review offers unbiased, complete and reproducible results that providing an audit trail for the researcher’s decisions and interpretations. However, following this structured process requires the research question that is being investigated to be fixed before the literature review starts. Therefore, a systematic literature review may hinder researchers from pursuing further literature if the process does not match the initially set question (Boell and Cezec-Kecmanovic 2010). As it is criticized by MacLure (2005), “diversions into unanticipated areas are not encouraged... Learning from adjacent areas is not recommended either”. It conflicts with the fact that a deeper understanding of the research problem is gained as the literature review progresses, with the researcher becoming more aware of what questions are most relevant or pressing (Boell and Cezec-Kecmanovic 2010). Besides, it is important that concepts included in the literature review cover the entire (relevant and related) scope of previous literature pertaining to the current research topic, even if it does not directly coincide with it (Denney & Tewksbury, 2013). Under this situation, the usage of pre-defined keywords in systematic approaches may miss relevant publications that could be found by using different wording (Denney & Tewksbury, 2013). Furthermore, systematic literature reviews require a considerable amount of effort that is likely to exceed the scope of a master thesis when applied thoroughly (Armitage & Keeble-Ramsay, 2009). Thus, a systematic literature review is unsuitable for the chosen research topic of the thesis.

As an alternative to systematic literature review, hermeneutic circle takes into account how the understanding of parts relates to the understanding of a larger whole and vice versa (Boell and Cezec-Kecmanovic 2010). Identifying the process of understanding development as open ended and circular in nature, hermeneutic provides a different framework for describing literature review as Figure 10 shows (Boell and Cezec-Kecmanovic 2010). It lies under the precondition that understanding of individual texts should proceed from a thorough reading of relevant texts instead of being an isolated process. In this way, reviewing literature is performed as an iterative process that can be described by moving from the whole relevant literature to particular texts and from there back to the whole body of relevant texts (Boell and Cezec-Kecmanovic 2010). In contrast to systematic literature review, the exact pre-definition of keywords as search term is not required, neither is the identification of all potentially relevant literature at the beginning of the process. Consequently, hermeneutic circle is considered to be more suitable for guiding the literature review process for this thesis.

When selecting keywords for search term, it is inevitable that wider searches will retrieve more documents making a more laborious selection necessary while narrow searches may omit relevant documents (Boell and Cezec-Kecmanovic 2010). Thus, broad search terms were used at the beginning to grasp the whole body of potentially relevant literature in order to develop understand of the research topic. The following search operators were used:

◆ (Industry 4.0 OR The Fourth Industrial Revolution) AND (Cyber-Physical System OR CPS)

Thereafter, the search is narrowed down to the integration between CPS and maintenance activities for a more thorough literature review to answer RQ1. The following search term was used:
(Cyber-physical system OR CPS) AND (Maintenance OR Maintenance management OR Physical Asset Management)

Figure 14. The “hermeneutic circle” (Boell and Cezec-Kecmanovic 2010)

Document types were limited to books, scientific journals and conference proceedings. The search process included databases such as Scopus, Primo, Baidu Scholar and Google Scholar. Sources that were written in Chinese were excluded as well as publications that are accessible through these databases. Thereafter, publications were sorted and omitted according to their relevance, number of citations as well as abstracts and keywords. The thorough reading of remaining literature provides additional potentially relevant texts based on reference tracking. Such a iterative process was repeated several times under the guidance of hermeneutic circle until the theoretical saturation was reached.

3.1.2 Case study

According to Yin (2003), case study is an appropriate research method for exploring a contemporary phenomenon within its real-life context. It can be used for description of phenomena, development and testing of theory (Cavaye, 1996). Moreover, it is especially effective when limited information is known about the phenomenon and current perspectives seem to be inadequate (Eisenhardt, 1989). Furthermore, as it is claimed by Dubois & Gadde (1999), case study research method is the best choice when the researcher focuses on understanding the interaction between a phenomenon and its context. In this thesis, the research subject is relatively young and it is crucial to investigate how CPS interacts with the environment within Industry 4.0 concept. For both research problems, the context has profound impacts on the phenomenon and it is almost impossible to answer the problems separately from its surrounding environment, the new production era with the fourth industrial revolution. As for the design of case study, single-case design allows researchers to investigate phenomena
Method and implementation

in-depth to provide rich description and understanding (Williamson, 2002). The single case in this thesis may be used as a pilot and findings may be generalizable to other cases when additional cases test and confirm the findings in other settings (Lee, 1989). In other words, this case study may be used as a reference for future studies and the results are possible to be confirmed by other researchers. The unit of analysis is maintenance process within the production system of the case company. Taking the analysis unit, and observation of key individuals involved in these maintenance activities, into account provide information required for fulfilling the research aim. In following sections, the case company is introduced and reasons for the choice are presented.

Case company

Eisenhardt (1989) suggests that the selection of cases involving extreme situations and polar type is meaningful when only a limited number of cases are studied. Therefore, this thesis was conducted in collaboration with Fuyao Group, which is the first company in China to start implementing Industry 4.0 and represents the polar type within the industry. As the biggest automotive glass manufacturing company, Fuyao occupies two-third of the automotive glass market in China. The company owns over 100 factories and warehouses all over the world and its business has been extended to countries including Russia, Australia, U.S.A, Japan etc. Production systems of the case company are highly automated while the main tasks of operators are monitoring and carrying out maintenance activities manually. Being a cross-national company which was formed in 1987, Fuyao is capable of providing a mature and relatively stable production environment to be studied and observed. Moreover, the case company is chosen by the government as the experimental field for implementing Industry 4.0 and results are supposed to be generalized to other companies. Taking these discussions above, and the existence of problems in maintenance activities of the company, into account makes Fuyao a decent choice as the case company. The factory located in the headquarters of Fuyao Group was chosen as the target to conduct the study.

3.1.3 Choice of methodological instruments

Interview

An interview is a purposeful conversation between at least two people in which the interviewer propose questions and the interviewee listens and responds (Saunders et al., 2012). According to Williamson (2002), exploratory interviews can be very useful in the early stages of most research projects. It is usually considered as a highly productive method of data collection, since the interviewer has the opportunity to pursue specific issues of concern as they emerge (Bryman & Bell, 2011). Moreover, given that personal contact is mandatory between the interviewer and interviewee, interviews are often easier to obtain a higher response rate than other research techniques (Williamson, 2002).

According to Williamson (2002), interviews can be categorized as structured, unstructured and semi-structured. Within this study, unstructured interviews were conducted with the production manager firstly to develop an overall understanding of the structure of the case company. Furthermore, as it was suggested by the manager, key individuals were identified as potential participants for later studies. Thereafter, semi-structured interviews were used to collect in-depth knowledge concerns the targeted research topic while participants have the possibility to provide additional information in the meantime. These two types of interviews allows interviewees to
explain, or build on their responds, which is crucial to grasp participants’ perceptions (Bryman & Bell, 2011). In the research process section, more details about these interviews will be explained and illustrated.

