THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Implementing Shop Floor IT for Industry 4.0

MAGNUS ÅKERMAN

Cover: Summary of the answers to the research questions and how they relate to each other and goals and effects of achieving an Industry 4.0 environment (see chapter 6).

Implementing Shop Floor IT for Industry 4.0

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ABSTRACT

The fourth industrial revolution, Industry 4.0, is a paradigm shift that is currently changing our society and the way we produce things. The first industrial revolution started at the end of the 18th century and was enabled by mechanisation and steam power. The spread of electricity enabled assembly lines and mass production during the first half of the 20th century, which was the second industrial revolution. Industry 3.0 came with the invention of the computer with an increase of automation such as programmable machines and robots. The fourth revolution is upcoming and is supposed to increase productivity and flexibility to the same extent as the previous three. The idea is to utilise recent advances in information technologies and the Internet to interconnect machines, tools, equipment, sensors, and people into decentralised intelligent systems that can sense and adapt to the environment.

The term Industry 4.0 was introduced 2011 by the German government as a national programme to boost research and development of the manufacturing industry. Many countries with, including Sweden, has since then started similar initiatives. The aim is to prevent further outsourcing of production to low-cost countries by improving competitiveness with increased automation and flexibility. However, the implementation is slow and many manufacturing companies have only started to computerise and are far from digitalised. There are many challenges in terms of technology, people, and organisation. Many manufacturing companies do not know how to start the process of digitalisation, they lack the knowledge and the organisation.

To implement a production environment according to the Industry 4.0 vision the manufacturing organisation and its view on technologies need to change. Part of this change is to design an information technology architecture that enables interconnection of machines, equipment, tools, and people on the shop floor. The aim of this thesis is to aid decision makers in the manufacturing industry to implement a shop floor IT according to the Industry 4.0 paradigm. This was achieved with the design science approach, which means that the researcher has implemented different artefacts (technologies) that have been evaluated. The work is based on six studies that connect to real problems found in the industry today. These studies are presented and discussed with respect to three research questions: important aspects, technological implementations, and effects. Results include concrete and practical examples of how to implement IT artefacts for the shop floor. Furthermore, it highlights the complexity of the problem and shows the need for a holistic and incremental approach.

Keywords: Industry 4.0, Cyber-Physical Production System, Interoperability, Information technology, Production, Manufacturing, Assembly.

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Gothenburg, Sweden, May 2018
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Appended publications

Paper I

Åkerman, M., Fast-Berglund, Å., Karlsson, M., & Stahre, J. (2016). Introducing Customized ICT for Operators in Manufacturing. Procedia CIRP, 41, 490-495. doi:10.1016/j.procir.2015.12.074

Contribution

Åkerman initiated and wrote the paper with contributions, content and review, from Karlsson and Fast-Berglund. Åkerman and Karlsson shared the work of data collection and analysis.

Paper II

Åkerman, M., Fast-Berglund, Å., & Ekered, S. (2016). Interoperability for a Dynamic Assembly System. Procedia CIRP, 44, 407-411. doi:10.1016/j.procir.2016.02.026

Contribution

Åkerman initiated and wrote the paper with Fast-Berglund as a reviewer. Åkerman developed the described solutions part of the overall system. The overall assembly system was developed by Åkerman, Fast.Berglund, and Ekered.

Paper III

Åkerman M., Fast-Berglund Å. (2018) Interoperability for Human-Centered Manufacturing. In: Debruyne C. et al. (eds) On the Move to Meaningful Internet Systems. OTM 2017 Workshops. OTM 2017. Lecture Notes in Computer Science, vol 10697. Springer, Cham

Contribution

Åkerman initiated and wrote the paper. Fast-Berglund acted as a reviewer.

Paper IV

Åkerman, M., Fast-Berglund, Å., Halvordsson, E., & Stahre, J. (2018). Modularized assembly system: a digital innovation hub for the Swedish Smart Industry. Manufacturing Letters. doi:10.1016/j.mfglet.2018.01.004

Contribution

Åkerman initiated and wrote most of the paper. Åkerman, Fast-Berglund, and Halvordsson developed the idea. Fast-Berglund and Halvordson contributed with content and as reviewers.

Paper V

Åkerman, M., Stahre, J., Engström, U., Angelsmark, O., Mcgillivray, D., Holmberg, T., . . . Fast-Berglund, Å. (2018). Technical interoperability for machine connectivity on the shop floor. submitted to Technologies special issue: Technologies for Industry 4.0.

Contribution

Åkerman initiated, decided the disposition, and wrote a large part of the paper. Stahre, Engtröm, Angelsmark, Mcgillvray, and Holmberg contributed with content and reviews. The paper describes project work that includes all authors.

Paper IV

Åkerman, M., Lundgren, C., Bärring, M., Stahre, J., Folkesson, M., Berggren, V., . . . Friis, M. (2018). Challenges Building a Data Value Chain to Enable Data-Driven Decisions: A Predictive Maintenance Case in 5G-Enabled Manufacturing. 28th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2018), Columbus, OH, USA.

Contribution

Bärring, Lundgren, and Åkerman initiated and wrote the major large part of the paper. The paper describes project work that includes all authors.

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3GPP	3G Partnership Project
API	Application Programming Interface
CPS	Cyber-Physical System
CPPS	Cyber-Physical Production System
EI	Enterprise Integration
ERP	Enterprise Resource Planning
HMI	Human Machine Interface
ICT	Information and Communication Technology
IoS	Internet of Services
IoT	Internet of Things
IP	Internet Protocol
ISA	International Society of Automation
IT	Information Technology
JSON	JavaScript Object Notation
LTE	Long Term Evolution
MAS	Multi-Agent System
MES	Manufacturing Execution System
NoSQL	"Not only SQL"
OT	Operational Technology
PLC	Programmable Logic Controller
REST	Representational State Transfer
SCADA	Supervisory Control and Data Acquisition
SOA	Service Oriented Architecture
SM	Smart Manufacturing
SQL	Structured Query Language

1 Introduction

This chapter presents the background, aim, and objectives. Research questions are formulated and delimitations are stated.

1.1 Background

For more than half a century, since the peak of mass production, the goal for the manufacturing industry has been to increase flexibility and responsiveness. The current paradigm is mass customisation where the aim is to mass produce individually customised products. The main trigger for this change does not come from a sudden increased demand for customised products. Globalisation, shorter product life cycles, changes in the market and demand, and fast advances in available technology, all contribute to a more volatile market, making flexible and responsive companies more successful (Spira & Pine, 1993). Coping with these demands, manufacturing companies have been moving away from dedicated manufacturing systems into flexible and reconfigurable systems to reduce the lead-time between different products (Koren et al., 1999). Flexibility is multifaceted; it is influenced by multiple factors at every level of both product and production system. Reconfigurable manufacturing systems require modularity, scalability, convertibility, and customisation while reconfigurable assembly systems also need mobility and the ability to change the degree of automation (Wiendahl et al., 2007). The next step towards customised products is called personalised production, which enables customers to be part of the design phase. Personalised production requires computational tools, i.e. digital technology, integrated with the manufacturing system (Hu, 2013). These systems, that merge the virtual world and the physical world of the production system, are called cyber-physical production systems (CPPS) which is an integral part and goal for Industry 4.0.

The term Industry 4.0 was coined in spring 2011 in Germany as a governmental strategic program aiming to modernise the German manufacturing industry ("Industrie 4.0 Plattform," 2015). It refers to the fourth industrial revolution, which suggests that new digital technologies can boost productivity comparable to the previous three revolutions (Figure 1). Industry 1.0 is the original industrial revolution, triggered by steam power in the late 18th century that enabled mechanisation. The second revolution (Industry 2.0) was triggered by the spread of electricity at the beginning of the 20th century, enabling the conveyer belt and mass production. The third industrial revolution became possible by the computer which enabled automation such as robotics, PLC´s, and CNC machines. The fourth industrial revolution, Industry 4.0, is a predicted future paradigm. Digitalisation i.e. integration of digital technologies with the production system enables CPPS that can sense its environment and quickly respond to changes.
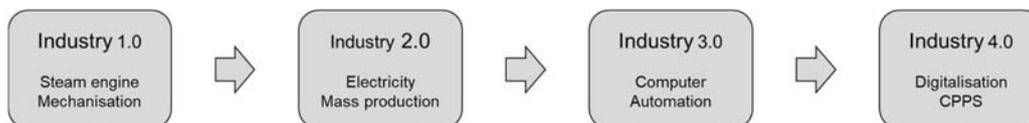
Figure 1: The four industrial revolutions from late 18th century to now.

Industry 4.0 started in Germany but quickly spread especially in Europe and is now a buzzword recognised internationally but other terms are also used to express the same concepts e.g. Smart Manufacturing (SM) that originates from the USA and is also common in other parts of the world, such as South Korea (Kang et al., 2016; Mittal et al., 2017). Industry 4.0 is based on the rapid improvements of information technologies that have transformed our society during the last decades. Smart and small devices together with Internet technologies enable interconnecting people, resources,

information, and objects into the Internet of Things and Internet of Services (IoT, IoS) (Kagermann et al., 2013). These new technologies are believed to have a huge impact on future productivity for the manufacturing industry (Manyika et al., 2013). The three main characteristics of CPPS: intelligence, connectedness, and responsiveness (Monostori et al., 2016) are all in line with the requirements that personalised production puts on manufacturing and assembly systems.

A shop floor IT is in this context defined as the information technology (IT), hardware and software, that is involved with the production processes and the operational organisation. With this definition, as will be more evident after reading chapter 3, the scope of the shop floor IT is widening and a strict border will eventually be difficult to find. The shop floor IT must be implemented to support future manufacturing and assembly systems as well as support functions e.g. maintenance and logistics. Production systems are socio-technical systems and shop floor IT must support both the technical parts and the humans. The IT system is an integral part of the production system, which means that if the production system needs to be reconfigurable and responsive, the IT system must follow the same principles. This requires that we change the traditional way of designing shop floor IT.

The current view of industrial and automation IT architecture is the 'automation pyramid'. This hierarchical model vertically cuts the systems of manufacturing operations into different levels that can be connected to certain types of information, systems, and timeframes, which have been defined in a standard model by International Society of Automation (ISA) (ANSI/ISA, 2005). The model, called ISA 95, is visualised in Figure 2. The top level is concerned with business planning and logistics and is often managed in an Enterprise Resource Planning (ERP) system. The level below controls the manufacturing operations, such as what processes should be executed and in what order. Systems that manage this are called Manufacturing Execution Systems (MES). Below that is the monitoring and supervision level where equipment is monitored through a human machine interface (HMI) or a supervisory control and data acquisition (SCADA) system. The equipment is controlled by the sensing and manipulating level, usually by a programmable logic controller (PLC).
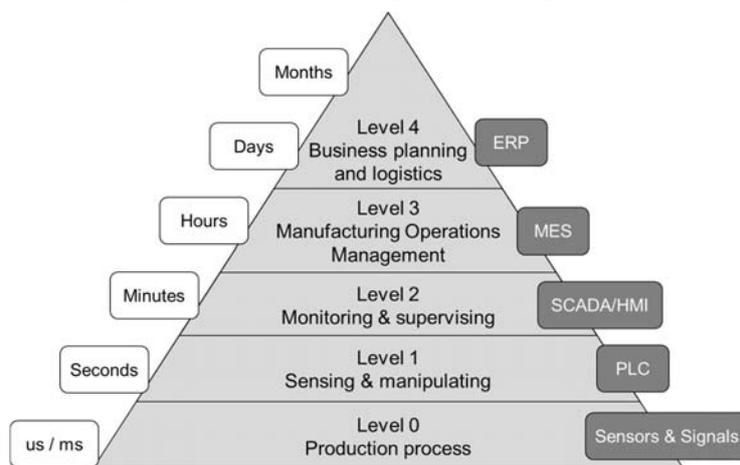

Figure 2: The automation pyramid according to the ISA 95 model. The five levels, 0-5, are defined in the middle. At each level, the typical system(s) used are showed to the right. Different levels are concerned with different timeframes which are visualised to the left.

A key characteristic of Industry 4.0 systems is decentralised decision-making (Alan et al., 2015; Mittal et al., 2017), which means that the common hierarchical layout of shop floor IT needs to change. The idea is that every entity of the system becomes more autonomous with the ability to communicate directly with any other part of the system. To achieve this there are three aspects of systems integration that needs to be solved: vertical networking, horizontal integration, and end-to-end engineering (Kagermann et al., 2013).