**Focus group**

A focus group is “a carefully planned discussion designed to obtain perceptions on a defined area of interest in a permissive, non-threatening environment...conducted with approximately 7 to 10 people by a skilled interviewer” (Krueger, 1994). It is a data collection techniques typically used in a case study research (Williamson, 2002).

### 3.2 Research Process

The working process and environment of the case company was complex and the researchers had no related knowledge regarding the production of automotive glass. Therefore, the research process of the case study comprises orientation study, which aims to develop an understanding of the factory and identify key individuals/phenomenon for further investigations, and the main study.

#### 3.2.1 Orientation Study

This phase of research process started with a Gemba walk along the whole production line while being accompanied by the production manager. The complete production processes were observed by the researchers along with the brief introduction presented by the manager. Thereafter, two semi-structured were conducted with the production manager and the vice manager separately. Both interviews were conducted in their office and lasted for approximately one hour and most questions were relatively general. Furthermore, as one of the questions included in the interviews, a list of key individuals who work directly with maintenance process was suggested by both managers. At the beginning of the interviews, both managers claimed that they were reluctant to be recorded. Therefore, in order not to interrupt the interviews, one of us was proposing questions while the other one was taking notes of what the interviewee said. There interviews laid a solid foundation for later main study since potential participant were identified and the information regarding when they were available was offered by the manager.

<table>
<thead>
<tr>
<th>Role</th>
<th>Type of interview</th>
<th>Location</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Manager</td>
<td>Semi-structured</td>
<td>Personal office</td>
<td>1 hour</td>
</tr>
<tr>
<td>Vice production manager</td>
<td>Semi-structured</td>
<td>Personal office</td>
<td>1 hour</td>
</tr>
</tbody>
</table>
3.2.2 Main study

The main study was conducted three days after the orientation study due to the consumption of time on sorting out notes from previous interviews and contacting the interviewees for the following study. Along with the support from the production manager, the fact that all interviewees being co-operative made it relatively easy to schedule all the interviews. Moreover, all interviewees were informed that their answers would only be used for the study without being exposed to other colleagues including their managers. As recording these interviews was not a possible option, field notes were taken during interviews and summarized shortly afterwards.

Interviews

Semi-structured interviews were conducted with the maintenance manager, two maintenance engineers and four maintenance operators. The maintenance manager, who was in charge of the maintenance department, was interviewed first since he was more likely to be capable of providing sufficient information regarding the overall maintenance environment of the factory. Thereafter, two engineers and four operators were interviewed with varied questions since they were responsible for performing different maintenance activities. All interviews were conducted individually in the meeting room according to the guideline designed in advance along with slight changes in sub-questions depending on the flow of the interview. Interviewees were encouraged to propose examples from their work experience in accordance with their answers. The overall information of these interviews were illustrated in Table 5.

<table>
<thead>
<tr>
<th>Role</th>
<th>Number of respondents</th>
<th>Location</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance Manager</td>
<td>1</td>
<td>Personal office</td>
<td>1 hour</td>
</tr>
<tr>
<td>Maintenance Engineer</td>
<td>2</td>
<td>Meeting room</td>
<td>45 minutes</td>
</tr>
<tr>
<td>Maintenance Operator</td>
<td>4</td>
<td>Meeting room</td>
<td>45 minutes</td>
</tr>
</tbody>
</table>

Focus group

Two one-hour focus groups are conducted in the case study. The authors acted as moderators. One group contains 8 maintenance operators working in the selected production line (Group A). These 8 operators come from two different working teams in order to validate the final results. The other group consists of 6 maintenance engineers who comes from three different production line (Group B). The reason to conduct two focus groups is that the maintenance operators and maintenance engineers have different tasks during the maintenance process. Maintenance tasks exception should be done by the maintenance operators while planning, scheduling, control and supervision should be conducted by the maintenance engineers. Group A was asked to give an account what restricts and drives them to complete their tasks effectively and efficiently while Group B was asked to give an account what restricts and drives them to make decisions effectively and efficiently. The results of these two focus groups were concluded in a simple force field analysis based on Lewin (1951) for both of two focus groups.
3.3 Summary

In this chapter, the researchers provided information that enables the reader to evaluate the adequacy of the research process and its outcomes. Furthermore, it is possible for the reader to repeat the research process and evaluate the validity and reliability of the study. At first, the adopted research methods in the thesis were presented. Thereafter, the choice of data collection techniques were motivated and the case company was explored. Lastly, details of the research process were revealed.
4 Findings and analysis

4.1 Theoretical findings

There are limited amount of studies regarding how CPS and Industry 4.0 could be integrated and applied for maintenance activities. In this section, the authors present findings from existing theory regarding how CPS might be used for maintenance in the context of Industry 4.0.

4.1.1 5C structure of CPS

Among all the structures/models in existing theory, the 5C structure proposed by J. Lee (2015) is considered to be the most appropriate for maintenance management. The model comprises five levels which guide the implementation and application of CPS-based maintenance in a sequential manner.

**Smart collection level:** This level starts with acquiring accurate and real-time data from the physical world. The data might be measured from various approaches and then be transferred to the central server via the internet or other similar networks.

**Conversation level:** This level mainly concerns the data-to-information process, in which the data collected will be transformed into useful information for understanding current condition of the system and thereby support the decision-making of manufacturers. To support and facilitate such a process, different analytic tools have been developed in recent years. For instance, the prognostics and health management (PHM) algorithms, which is able to bring self-awareness and self-predictability to machines, has been developed quite aggressively in recent years (J. Lee, 2015).

**Cyber level:** This level refers to the cyberspace where all the information is stored. In contrast to current industrial tools whose cyberspace is simply used for storing data, this level adopts specific analytic tools are used to provide better insight over the status of individual machines among fleet which provide machines with self-comparison (Lee et al., 2015). On the other hand, similarities between machine performance and previous assets (historical information) can be measured to predict the future behavior of machinery (Lee et al., 2015).

**Cognition level:** The cognition level generates a thorough knowledge of the system monitored and provides reasoning information to correlate the effect of different components within the system (J. Lee, 2015). Since comparative information as well as individual machine status is available, decision on priority of tasks to optimize the maintaining process can be made (Lee et al., 2015).

**Configuration level:** The configuration level concerns feedback from cyberspace, where actions are taken as either human-in-the loop or a supervisory control to make machines self-configure, and be self-adaptive and self-maintained (J. Lee, 2015). As the ultimate goal of CPS-based maintenance systems, the factory will be able to self-adjust for variations and self-optimize for disturbances.
4.1.2 Prognostics and Health Management (PHM)

Along with the development of different maintenance concepts, various issue identification techniques have been proposed to support these concepts. As each maintenance approaches possesses its own strengths and weaknesses and suit different scenarios, different issue identification techniques are deployed as it is shown in table 6 (Donovan, 2015).