Vertical networking, or vertical integration, aims to flatten the automation pyramid and reduce the number of steps between decision and system control. The biggest challenge with vertical integration is to merge two different types of networks: the industrial communication network for automation, called field level network, and the traditional office network connecting information systems together, based on Internet technology and the Internet Protocol (IP), known as IP network. This has been a continuous effort for decades but there is still some way to go (Thilo Sauter, 2010). Horizontal integration means to improve information sharing between vertical organisations, which adds an organisational aspect to the automation pyramid. Both vertical and horizontal integration are required to achieve end-to-end digital integration for engineering, which allows for seamless communication across the value chain.

If systems integration is the goal, then interoperability is the means to achieve it. Interoperability can be described as the ability for one entity to perform operations for another. This interoperation can apply to two or more pieces of software, processes, systems, business units, etc. (F. B. Vernadat, 2010). To maintain flexibility, interoperable systems do not fully integrate entities with hard coupled connections. Instead, a more federated approach is preferred where communication is managed more dynamically (David Chen & Daclin, 2006). Because there are so many aspects of system integration in a future heterogenic IT environment, interoperability has become a research priority for Industry 4.0 (Thoben et al., 2017).

The vision to manage integration challenges and build interoperable systems is to utilise new and existing information technologies on the shop floor. Connectivity of ubiquitous equipment has already been mentioned together with the IoT paradigm. For free connectivity, without a strict hierarchical structure, the most discussed solution is to use a service-oriented architecture (SOA), which has successfully achieved interoperable Internet-based applications. Another important enabling technology is Big Data applications, which utilises data analytics to predict system behaviour, enabled by IoT, IoS, and Cloud Computing. The theoretical and technical foundations for realizing the vision of Industry 4.0 are, at least to some extent, already in place. However, in general, the manufacturing companies have not reached very far in the pursuit of digitising their production systems. Most companies utilise pen and paper for many documentation tasks, and in terms of computerisation on the shop floor, this often does not stretch further than utilising digital applications to create e.g. work instructions.

1.2 Aim and research questions

Industry 4.0 was introduced in 2011 and has since then become the dominant current manufacturing paradigm for state of the art production systems. However, current shop floor systems do not follow the architecture set up by the Industry 4.0 vision, which means that the promised productivity gains are absent. Therefore, the aim of this thesis is to aid decision makers in the manufacturing industry to implement a shop floor IT according to the Industry 4.0 paradigm. Three research questions have been formulated to guide the research towards the aim.

RQ1

The first research question focuses on the connections between the three different areas involved with the aim: shop floor, IT, and Industry 4.0. To understand where these areas are related and how the following question is stated: *What aspects are important when implementing a shop floor IT according to Industry 4.0?*

RQ2

Based on the characteristics from RQ1, the second question is related to the actual implementation phase of shop floor IT. There are no limitations as to how to implement the entire shop floor system since each system is unique, including its IT, but to understand how it could be done good examples are needed. Therefore, the second question is: *How can a shop floor IT be implemented to enable an Industry 4.0 environment?*

RQ3

To close the loop, the implementation methods from RQ2 should enable the capabilities that are promised in the Industry 4.0 paradigm. The third question is: *What are the effects of implementing a shop floor IT according to the Industry 4.0 paradigm?*

1.3 Delimitations

The scope of this thesis is limited to the implementation of the shop floor IT. Shop floor IT is defined as the information technologies, software and hardware, that enables digital applications in production (Figure 4). This means that promising digital applications, even if described for reasons of clarification, are not of focus. Such digital applications include but are not limited to multi-agent systems (MAS), algorithms for data analytics, augmented and virtual reality applications, enterprise systems, robotics, assembly systems, etc.
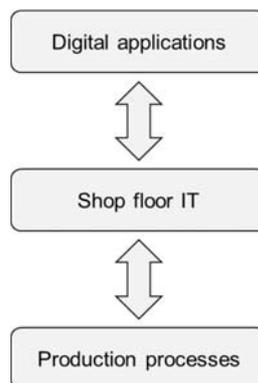
Figure 3: The scope of this thesis is limited to implementing shop floor IT, which lies between the production processes and digital applications in production.

Cyber-security is often brought up as an important factor for Industry 4.0 implementation but that subject is also excluded from this work.

1.4 Thesis outline

The thesis consists of seven chapters followed by the appended papers.

1. Introduction: The introductory chapter introduces the research area, presents the aim and research questions as well as delimitations and this outline.

2. Methodology: Describes the research approach, design, and the methods used. The research approach is partly based on the research questions found in the introduction chapter. How the methodology connects to the research is further reflected upon in the discussion chapter.

3. Theoretical framework: The theory chapter consists of three parts. The first part describes the concept of Industry 4.0 and how it relates to other similar concepts. The second part goes into the aspects of shop floor IT from a historical perspective. The third part is an overview of the different existing and future technologies that can enable Industry 4.0.

4. Summary of appended papers: Presents a short summary of each of the six appended papers.

5. Answers to the research questions: Provides answers to the research questions by discussing the results from the appended papers and theory.

6. Discussion: This chapter discusses the answers to the research questions on a holistic level. Furthermore, the scientific and industrial contribution, as well as the validity of the research, are discussed.

7. Conclusions: Concluding remarks of the thesis.

2 Methodology

This chapter describes the research approach, design, and the methods used. The research approach is partly based on the research questions found in the introduction chapter. How the methodology connects to the research is further reflected upon in the discussion chapter.

2.1 Research approach

According to Creswell (2014), the research approach should be influenced by the researcher's worldview, personal experience, and the nature of the research problem. The selected approach should then influence the research design, which are the procedures of inquiry, and what specific methods to use. The practical nature of the research problem, derived from the research questions, follow the applied research paradigm. Applied research, opposed to basic or fundamental research, is designed to solve practical problems (Williamson et al., 2002). The pragmatic worldview is fitting for practical applied research problems and a pragmatic researcher is interested in consequences of actions, is problem-centered, pluralistic, and focused on real-world problems (Creswell, 2014).

As briefly described in chapter 1, Industry 4.0 can be derived from the merging of two fields, production engineering and software sciences. The research questions relate to two distinctly different types of research, implementing technology (RQ2) and exploring aspects and effects (RQ1 and RQ3). Furthermore, with a deep knowledge and experience in software development, it was natural for the researcher, in the context of implementing an information system (shop floor IT), to actively participate in the design, development, and evaluation of innovative information technologies as part of the research procedure. Therefore, the research approach of this thesis should connect to the research paradigms from both social sciences and the computer science field. These two aspects are embedded in an established approach used for designing and evaluating information systems, it is called design science.

2.2 Design science research

As defined by A. Hevner and S. Chatterjee (2010), "design science research is a research paradigm in which a designer answers questions relevant to human problems via the creation of innovative artefacts, thereby contributing new knowledge to the body of scientific evidence. The designed artefacts are both useful and fundamental to understanding that problem." The paradigm originates from the work of Herbert E. Simon who separated the science of the artificial from natural sciences since the design of the artificial depends on the goal of the designer (A. Hevner & S. Chatterjee, 2010).

In the domain of information systems, Nunamaker Jr et al. (1990) developed a five-step process for system development research where each step is connected to different research challenges. The steps are: Construct conceptual framework, develop a system architecture, analyse and design the system, build the (prototype) system, and observe & evaluate the system. This was later elaborated upon into a research methodology framework (see Table 1) (A. Hevner & S. Chatterjee, 2010; Peffers et al., 2007).

Table 1: Design Science Research Methodology (DSMR), adopted from (A. Hevner & S. Chatterjee, 2010; Peffers et al., 2007).

Activity	Description
1: Problem identification and motivation	Define the problem and justify why it needs a solution. The justification happens with motivation and acceptance of the results.
2: Define the objectives for a solution	The goals (requirements) of what the artefact should accomplish, which could be explained qualitatively or quantitatively.
3: Design and development	This is where the researcher creates the artefact, which could be constructs, models, methods, or instantiations (applications).
4: Demonstration	Demonstrate that the artefact solves the defined problem in one or more ways. This activity can involve empirical methods like experiments, simulations, case studies etc. or logical proof.
5: Evaluation	In the evaluation step, the artefacts ability to solve the problem is measured and evaluated. Like with a demonstration, this activity can be done with any appropriate empirical method or logical proof.
6: Communication	Disseminate the problem, solution, and evaluation results to relevant audiences.

To further explain the design science paradigm for information system research, Hevner et al. (2004) proposed the information system research framework (see Figure 4). IS research is represented in the middle with the activities to design and evaluate artefacts. The design is both relevant (useful) and rigorous (true) because it is based on both the practical needs of appropriate environment and applicable knowledge from the appropriate knowledge base. The appropriate environment, with its people, organisations, and technology, can be improved when the artefact is applied as an application. Also, the knowledge base, with its foundations and methodologies, can receive new additions from the design research.
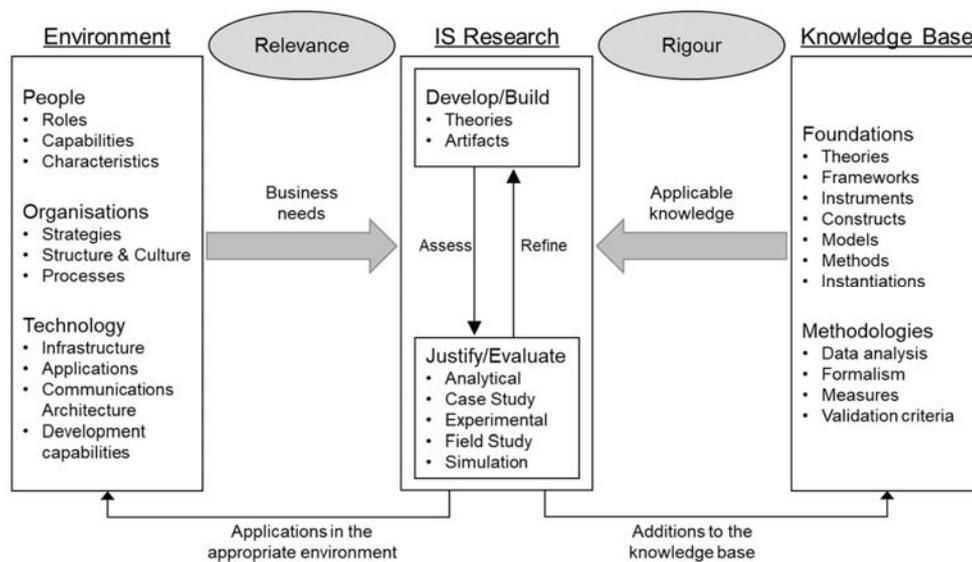

Figure 4: Information systems research framework, adapted from (Hevner et al., 2004).

2.3 Research design

As mentioned in Table 1, evaluation can be done different ways. Hevner et al. (2004) mention 12 different evaluation methods, see Table 2. In this thesis, four of these are used: case study, experiment, architectural analysis, and informed argument.

Table 2: Design evaluation and demonstration methods, adapted from (Hevner et al., 2004).

Observational	Case study: An in-depth study in an appropriate environment.
	Field study: Monitor use in multiple projects.
Analytical	Static analysis: Examine the structure of artefact for static qualities.
	Architecture analysis: Study fit of artefact in technical architecture.
	Optimisation: Demonstrate inherits optimal properties of the artefact.
	Dynamic analysis: Study artefact in use for dynamic qualities.
Experimental	Controlled experiment: Study artefact in controlled environment.
	Simulation: Study artefact with artificial data.
Testing	Functional testing: Black box testing. Look for failures.
	Structural testing: White box testing. Test holistically by some metric.
Descriptive	Informed argument: Use knowledge base to build a convincing argument.
	Scenarios: Construct detailed scenarios around the argument and demonstrate its usefulness.

In the paper I, the artefact is evaluated through a case study, which requires some further elaboration. According to Yin (2014), a case study is an empirical method of inquiry that "investigates a contemporary phenomenon in depth within its real-life context", and is especially useful when the "boundaries between phenomenon and context are not clearly evident". The evaluation in paper II is done in an experimental setup, meaning that the artefact was tested together in a laboratory environment. In papers III, and IV, the artefacts are theoretical and the evaluation is logically derived from existing knowledge. In paper V, the artefacts are tested in a real production environment The evaluation method could be viewed as a case study but the term architecture analysis probably is a better fit, meaning that the artefacts are analysed in regards to how well they fit the overall technical architecture (Hevner et al., 2004).