Table 6. Issue identification techniques (Donovan, 2015)

<table>
<thead>
<tr>
<th>Technique</th>
<th>Strategies</th>
<th>Description</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Intelligence and reporting</td>
<td>Corrective</td>
<td>Manually assess if a particular parameter is outside expectation</td>
<td>Largely manual process with a dependency on the ability of the expert</td>
</tr>
<tr>
<td>Fault detection and diagnosis</td>
<td>Corrective</td>
<td>Identify potential issues based on input data through a set of encoded fault logic</td>
<td>Logic employed is typically specific to equipment, and detection means that the issue is already present</td>
</tr>
<tr>
<td>Condition-based monitoring</td>
<td>Corrective</td>
<td>Focus on monitoring particular measurements to determine if an issue has, or is likely to occur</td>
<td>The condition is specific to equipment. Therefore, performance and accuracy is dependent on the choice of appropriate parameters</td>
</tr>
<tr>
<td></td>
<td>Preventative</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predictive maintenance</td>
<td>Preventative</td>
<td>PM employs statistical learning techniques to predict the occurrence of an issue</td>
<td>Vast amount of high-quality data must be available to develop an accurate statistical tool</td>
</tr>
<tr>
<td>Prognostics and health management</td>
<td>Corrective</td>
<td>PHM uses a holistic approach to issue identification, and comprises FDD, CM, and PM, to highlight issues at different stages</td>
<td>Implementation of PHM is more complex than any single technique</td>
</tr>
<tr>
<td></td>
<td>Preventative</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
As smart manufacturing places a strong emphasis on developing predictive capabilities throughout the factory, PHM is considered to be the most relevant to future maintenance in smart manufacturing among these techniques (Donovan, 2015). According to Lee & Bagheri (2015), PHM is a leading maintenance methodology that address invisible issues in industry. Comparing to other maintenance issue identification techniques, PHM is capable of identifying the degradation of component or system by trace assets condition through analyzing sensory and system level data (Lee & Bagheri, 2015). In current stage, PHM algorithms are applied to limited amount of current data from assets while the application of CPS enables the possibility of developing CPS-based PHM systems. As it is claimed by Lee et al. (2014b), the vast amount of data brought by CPS allows the peer-to-peer comparison among the fleet of assets to increase the likelihood of capturing certain failure modes and predict remaining useful life of equipment. Moreover, historical utilization patterns of similar asset at various health stages provide required information to simulate possible future utilization situation and their outcome for the target asset (Lee et al., 2015). Consequently, a simulation model can be developed in the cyberspace to perfectly simulate the physical production system and thereby enables the system to self-predict.

4.2 Empirical Findings

This chapter contains the findings of the case study. The authors present it in a chronological order of the used research techniques including interviews and two focus groups.

Given that the findings are intimately bound up with the production system, a more detailed description of the facility is necessary to make the findings understandable for the reader. The automotive glasses are produced through a highly automated production line, which comprises two parts called “cold-end” and “hot-end” respectively. In the “hot-end” part, raw materials are melted and further processed into molten glasses, which are then transported through the surface of the tin bath. As such a chemical transformation is performed under around 1200 °C temperature, all the production processes in the “hot-end” are conducted in a sealed furnace, which in turn results in the increased difficulty in manually monitoring, controlling and maintaining the machines in this part. In terms of the “cold-end” part, the glasses go through processes including quality check, surface cleaning, cutting into desired size and finally being picked up by electronic arms. The factory consumes a fixed amount of raw materials everyday (300 tons) while the volume of finished products varies from batch to batch as the defects rate differs for various products. Staffs in the production department work in three shifts with 8 hours per shift. Each shift is performed by one sub-manager, two engineers and 8 operators. However, the maintenance department is separated from the production department, which means workers in production department are responsible for contacting the maintenance department when maintenance activities are needed. The maintenance department adapts the same rules of shifts as the production department. A six-steps model was adapted as the guide for conducting maintenance activities by the maintenance department, which was also used by the researcher as a guide to conduct interviews in order to get a more systematic view of the whole maintenance function.
4.2.1 Interviews

The findings from the interview are summarized and thereafter presented in accordance with the six-steps workflow adopted by the company. The findings include both the useful functions and main problems in the maintenance system.

Step 1: Study and Define Maintenance Activities

In the case company, the task of studying and defining maintenance activities were conducted by the maintenance engineers accompanied by occasional advice given by the consultants hired by the company. The main input of this step covered documents including the instructions of the production line, records of facility register and history reports (such as historical FMEA analysis) derived from the daily maintenance activities. At this stage, required maintenance actions were defined to achieve desired outcomes for the production.

According to the respondents, a so-called “three-level maintenance model” was adopted as the main maintenance strategy in the case company. First of all, components, equipment and machines were classified into three types which correspond to different requirements of maintenance activities.

Type 1: A component/equipment /machine that would be replaced only after a failure/variation does occur. This type of strategy fits in with the traditional breakdown maintenance concept. Items that belong to the first type generally had a limited effect on other devices of the production system even if they failed. Furthermore, the replacement of the component /equipment/machine had relatively less impact on the production.

Type 2: This type of component/equipment / machine adopted the same maintenance concept as the first type (BM). In contrast to type 1, the presence of these items was critical for the optimal function of the production system and replacement of these items has a greater negative influence on the quality of finished products. Therefore, the company stored a certain amount of spare parts of these items in their inventory in order to replace them as soon as possible. The amounts of spare parts of “type 2” items vary according to their remaining useful time (RUL) and the possibility of failures. In other words, component/equipment/machine that had relatively short RUL and higher potential of breakdowns tended to have more spare parts in inventory than other devices. However, since several specific components were very expensive, the company had been struggling to strike at the balance between safe amount of inventory and tight budget.

Type 3: A component/equipment/machine that should be replaced at established time intervals regardless of the actual condition.
(Note: these three types of components/equipment/machine are abbreviated as Type 1, Type 2 and Type 3 respectively)

In terms of “Type 1” maintenance, the condition of “Type 1 items”, of which the majority are machines, was monitored every day by the staffs of maintenance department. The workers went through the production line and judge whether the machines were functioned at optimal status through the measurement of parameters such as temperature, noise etc. In most cases, these measurements were done manually without any tools. In other words, the operators measured the temperature
of the target machines by touching the surface while the noises were measured by listening. Occasionally, the operators employed tools to conduct more accurate measurement of these parameters. The replacement would be conducted directly after an variation/failure was detected. In the second level, Type 2 was monitored at pre-determined time interval. The backup of Type 2 is used at that time. The results determine whether it should be replaced or not. In the third level, Type 3 should be changed directly at regular interval.

During the interview with the production manager, it was emphasized that the most machines of the production line in the case company was purchased from another company (called company B in the following part). It in turn increased the difficulty in developing core knowledge regarding the restraints and weakness of the equipment. The specifications of the components included in these machines were clarified in the instructions given by Company B. However, as it was claimed by the maintenance manager, some of the specific components were considered too expensive for the given budget. Therefore, the case company kept seeking for alternative brands that produced similar products to these components. In order to prepare these spare parts, the general data of components/parts was collected. The storage quantity of each spare part was determined according to the history record. The storage quantities of some sensitive spare parts could be over 100. According to the maintenance engineers, the principle to define the storage quantities of these parts was “more is better”. However, such a principle had considerably increased the expense spent on inventory management.

The maintenance procedures and work instructions were described in this step as well. In addition, work procedures were specified as a guide for operators to complete a task. Finally, key performance indicators (KPI) were defined to evaluate the maintenance system. In this case company, KPI included availability of equipment, downtime, maintenance cost, time to failure, proportion of planned vs unplanned failure etc.

**Step 2: Work Planning**

Maintenance engineers worked out a plan including the work list everyday as well as the required sources (such as human skills, spare parts, equipment etc.) to complete these tasks. The maintenance engineers mainly considered factors including the health condition of the components/parts/machine, the history record which showed the current status of the production line as well as the documents of FMEA.

One of the most important contents of maintenance activities planning was the negotiation and communication with production planning. The production tended to be unstable when changes were being done in the size/color/thickness of the glasses between batches, which leads to a rather fluctuated quality of products. Therefore, maintenance activities were usually conducted while avoiding these changes. In addition, the maintenance engineers should also take the budget into consideration. It was interesting to notice that the case company had a fixed monthly financial budget for the maintenance department of each production line. In cases when the actual expenditure exceeds this budget, wages of all employees in the maintenance department would be deducted. The amount of such deduction depended on the extent of overspend. The high-management of the case company believed this was a sensible way to motivate the maintenance department to avoid unnecessary expenses.
**Step 3: Work Scheduling**

In this phase, the maintenance engineers decided the time schedule and assign the resources needed to implement the work plan.

Assignment of human resources was a key part of work scheduling. There were 4 eleven-person teams working at three shifts. The 11 persons in one team were all maintenance operators and were assigned with different tasks based on their skills and knowledge. The main maintenance activities in the company included routine maintenance (cleaning, lubrication), fault diagnosis, monitoring, and repair. Basically, the role of each employee was settled and would not be changed without special reasons. There were certain cases when the maintenance activities required more than one working team and the maintenance manager was responsible for contacting people in other teams in the same production line or from the other production lines. It could be time-consuming and complicated to request for help from other production lines as they had their own jobs to be done.

The purchase of required spare parts to maintain a safe inventory was done in this stage as well. According to the maintenance manager, the purchasing department was responsible for the procurement of spare parts. Although the brands of most components/machinery were given by Company B along with their specifications, the case company had been trying substitutes which were relatively cheaper. As it was claimed by the maintenance manager, such an attempt had decreased the overall costs while increased the possibility of failures at the same time. In addition, the maintenance department should ensure tools, equipment and spare parts were available at any time. The maintenance operators were obligated to check out the inventory of spare parts every day and report to the maintenance engineers by email.

Another function of this phase was to determine the priority of tasks as the resources were limited. For instance, according to the respondents, some of the broken components had little influence on the production system. The production system could run well for days after these components fails. Hence, this kind of components have a low priority in the schedule.

The case company also covered employee training in this step. There were two types of training courses in this case company. They were safety training and skills and knowledge training. An unique condition of this case company was that the required skills and knowledge were mainly acquired from every day operations. Therefore, as it was claimed by the production manager, it took averagely 6 months for training a newly hired employee.

**Step 4: Work order release and assignment**

Every day in the morning, the maintenance engineers transmitted the schedule to the maintenance manager in paper format or by message. The maintenance manager then conveyed the message of the scheduling sheet orally to the maintenance operator team. According to the respondents, normally this way worked well because these daily tasks were more or less the same. However, this method had some obvious drawbacks. For example, once the case company decided to update the production line, so there were many special tasks that day. It took much more time to update the production line than planned because the employees could not remember all the tasks at one time so that they had to check what the next task was after they completed one task.
Step 5: Carry out the work

The very first step in this phase was that the maintenance manager provided a record indicating the original information (such as layout positions of the components) of the components/machines. According to the maintenance operators, after reconfiguration of the plant, this kind of information is especially important.

In the case company, most of the maintenance works were done manually, except from few machines and conveyors that could be cleaned automatically. The measurement of parameters including smell, noise and temperature was critical for determining the necessity of maintenance activities. Apart from the temperature, measurement of the other two parameters was conducted mainly by human sense. The skills to complete this kind of tasks could only be obtained through experience. It significantly increased the difficulty of employee training. It could also lead to a situation where the results obtained were very subjective and often inaccurate.

The production line of this case company had its unique feature that the entire production line would be destroyed if it stopped running (the production manager refused to answer the reasons behind such a phenomena). That is, a breakdown of critical parts could destroy the entire production line if it was not dealt with accurately and timely. However, the company was not capable of obtaining real-time condition of the items. As a consequence, unpredicted failures kept emerging which needed the maintenance operators react rapidly. It unduly burdened the operators as well as managers. For instance, as it was claimed by the maintenance manager, he was always ready for work calls even during weekends and holidays. Moreover, according to the maintenance operators, there were certain parts inside the machines could not be measured manually and the health condition of these parts could not be monitored directly. The maintenance operators could only deduce the health condition of this parts from the performance of the machines.

According to the respondents, the temperature in the field was approximately 45 degrees Celsius. As most of the maintenance tasks were conducted in the field, the high temperature environment could potentially influence the judgment of employees. Another problem was that maintenance activities such as components replacement should be done manually. Due to the high temperature of machines (almost 60 degrees Celsius), the employees were easy to be scalded. The protection equipment was generally simple and basic as more advanced equipment required more expenses. According to the maintenance engineers, new problems kept emerging in this production line. Moreover, the production system was complex and the impact of changes could only be observed days or even weeks afterwards. Consequently, in most cases the maintenance engineers could not immediately figure out what the root cause was when a breakdown happened.

Step 6: Closure of the work order

Most of the respondents believed the actual information should be captured as valuable history for continuous improvement. In this phase, values of the KPI were recorded such as cost of job covered by the work order, downtime of equipment, proportion of planned and unplanned tasks etc. Different types of information were recorded by related operators and were sent via email. Another function of this step was to record the activities done in a specific period. Normally, this information would be reported to the maintenance manager and engineers at established intervals.
The maintenance department were dedicated to documenting historical data of all the failures occurred and their corresponding solutions. Since most of solutions to correct some failures were based on working experience, it was always difficult for the maintenance engineers to judge how useful these documents were.

**Step 7: Production of report & Report analysis**

As the last step, the information was categorized and standardized by both maintenance operators and engineers according to the different analytical purposes. These reports were analyzed to assess the maintenance performance and propose recommendations to improve the maintenance process. The most common method used to analyze these information was the FMEA. According to the maintenance engineers, the FMEA about the maintenance process was to evaluate the process to identify where and how it might fail and to assess the relative impact of different failures in order to identify the parts of the process that were most in the need of change. According to the maintenance engineers, although they were expected to generate one FMEA result every time they conducted the reports analysis, the fact was that they only update the FMEA document when big changes occurred in the production system.