There are two main branches of design science: design as research and researching design (A. R. Hevner & S. Chatterjee, 2010). Design as research means, as described above, that the designed artefact somehow contributes to the knowledge base. Research design looks inward towards the design, designers, and design process. The appended papers I to V belong to the design as research branch, meaning one or several artefacts were designed, by the researcher, author, or other, and that these artefacts were useful to the knowledge base and sometimes also useful to the appropriate environment, which in this case is the production system. Paper VI presents a study that fits the researching design branch since the focus is towards the designers' collaboration and knowledge. Table 3 is a list of the appended papers with a brief description of the research presented from a design science perspective.

Table 3: *Brief description of the research approach for each of the appended papers.*

Paper	Type of research	Designer(s)	Artefact/artefacts	Focus and research activities	Evaluation method	Artefact(s) contributed to
I	Design as research	Other	ICT for operators	Evaluation of customised mobile application	Case study	Heat treatment facility and knowledge base
II	Design as research	Researcher Researcher	No PLC RFID reader Web service and application	Design, development, and demonstration of the IT part of a mobile and dynamic assembly system	Experiment	Assembly system in laboratory environment and knowledge base
III	Design as research	Authors	Interoperability framework for human-centred manufacturing	Problem definition, design, and demonstration of a framework based on previous designs and knowledge base	Informed argument	Knowledge base
IV	Design as research	Authors	Conceptual IT architecture for a flexible production system	Problem definition, design, and demonstration of a framework based on knowledge base	Informed argument	Knowledge base
V	Design as research	Authors	Technical solutions to connect a grinding machine to a cloud	Objective definition, design, development, demonstration, and evaluation of stationary and mobile solutions using 5G connectivity	Architecture analysis	Production system and knowledge base
VI	Researching design	Authors	Digital value chain for Big Data applications	Knowledge gap between designers' different domain	N/A	Production system and knowledge base

3 Theoretical framework

This chapter provides the theoretical framework. It consists of three parts. The first part describes the concept of Industry 4.0 and how it relates to other similar concepts. The second part goes into the aspects of shop floor IT from a historical perspective. The third part is an overview of the different existing and future technologies that can enable Industry 4.0.

3.1 Industry 4.0

Before the concept of Industry 4.0 was introduced, the SmartFactory[KL] initiative had already pushed the boundaries of incorporating smart sensors and IoT for industrial applications. The SmartFactory[KL] is a functional demonstration and development platform focusing on integrating information and communication technologies (ICT) in automated systems and emphasises modularity, decentralisation, standardisation, self-organisation, and human-centred technology (Zuehlke, 2008). These ideas were developed into the German national research programme Industrie 4.0, introduced at the Hannover Fair 2011, with the aim to reindustrialise and modernize the German manufacturing industry ("Industrie 4.0 Plattform," 2015). Since then, many countries have followed with their own strategic initiatives like the 'Advanced Manufacturing Partnership' in the USA ("President Obama Launches Advanced Manufacturing Partnership," 2011) or 'Made In China 2025' (Wübbeke et al., 2016). In Japan, the government is pushing the implications of their R&D programme by calling it 'Society 5.0' (*Report on The 5th Science and Technology Basic Plan*, 2015). As a buzzword, Industry 4.0 quickly gained traction internationally but outside Europe, the term 'Smart Manufacturing' is very popular, which originates from USA (Mittal et al., 2017). Industry 4.0 and SM differ mostly in name, and common goals are towards data focused supply networks, ICT and automation integration, increased automation and keeping the human in the loop (Thoben et al., 2017).

The vision of Industry 4.0 can be realised with Cyber-Physical Systems (CPS), or more precisely, Cyber-Physical Production Systems. CPS are systems that can sense and interact with their environment in real-time while CPPS are production systems where these ideas have been fully implemented (Monostori et al., 2016). CPPS is possible because of the merger between the virtual (cyber) and the physical worlds. A rapid development of information technology in the last decades has enabled interconnected production systems through Internet technologies known as the Internet of Things (IoT) and the Internet of Services (IoS). With the advances of Cloud Computing and Big Data application, it is also possible to collect and analyse the large amount of data that is accessible in a production system (Kagermann et al., 2013).

When examining the literature, Hermann et al. (2016) found four design principles on which Industry 4.0 systems are based: interconnection, information transparency, decentralised decisions, and Technical assistance (see Figure 5). The interconnection principle is the most fundamental requirement. It means that machines, devices, sensors, and people need to be connected to enable communication and collaboration. Information transparency means to collect data from the virtual and the physical world and combine it into context-aware information. With usable information, decision makers, humans or machines, can make decisions based on facts. Decentralised decisions are important to reduce the complexity of the many different autonomous decision makers involved. Finally, technical assistance for human workers becomes more important in an Industry 4.0 environment because of the increased complexity and the change towards more strategic tasks.
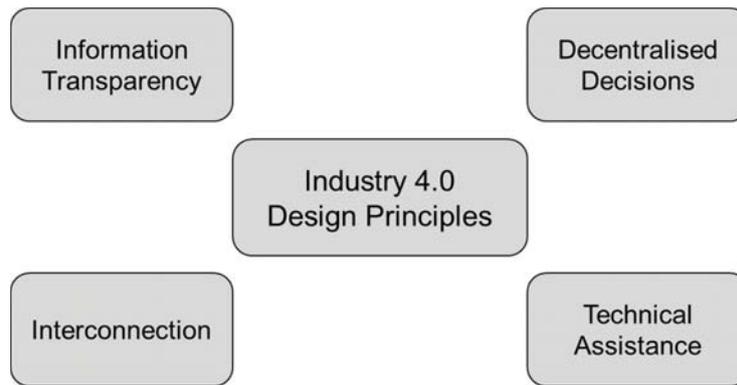
Figure 5: Industry 4.0 design principles, adapted from (Hermann et al., 2016).