**4.2.2 Focus group**

The focus group was used to validate the findings of the semi-structured interviews. The focus group lasted for 1.5 hours with 11 employees present. The main topic was about what motivate them and what restricts them to achieve a better maintenance performance. The authors used the force field analysis to summarize the result of the focus group. The final result was presented in the following table:

<table>
<thead>
<tr>
<th>Driving Forces</th>
<th>Restraining Forces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sufficient supply of drinks and food</td>
<td>High temperature working conditions</td>
</tr>
<tr>
<td>Sufficient medicine and medical devices</td>
<td>Limited protection of dangerous tasks</td>
</tr>
<tr>
<td>Proper work shift</td>
<td>Errors of information</td>
</tr>
<tr>
<td>Skills and knowledge training</td>
<td>Bad information sharing between departments</td>
</tr>
<tr>
<td>Technology support from the machine provider</td>
<td>High cost on backup components</td>
</tr>
<tr>
<td>Rich experience</td>
<td>Difficult and dangerous work tasks</td>
</tr>
<tr>
<td>Coordination with other departments</td>
<td>Not enough tools to monitor equipment conditions</td>
</tr>
<tr>
<td>Facility register</td>
<td>Too much reliance on employee experience</td>
</tr>
<tr>
<td>Components/parts condition monitoring</td>
<td>Limited annual budget</td>
</tr>
<tr>
<td></td>
<td>Interference coming from other departments</td>
</tr>
</tbody>
</table>
To make decisions effectively and efficiently.

<table>
<thead>
<tr>
<th>Driving forces</th>
<th>Restraining forces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production line instructions from the Spanish company</td>
<td>Bad spare part prediction</td>
</tr>
<tr>
<td>Technical support from the Spanish company</td>
<td>Dependency on the Company B</td>
</tr>
<tr>
<td>Knowing the inventory of the spare parts and other resources</td>
<td>Too much data need to be processed</td>
</tr>
<tr>
<td>Utilization of FMEA</td>
<td>Low accuracy of current components/parts life time prediction</td>
</tr>
<tr>
<td>Collaborative decision-making</td>
<td>Lack of core knowledge about the entire production system</td>
</tr>
<tr>
<td>Facility register</td>
<td>Some parts/components cannot be assessed directly and accurately</td>
</tr>
<tr>
<td>Components/parts health condition monitoring</td>
<td>Lack of the dynamics of the entire production systems</td>
</tr>
<tr>
<td>History record from the maintenance operators</td>
<td></td>
</tr>
<tr>
<td>Measurement of the maintenance performance</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Analysis

The findings of the case study described the current condition of the maintenance system including functions which run well in the maintenance process and the problems in the current maintenance systems. As the findings covers factors that were not related to technology aspect, the analysis section started with a categorization based on the “HTO (Human, Technology, Organization) Model”. In other words, the difficulties/problems that existed in the case company regarding maintenance activities were divided into three aspects respectively for further analysis.
Personnel (Human)

The main issue related to the human perspective was the lack of systematic training for new employees. Conventional training of new employees usually covers a certain period of time spent on taking lectures given by experienced employees or trainers, reading documents, practicing related works etc. However, in the case company, as it was claimed by both the managers and operators, new employees usually studied through observations on experienced employees to develop required skills and knowledge from daily operations. Consequently, it was always time-consuming for these new employees to get fully prepared. Moreover, as the skills and knowledge were generated from experiences, new employees were generally not capable of dealing with accidents or failures that occurred rarely. According to the production manager, most competitors of the case company in Chinese market adopted the same way of training new staffs. Such a strategy had resulted in the dependency on experienced workers, which in turn led to the emphasis on keeping the royalty of these employees.

During the interviews with participants, it could be concluded that the management of the case company motivated their employees mainly by manipulating the payment. On one hand, managers and workers would be rewarded with extra salary for the outcomes that exceeded expectations. On the other hand, the payment would be deducted if the performance of production failed to reach the pre-determined level. The case company held the belief that such a policy would motivate the employees to perform at the optimal level. However, as it was claimed by the production manager, the company tended to ignore the importance of ensuring the royalty of employees. Therefore, as the production manager said, “most employees are only royal to money instead of the company itself”. As an experienced employee was so valuable for Fuyao, maintaining their royalty. As a matter of fact, several powerful competitors of the case company were managed or even owned by people who worked in Fuyao previously as the managers or engineers. In addition, as the company adopted a job-based payment structure, the operators only focused on what were required in their job content while refused to take responsibility and initiative for works that were not included in the job description. Consequently, the creativity of the operators were limited and continuous improvements which stemmed from the shop floor became nearly impossible in the case company. Therefore, it was critical for the top-management of Fuyao to realize motivations of their employees other than monetary stimulation.

In addition to these problems above, it was noticed that the four operator teams worked at changing shifts. In other words, the team worked at daily shift might work at night shift the day after. Although such a way of shifting ensured that one of the four teams would be spare all the time, it also resulted in heavier physical loads on these operators as they had to adapt to different working hours continuously. According to the respondents, there was only a single one-hour-break for meal during a eight-hours-shift. Such an schedule forced the employees to work under high pressures as their job were demanding given the difficulty and complexity of the maintenance activities.

Organization

In terms of organization structure, Fuyao had a strict hierarchy with centralized decision-making like most other companies in China. Blue-collar workers were rarely involved in any kinds of decision-making. In contrast, they were supposed to obey and execute the plans or standards proposed by the top-management. Besides, as it was claimed by the maintenance engineers, the top managers of the case company took the
“Gemba walk” occasionally with all the employees being informed in advance. Thus, several specific activities, such as cleaning the surface of machines, sorting out spare parts exactly according to standards (usually they were sorted roughly), were carried out by the operators before the visit. Such a phenomena could be problematic as people who made decisions may not have abundant and accurate information of the problems, which in turn leaded to inaccurate decisions. For instance, both monthly and annual budget for the overall expense of the maintenance department was determined by the finance department without the involvement of maintenance staffs. The budgets were determined based on the overall costs of previous years while current status and requirements of maintenance activities were ignored. The ignorance of opinions and suggestions from the maintenance department was complained by few maintenance operators. Such a way of decision-making made these commands neither convincing nor reasonable for the workers. Moreover, as the case company was a family business, several important positions were occupied by the relatives of the boss although they might not have required knowledge or educational background. For example, the boss had assigned his cousin, who studied indoor decoration in university, as the top manager of the R&D department. The lack of information and knowledge had significantly increase the likelihood of making wrong decisions which would still be executed by workers.

Another shortcoming related to organization aspect was that the co-operation between departments were not that effective and efficient. For example, the maintenance department was independent from the production department instead of being an integrated part of it like other companies. However, the responsibility allocation between these two departments were not clear as they were intimately bound up with each other. For instance, there were some maintenance activities, such as cleaning of the cooling pipe, monitoring of the heating resistor, carried out by both the maintenance department and production department. The blurred boundary had resulted in waste of resources and the denial of obligation from both departments when unplanned breakdowns occurred. Another example was that despite three production lines in the factory composed similar layouts and machines, the information exchange among these lines were limited to personal conversations between managers of each line. In other words, failures that occurred in one production line might have already happened in another production line and could possibly be avoided if the information was shared in time.