There are two similar models for CPPS that, to no surprise, are very similar to the design principles described above (see Figure 6). The first one is the 5C architecture (Lee et al., 2015), which describe how a CPPS can be designed in five levels: Connection, Conversion, Cyber, Cognition, and Configuration. The second is the Industry 4.0 maturity index (Schuh et al., 2017) that includes six steps that indicates how far a company has reached towards implementing Industry 4.0. Let's first examine the 5C architecture. In the first level, Connection, data is collected from 'smart' sensors or software systems. Having the data enables condition monitoring of the system. The second level is the conversion level, here, value is added to the data by computation or analytics, this provides self-awareness to individual machines/sub-systems. The third level is the Cyber level, this acts as a central information hub where all information is gathered. This enables machines and sub-systems to compare information with similar systems. All this information is presented in the Cognition level, allowing proper decision support. In the last level, configuration, the system self-adapts based on the information from the lower levels.
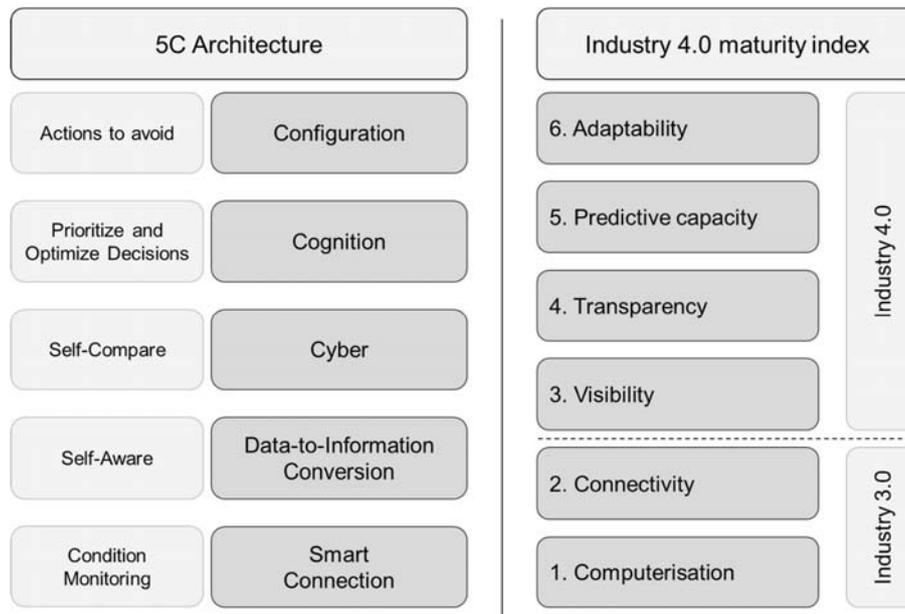
Figure 6: Two models of CPPS, the 5C architecture and Industry 4.0 maturity index. Adopted from (Lee et al., 2015) and (Schuh et al., 2017).

The Industry 4.0 maturity index is not an architecture, it is more focused on achieved capabilities than how to implement them. The 5C architecture is, therefore, a way to achieve Industry 4.0 maturity. The first two levels of the maturity index are capabilities that can be achieved by computerising and connecting systems, which predates Industry 4.0. When computerisation and connectivity are achieved, it is possible to create a single source of truth, or a digital shadow, which is the visibility step. In the transparency step, the data from the digital shadow is aggregated, computed, or analysed to understand what is happening. In the fifth step, predictive capacity, a company can combine different results and perform more analysis or simulations to produce multiple future scenarios and predictions. And finally, in the adaptability step, there is a feedback loop that automatically adapts the system based on the results.

These models go quite far considering many companies are not even computerised or connected today. To solve these more acute problems, it can be better to step back and look at some other perspectives. The same year Industry 4.0 was released, Gartner discussed the same ideas but as the merger of IT and OT (Operational Technology) ("Gartner Says the Worlds of IT and Operational Technology Are Converging," 2011). With operational technology, they meant physical-equipment-oriented technology that had been developed separately from IT. This sounds like it is the same as for Industry 4.0 and SM, which it is for the manufacturing industry. However, in this case, the industry is not specified and among mentioned industries, we find healthcare, transportation, energy, aviation, mining etc. This wider perspective is important to consider since it is the same enabling technologies (IT) that are targeted.

An important principle for Industry 4.0 and SM are decentralised decisions (Hermann et al., 2016; Lasi et al., 2014). Decentralised systems require that every entity can communicate with any other entity in a free and open environment, which emphasizes interoperability (Alan et al., 2015).

Interoperability

Interoperability "is the ability for two systems to understand one another and use the functionality of one another" (Chen et al., 2008). Interoperability is often divided into four levels: technical, syntactical, semantic, and organisational (Rezaei et al., 2014). Technical interoperability is the hardware/software aspects of systems connectivity. Syntactic interoperability concerns how data is transferred, usually managed by standardised communication protocols. At the semantic level, the data is used according to agreed-upon definitions and includes both humans and other systems. Organisational interoperability measures how well entire organisations can exchange data and information. To reach each interoperability level requires successful implementations of the levels below. (Rezaei et al., 2014).

From the enterprise perspective of interoperability, Koussouris et al. (2011) came up with 12 areas of interoperability issues. These areas were categorised into four granularity levels where issues from lower levels are sub-sets of the higher levels. How these are connected can be viewed in Figure 7.
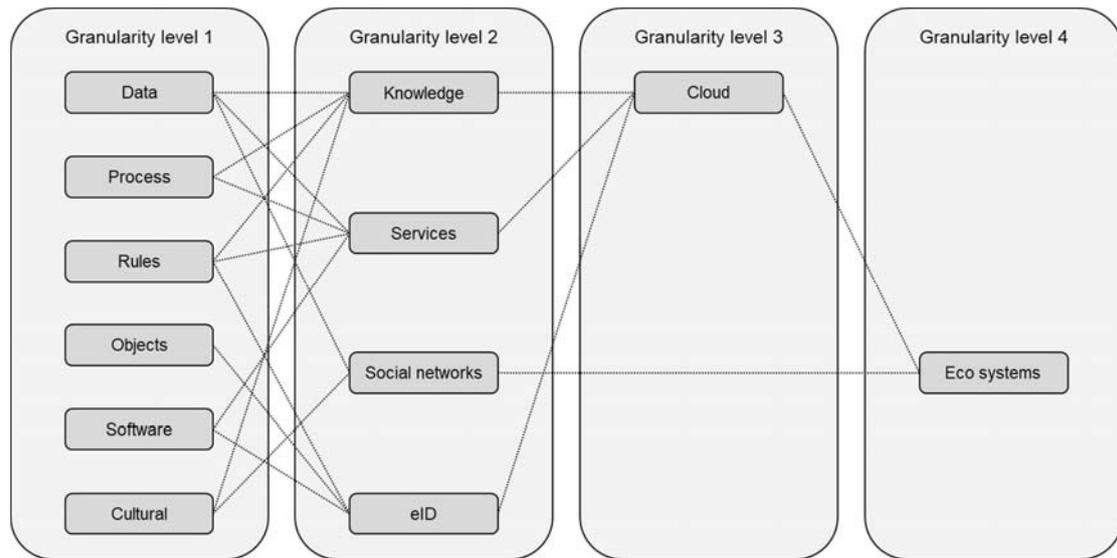
Figure 7: Areas of interoperability issues (Koussouris et al., 2011). Illustration adapted from (Rezaei et al., 2014).