Technology

Generally, these shortcomings related to technology aspects could be divided to three categories. Firstly, most technological shortcomings stemmed from the lack of understanding of the core technology regarding the whole production line due to the fact that Fuyao purchased almost the whole production line from Company B. As it was claimed by the production manager, there were situations in which they still needed to request supports from Company B even though they had run the production line for several years. In addition, two of the production lines were purchased and installed exactly according to the Company B while the third production line was installed by the case company itself as an attempt to decode the production process. Consequently, the third production line experienced a higher frequency of failures as well as unique problems that never occurred in other lines. The lack of understanding of core technology had significantly hindered the company’s capability of identifying root causes of the failures, which in turn increased the difficulty of problem solving.
Secondly, the company had trouble seeking for appropriate systems/sensors/components that were able to support automation of the production. For instance, according to the maintenance engineers, existing sensors could not work in such a high temperature environment while maintaining the desired level of functions. As a matter of fact, sensors that Fuyao used could only present vague pictures of the interior of the furnace. As it was claimed by the maintenance manager, they once tried a system that could automatically check the pressure of the furnace and released the alarm if needed. However, it turned out the possibility of fake alarm was too high that they would rather stick to the previous way in which the operators measure the pressure manually everyday. Another example was that the whole production line was extremely subjective to stoppage because of technological limits. Thus, almost all respondents were skeptical about the possibility of realizing fully automation in such a environment which had zero tolerance for errors.

Thirdly, other shortcomings were related to technologies that already existed but the company did not adopt. First reason behind this was that some improvements were too expensive for the budget. For instance, there were multiple cooling pipes which were inserted into the furnace in order to flexibly control the temperature. In terms of cleaning of these pipes, two of them could be automatically pulled out from the furnace through remote control which enabled by the embedded electronic engine and further be cleaned by the operators, while rest of them needed to be pulled out manually. Although it had been proved that the maintenance of the two automatic cooling pipes were more efficient than others and had little negative impact on the production, the company refused to equip all pipes with the electronic engine as the expense would exceed the budget. As it was mentioned by both the production manager and maintenance manager, proposing a costly improvement which may be beyond the budget was always difficult to be permitted by the top managers of the company. The second reason of not employing advanced technology was that the company did not considered these improvements as necessary. For example, the operators took responsibility for documenting all the failures and their respective solutions on paper. These documents would be manually digitized as tables by maintenance engineers. However, due to the lack of, software to manage the data, appropriate database to save the data, and analytic tools to standardize the data, these documents were difficult to be categorized and standardized for further analysis, which in turn resulted in a more complicated data-to-information process.

Based on these findings, the authors summarized the functional requirements of a support system. That is, these requirements can both enhance the advantages of current maintenance system and solve problems of the system.

1. Digitized documenting

The case company were dedicated to document useful data and records and derive meaningful insights from these documents for improvements. These documents covered massive information including basic specification of machines, historical records of failures and respective actions taken, indication of likely breakdowns, various types of defects and respective root causes, etc. Recording the massive amount of data on paper made it time-consuming and resource-demanding to standardize, categorize and store the data. Thus, an appropriate software should be adopted by the company to help manage the input and output of data. Specific operators should be trained and thereafter assigned with the responsibility for entering the data correctly and searching for the data timely when needed. In this way, the case company would
be more efficient in managing all the documents, which in turn facilitated the maintenance department to take full advantage of the data.

2. Communication and negotiation between departments

As it was mentioned in the findings, the production environment was rather sensitive to the actions taken by the employees. Thereby, efficient communication between the maintenance department and the production department could lead to the situation where these two departments conduct their works at the same time. For instance, the maintenance department could replace aging components while the production department was changing the settings for next batch of products. In addition, as employees of the production department would be able to notice the symptom of defects, they may be able to recognize degraded machines and report to the maintenance department as soon as possible. Sharing of such information would significantly increase the possibility and accuracy of failure detection and prediction. Besides, information sharing among production lines regarding the historical records of failures would be helpful for preventing similar failures to occur.

3. Tether-less access to the information

As the case company owned hundreds of production sites across the world, it would be meaningful if all the sites had access to all the documents even from a distance. Besides, as it was noticed in the interviews, all employees in the maintenance department needed to stay in contact even during weekends or holidays. Thereby, having tether-less access to the information means that the managers and engineers could contribute to the decision-making without being physically present. In addition, the operators could also be informed with working schedules, monthly targets, the decisions made and so on through the system in time. Building an online platform to provide the access to the information when necessary is critical for laying a solid foundation for future revolutions.

4. Measure and monitor machines by sensors

The maintenance operators inspected the machines everyday by measuring noise, temperature, humidity etc through human senses. Thereafter, judgments regarding whether the machine was functioning at the optimal status were made based on personal experience. It was difficult to fully trust these subjective judgments as no accurate numerical results were presented. Therefore, installing sensors on machines to measure the pre-determined parameters automatically and continuously was critical. On one hand, the workload of operators would be relieved so that they could be more committed to prioritized works such as replacement of key components. On the other hand, maintenance managers and engineers would be able to make reasonable decisions based on more accurate and timely data. Embedding sensors was also the very first step for developing a CPS for future maintenance.

5. Involvement of all employees

As it could be concluded from the case study, maintenance operators were barely involved in any kind of decision-making and had basically no room for taking initiatives without requesting. This was problematic as the top managers who were in charge of making decisions might not have necessary information. By contrast, involving the operators in meetings would be helpful as they had abundant
understanding of the production regarding strengths and shortcomings. Moreover, the involvement of all employees in decision-making could also be a strong motivation for employees as they would feel respected. A motivation besides money was critical for keeping employees royal to the company.

6. Systematic training of employees

To begin with, experienced employees should transform their experience into more systematic knowledge together with existing theories. Coaching could be a decent choice for ensuring the success of the process. In addition, the digitized documenting mentioned in the first suggestion would laid a solid foundation for this process. New employees should start their training by developing understanding of the whole production system based on theories and visit to the production line. Thereafter, experienced employees should take the responsibility for sharing their skills and knowledge with the newbies. Afterwards, new employees could start practicing their works respectively while accompanied and guided by experienced employees. This would lead to more well-trained employees while shorten the time spent on training at the same time.

7. Spare parts management

In order to execute the three-level maintenance method in the case company, spare parts need to be available at any time when required. However, maintaining an unnecessary amount of inventory will not only increase the cost of inventory management but also impose more pressure on the capital of the company. Therefore, the company should be more precise about how many spare parts might be required. This could be achieved by both drawing conclusion from previous experience and requesting for data from the company B if possible.