3.2 Shop floor IT

Figure 8 shows the evolution of the state of the art of shop floor IT and enterprise systems from 1980 until now. Shop floor IT manages the automation and information systems involved in manufacturing operations and interactions with business and support functions. As explained in the introduction, Industry 4.0 changed the previous view of the hierarchical automation pyramid. The lower part of this pyramid is the field level network. This was, in the beginning, the only digital part of the shop floor IT, which at that time was not a pyramid but only separated islands of automation systems. The pyramid was cemented when software systems were introduced at the higher levels to connect business functions with manufacturing operations. The field, dealing with these connections is called Enterprise Integration (EI).

EI is a part of the Industrial Engineering community that has focused on manufacturing systems engineering and building enterprise architecture frameworks for that purpose (Romero & Vernadat, 2016). The goal of enterprise integration is to improve the interactions between people, departments, services, and companies and interoperability is the ability for two entities to interact (or interoperate) (F. B. Vernadat, 2007). The range of integration goes from fully integrated, tightly coupled, systems where entities are inseparable from each other to a loosely coupled system where entities can exchange information but are not dependent on each other (Chen et al., 2008). Interoperability is the means by which to achieve integrated systems.
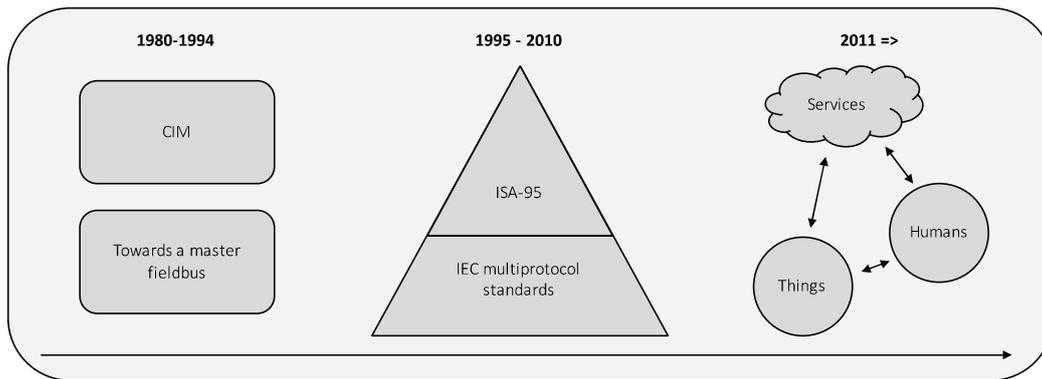
Figure 8: History of principle architecture of shop floor IT since 1980.

1980-1994

Between 1985 and 1996 the European organization AMICE Consortium worked with definitions and architecture design at an operational level, referred to as Computer Integrated Manufacturing (CIM) systems (Doumeingts et al., 1995). This work resulted in the Open System Architecture for CIM (CIMOSA). In parallel, the GRAI/LAP laboratory at the University of Bordeaux developed their own framework to support enterprise integration. GIM or GRAI Integrated Methodology (D. Chen et al., 1997). CIMOSA and GIM/GRAI are both products of European efforts but at Purdue University of Indiana (USA) another framework was developed under the name Purdue Enterprise Reference Architecture (PERA) (Theodore J. Williams, 1994). PERA is a reference architecture including both human and manufacturing components. These three frameworks were selected when an IFAC/IFIP task force decided to develop a unified model. The result was Generalized Enterprise Reference Architecture and Methodology or GERAM. The framework was supposed to aid the integration of the various parts of an enterprise like products, processes, development, and management (*Handbook on enterprise architecture*, 2003). The general focus during this era referred to as "the CIM era", was to integrate technology and find a "best" design model for the entire information system (T.J. Williams et al., 1994).

The early implementations of ERP systems utilized a general-purpose architectural strategy since that allowed for customization. The customizations for manufacturing enterprises were supposed to align with the CIM frameworks, but that proved to be difficult. Complex proprietary systems were created that were difficult to reconfigure and combine with other systems. Regarding the enterprise modelling frameworks, they were regarded to be very useful but keeping them up to date was identified to be very difficult (Kosanke et al., 1999). Furthermore, the enterprise integration projects didn't manage to meet the high expectations of the time, they were too complex and impractical (Chen et al., 2008; F.B. Vernadat, 2002). Some similarities in the industrial automation field could be seen in the search for a universal fieldbus. Later that idea was discarded and international standards supporting multiple protocols were created instead (Thilo Sauter, 2010).

1995-2010

ISA-95 was developed from the CIM frameworks and it includes processes, activities and information types that are required for business and manufacturing operations (ANSI/ISA, 1999). ISA-95 defines information types and activities but clearly states that correct implementation and integration of the different functions depends on the manufacturing process (ANSI/ISA, 2005). The customizable enterprise systems had to be reduced in complexity by implementing more domain-specific modules. The usefulness of the domain-specific approach was identified and further developed into the IERP (Industry-oriented ERP) systems. The main advantage of the IERP systems, with more emphasis on the domain-specific architecture, was the possibility to reuse software components (Wu et al., 2009).