8. Flexible maintenance budgeting

During all the interviews as well as the focus group, the word “budget” kept being mentioned by the respondents. The case company provides the maintenance department with 100 thousand Chinese yuan as the monthly financial budget in order to control running costs. However, a fixed budget that was not determined by the maintenance department had limited the room to make improvements. As a matter of fact, this kind of policy would encourage employees to avoid taking initiatives unless the task was absolutely necessary. Therefore, the company should be more flexible in target costing the maintenance expense. Proposals beneficial for the production performance should be considered carefully even if the expenses exceed the budget.
5 **Discussion and conclusions**

5.1 **Answering Research Question 1**

In contrast to Industry 4.0, the term CPS is already well-defined by researchers as the automated systems that enable the connection of physical operations with computing and communication infrastructures (Baheti & Gill, 2011). It is critical to realize that CPS is about the intersection, not the union, of the physical and cyber world (E.A. Lee, 2015). Based on both theoretical and empirical findings, there were several requirements to be filled in order to achieve CPS-based maintenance in the context of Industry 4.0.

The application of a Cyber-Physical System starts with acquiring accurate and real-time information from the physical world. This requires a thorough understanding of all the machines/components in the production line regarding their respective functions, specifications, impacts on other items etc. Thereafter, the data might be measured by the sensors or obtained from popular industrial tools such as ERP systems. The data would then be transferred to the central server via the internet or other similar networks. To achieve such a transformation of data, the sensors are usually installed together with actuators or micro-computers to form embedded systems that enable tether-free communication with the central server.

Thereafter, the data collected needs to be transformed into useful information for understanding current condition of the system and thereby support the decision-making of manufacturers. This process requires an efficient and effective software to categorize, normalize, and standardize the data collected for further analysis or review. In addition, abundant memory space to appropriately store the data is also necessary. Thereafter, analytic tools are required for facilitating the data-to-information process. These tools may include various issue identification techniques such as Fault detection and diagnosis (FDD), Prognostics and health management (PHM) etc., which are suitable for different strategies and situations. For instance, FDD identify issues based on input data through a fault logic while PHM conduct issue identification through a holistic approach (Donovan, 2015).

In addition, the criteria include a central server where all the information is stored. The server has to be stable and the security of information also needs to be guaranteed. In this level, specific analytic tools are used to provide better insight over the status of individual machines among fleet which provide machines with self-comparison (J. Lee, 2015). Meanwhile, similarities between machine performance and previous assets (historical information) can be measured to predict the future behavior of machinery (Lee et al., 2014b). To achieve the desired outcomes, advanced analytic tools are necessary to enable identification of certain patterns of failure modes among similar machines. In addition, this level also includes creating a twin model for machines and components in the cyber space. The twin model will keep running and recording useful information along the whole life cycle of these items even though the actual machines or components fail. The continuous simulation of such a twin model requires a powerful computer that is capable of processing all the data.

Thereafter, the target is to arrive at cognition level which generates a thorough knowledge of the system monitored and provides reasoning information to correlate the effect of different components within the system (J. Lee, 2015). It also enables remote virtualization of current status of the production system for human. Such a function requires a reliable network to transform required data as well as an
appropriate application which provides access to the data for all the employees. Since comparative information as well as individual machine status is available, decision on priority of tasks to optimize the maintaining process can be made (Lee et al., 2014). In order to achieve collaborative diagnostics and decision making, the employees and managers need to be well-trained to take full advantage of the information and make reasonable decisions.

Finally, the CPS collects feedback from cyberspace and actions are taken as either human-in-the-loop or a supervisory control to make machines self-configure, and be self-adaptive and self-maintained (J. Lee, 2015). As the ultimate goal of the CPS-based maintenance management, these tributes need to be supported by advanced smart central processing unit which is capable of self-learning different failure modes and reacting respectively.

Table 7. Criteria and requirements for CPS-based maintenance management

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Thorough understanding of the production system</td>
</tr>
<tr>
<td></td>
<td>Industrial tools such as ERP systems</td>
</tr>
<tr>
<td></td>
<td>Sensors embedded on machines</td>
</tr>
<tr>
<td></td>
<td>Networks such as the Internet or Intranet that enables data transformation</td>
</tr>
<tr>
<td>Information</td>
<td>Appropriate software to standardize and categorize the data collected</td>
</tr>
<tr>
<td></td>
<td>A reliable database to store the data</td>
</tr>
<tr>
<td></td>
<td>Issue identification techniques to facilitate data-to-information process</td>
</tr>
<tr>
<td>Cyberspace</td>
<td>A reliable central server</td>
</tr>
<tr>
<td></td>
<td>Advanced analytic tools to identify various patterns of failure modes among the fleet of similar machines</td>
</tr>
<tr>
<td></td>
<td>Powerful processing unit to sustain the continuous simulation of the twin model</td>
</tr>
<tr>
<td>Cognition</td>
<td>Appropriate application with well-designed user-interface</td>
</tr>
<tr>
<td></td>
<td>Experienced employees to make reasonable decisions based on given information</td>
</tr>
<tr>
<td></td>
<td>Distanced access to information at any time</td>
</tr>
<tr>
<td>Configuration</td>
<td>Advanced central processing unit for self-learning</td>
</tr>
<tr>
<td></td>
<td>Smart devices designed with self-maintenance capability</td>
</tr>
<tr>
<td></td>
<td>Well-trained operators to deal with situations when the system fails</td>
</tr>
</tbody>
</table>
In conclusion, the application of CPS-based maintenance in Industry 4.0 context has multiple criteria as prerequisites. Based on the 5c structured developed by J.Lee (2015) as well as the findings from the case study, table 7 presents the criteria that needs to be fulfilled by the case company for developing an ideal CPS-based maintenance management system.

5.2 Answering Research Question 2

Based on the criteria that was presented above as well as analysis of the findings from the case study, a road-map for the company to solve maintenance problems and eventually achieve CPS-based maintenance management was proposed.

Firstly, among all other steps toward the CPS-based future maintenance, the sound training of employees is the most fundamental one. The application of a CPS-based maintenance system might lead to the “irony of automation” situation, where the employees lack the experience to deal with accidents when the system fails. Therefore, instead of the slow process of studying from daily observations and operations, new employees should be taught with related knowledge and theories about the production system. Experienced employees should share their knowledge regarding the difficulties and problems might occur when carrying out the works based on their experience. Moreover, different patterns of failures and their respective solutions should be introduced in order to avoid the irony of automation. Secondly, the company needs to treat the royalty of employees seriously as the loss of an experienced employ will probably weaken the case company while strengthen competitors at the same time. The company is suggested to motivate the employees by taking measures such as improving the working environment, increasing room for freedom of choice and so on, instead of relying solely on manipulating the payment. Thirdly, the company is suggested to develop thorough understanding of the core technology of the machines and components that are comprised in the production process. This could be achieved by hiring engineers from Company B as the consultant to teach maintenance engineers. Meanwhile, the digitization of existing written documents should be carried out in order to make it easier for entering, managing and searching when needed. A central server should be built to harbor all the information and ensure the accessibility of data for anyone at any time. Fourthly, the communication and co-operation among department should no longer be limited to personal conversations. Instead, a platform should be erected for sharing information regarding working schedules, priority of tasks, newly discovered errors and so on. Negotiations should be made based on the information to reach the optimal performance while eliminate the waste of resources. Fifthly, the budget for maintenance expense should be more flexible and staffs from the maintenance department should be involved when determining the target costs. Blue-collar workers should also be granted with the freedom to propose suggestions and criticism. Thereafter, the company could focus on resolving technology-related shortcomings by starting with installing sensors on machines to measure and monitor them automatically and continuously. The data collected by sensors would be categorized and standardized as same as the data from previously written documents. Afterwards, different issue identification techniques might be used to analyze the data based on which maintenance concept is adopted. A twin model in the cyberspace could only be established after the company is able to take full advantage of the data collected. Continuous running of the twin model and ensure it is identical to the physical production system could be the next step. Thereafter, the data collected from the twin model could be taken into account for predicting and preventing upcoming failures. The ultimate goal the company is to build a smart central processing unit(CPU) that is capable of self-learning and analyzing the information collected from
sensors in the physical world as well as from the twin model in the cyberspace. Eventually, the smart CPU will be able to react to different situations and make decisions regarding what maintenance activities are required for which machine and thereby self-optimize the performance of the whole production system.

5.3 Discussion of method

The research methods adopted in this study included literature review and case study method and they were considered to be the most appropriate choice for the research purposes. Considering the immaturity of the research field, the hermeneutic circle was used to guide the literature review. In contrast to systematic literature review, the hermeneutic circle allows the researchers to keep redefining the search term and direction as the literature review proceeds. Therefore, the literature review was performed in a circular manner to answer the first research question and thereby offers a theoretical foundation for the second research question.

Case study was chosen as the other research method of the thesis due to its ability of allowing researchers to develop deep understanding of a phenomenon in its real-life context. Research techniques including interviews, focus group were used in the case study to achieve triangulation in order to increase the reliability and validity of the study. Semi-structured interviews were conducted with the production manager and maintenance manager in order to get an overview of the maintenance works of the case company. Thereafter, few maintenance operators were chosen as the interviewees for more detailed information of their maintenance activities. Furthermore, with the help of the production manager, two focus groups were organized to collect useful information with a strong focus on the research questions. As the managers and engineers of the maintenance department have different responsibilities from the operators’, they were divided into different groups for adapting the focus group technique. All the participants were co-operative so that large amount of data was collected from both focus groups. In addition, the use of force field in the first focus group turned out to be helpful for the improvement of the second focus group attempt. Given that the frequency of most maintenance activities in the case company varies, observations were not considered to be an appropriate choice. For instance, some of the maintenance activities were performed once every half year so that it was impossible for observing these activities.

Due to the time limit, only one case study was conducted in the thesis. However, as the case company presents a polar type (large scale manufacturer with highly automated production system), the results of the study can be viewed as useful example for other contexts. The external validity of the study can be further tested by comparing the results with related researchers. As the research process was clearly presented in the thesis, it is possible for the reader to repeat the study in other settings and check the consistency of the results.

5.4 Discussion of findings

As it can be concluded from the study, implementation of CPS will bring multiple benefits for future maintenance. However, the criteria and requirements shows that developing a CPS-based maintenance management system could not be achieved in a short period of time. It is also generally believed by other researchers that implementation of CPS in Industry 4.0 context is extremely difficult for any organization currently (J.Lee, 2015; E.A.Lee, 2015; Donovan, 2015). In spite of all the efforts have been devoted into the research of CPS and Industry 4.0, there are still
massive difficulties and problems companies need to overcome to actually implement the revolution (Geisshauer et al., 2015). Moreover, in order to take advantage from such a revolution, it requires changes and improvements to be done in every aspect of the company instead of simply focus on technological innovations (Lee et al, 2014a). For instance, besides all the technical innovations, the successful application of CPS-based maintenance management system might require a entirely new model for the organizational structure, sound training of employees to avoid the “irony of automation”, and machines designed for self-maintenance etc. These prerequisites of CPS challenge companies’ willingness to devote themselves into the development of CPS-based maintenance management systems.

The findings from the case company had shown that maintenance management could be affected by factors from different aspects other than technical shortcomings. Therefore, improvements of maintenance management need to considered and conducted in all aspects instead of focus solely on solving technical shortcomings. This opinion is also held by other researchers including Yoshida et al. (1990) and Kumar (2004) as they claimed that maintenance management needs to be considered at a strategic level. Despite the promising future bring by development of CPS and Industry 4.0, solving shortcomings related to human and organizational aspects is just as important and more likely to get quick benefits.

5.5 Conclusions

The aim of the thesis was to explore what the two popular terms “Industry 4.0” and “Cyber-Physical System” integrates regarding on maintenance management. Moreover, how such an integration may contribute to maintenance in today’s industry environment. As it can be concluded from the findings of the literature review, the emerging technologies covered by these two terms offer new solutions for the development of new maintenance strategies and techniques. Regarding maintenance management, CPS plays the role as the data-collector which gathers accurate real-time information of the production system through smart sensors and thereafter normalize, categorize, present the data to the end user. Meanwhile, the technologies covered in the term Industry 4.0 provide smart data analytics and smart devices that can self-reconfigure and self-aware. By integrating Industry 4.0 and CPS, smart devices are able to access and analyze abundant data of themselves as well as other items and thereby automatically react to current health condition. Ultimately, it will be possible to realize a self-organize and self-maintain production system that continuous function at the optimal performance without the presence of manpower.

Despite all the potential benefits bring by the CPS-based maintenance management system, it might not deserve the incredible amount of time and resources required for the implementation. With that being said, developing a CPS-based maintenance management system might only be suitable for mature large-scale companies that focus on augmentation in long-term competitiveness. Moreover, as efficiency and effectiveness of maintenance management is affected by multiple factors other than technological innovation, spending huge investments on implementing a CPS is definitely not the only way for improving maintenance management. As a matter of fact, it could probably be the least cost-effective way of improvement. Shortcomings that are related to personnel and organizational management could be solved with less expenses while being rewarded in a shorten time comparing to technological innovations. Besides, solving these shortcomings lays a solid foundation for technological revolutions. In other words, it is more effective and efficient to
implement CPS-based maintenance management after shortcomings related to human and organization aspects are resolved.
6 References


Ahmed, Mohammed Hamed. (2013). OEE can be your key, Industrial Engineer, 45(8), 43-48.


References


Carter, R. A. (2001), Shovel maintenance gains from improved designs. Tools and Techniques 106(8), S7 (Elsevier Engineering Information).


Macaulay, S. (1988), Amazing things can happen if you ... Keep it clean, *Production, May*, pp.72-74


Schlaepter, R.,& Koch, M., Challenges and solutions for the digital transformation and use of exponential technologies. *Switzerland: Deloitte*.