The network setup of an automation control system is hierarchal with very many vertical levels. The logic in such systems lies in the Programmable Logic Controllers. A group of controllers may be supervised with a SCADA system. Human machine interfaces give human operators direct or indirect control of equipment or processes. SCADA systems can collect, filter and present information about the current state of the manufacturing process.

Merging the field level network with IP networks still has some way to go but in general, there has been a large success in flattening the automation pyramid (Thilo Sauter, 2010). Three previously separated data types are now possible to combine: production, personnel and quality assurance. This led to a new type of management system known as Manufacturing Execution System (*Manufacturing Execution Systems – MES*, 2007). The fifth part of ISA-95, which is still being developed, deals with the communication between the business and manufacturing processes. Within this part, an XML implementation called B2MML has been developed and is managed by MESA (Manufacturing Enterprise Solutions Association) (MESA, 2013).

During the 1980's many propriety field-bus systems disappeared and it became clearer that standardization and openness were crucial factors for survival (Thilo Sauter, 2010). The next step was to adopt the Ethernet interface to allow for future IP based communication. Several Industrial Ethernet standards were developed which advanced the propriety systems to the transportation layer. This change simplified physical connectivity but there was a need for a system that could collect data from different types of field-bus systems e.g. to set up a SCADA system. OPC (Object Linking and Embedding for Process Control) became the de-facto standard for this types of connectivity quickly after it was released in the late 1990's (OPC Foundation, 2016).

Challenges during this era were to align the semantics over the different layers by applying standards and middleware. Overall integration did come a long way but problems emerged when systems were scaled up and the technological platform lacked in maturity (Chen et al., 2008; Panetto & Molina, 2008).

2011-

The concept of enterprise modelling and integration continues to grow in scope and now has a very holistic perspective (Romero & Vernadat, 2016). In order to interconnect the large heterogeneous future systems enterprise architectures need to become less rigid and more decentralized (Mourtzis & Doukas, 2012). The third generation of ERP systems was designed to handle a much broader spectrum of information types, e.g. social aspects, human resources and their knowledge. The Service-Oriented architecture approach is considered crucial for the success of highly complex ERP systems of the future. SOA has many advantages for integration, extensibility, agility, and reusability (Rosen, 2008).

Utilizing service oriented web-based systems can enable decentralization of process planning decisions (Wang, 2013). A future scenario would be to incorporate the cloud service models in the manufacturing process into a cloud manufacturing model (X. Xu, 2012). The hierarchy model is

continuously being flattened but the focus is also towards horizontal integration, logical (functions) and physical (geographical) inter-domain communication. Openness increases in importance and one example of this is the OPC-UA platform (Grossmann et al., 2008).

IoT technology is becoming an alternative to interconnect e.g. smart sensors. Cellular networks and Wi-Fi networks are becoming a serious alternative for industrial connectivity. Future 5G networks are commonly discussed as a promising technology to enable ubiquitous and scalable connectivity for the shop floor.

3.3 Technologies enabling Industry 4.0

In the previous sections, it is shown how the shop floor IT and the enterprise systems have slowly merger together and that this is a general trend that is happening in many industries. This change is being enabled by technological innovations in computer science and surrounding fields that have already changed so much. This section will briefly go through some of these technologies.

5G

Wireless technologies are not usually considered for shop floor IT. First, the requirements for low-level machine communication have not been met with wireless systems. Second, most connected machines and equipment are fixed so why bother. This viewpoint is now changing. With many more connected industrial things, it will be inconvenient, or perhaps impossible, to connect everything with wired systems. Furthermore, a flexible and reconfigurable system also requires higher mobility. Therefore, it is believed that the next generation of cellular wireless technologies, 5G, will be an important enabler for Industry 4.0. 5G technologies will be built on the current cellular system called Long Term Evolution (LTE), it does not exist yet but initial rollout is set for 2020. Currently, the requirements for 5G are being defined and standardised through the 3G Partnership Project (3GPP) ("3GPP TS 22.261: Service requirements for the 5G system; Stage 1," 2017). The key to why 5G will be such a big difference from current cellular and wireless technologies lies in the diversity of future use case scenarios that the requirements are based on.

Scenario family	Requirements			
	Data rates	Latencies	Mobility	Density
Broadband access in dense areas	DL: 25 Mbps – 1 Gbps UL: 50 Mbps – 500 Mbps	10 ms	Pedestrian 0-100 km/h	200 – 150 000 / km²
Broadband access everywhere	DL: 10 Mbps – 50 Mbps UL: 10 Mbps – 25 Mbps	10 ms - 50 ms	On-demand 0-120 km/h	16 – 400 / km²
High user mobility	DL: 15 Mbps – 50 Mbps UL: 7.5 Mbps – 25 Mbps	10 ms	Cars (<500 km/h) Airplanes (<1000 km/h)	Cars (2 000 / km²) Airplanes (~0.3 / km²)
Massive IoT	Low power (1-100 kbps) Broadband (50+ Mbps)	Low power (seconds) Broadband (10 ms)	Low power (0-500 km/h) Broadband (0-100 km/h)	200 – 200 000 / km²
Real-time communication	DL: 25 Mbps UL: 25 Mbps	<1 ms	Pedestrian	Not critical
Lifeline communication	DL: 0.1-1 Mbps UL: 0.1-1 Mbps	Not critical	On demand	10 000 / km²
Ultra-reliable commnunication	DL: <= 10 Mbps UL: <= 10 Mbps	1 ms - 10 ms	On demand	Not critical
Broadcast	DL: <= 200 Mbps UL: Low	<100 ms	On demand	Not critical

Figure 9: 5G use case scenarios and their requirements, adapted from (NGMN 5G Whitepaper, 2015).

17

These scenarios include high bandwidth, mobility, IoT, and real-time communication (*NGMN 5G Whitepaper*, 2015). Since the requirements are so diverse (see Figure 9) it will require different technologies to accommodate them and it will not be possible to fulfil all requirements everywhere.

SOA

Loosely coupled systems enable interoperability without forcing homogeneity (F. B. Vernadat, 2007). A way to achieve this is through the service oriented architecture that consists of service providers and consumers. A service is a self-contained logical representation, that fulfils a function and has a specified outcome. A service may contain other services and must not expose its implementation or have any side effects (it should be perceived as a black box). (The Open Group, 2009). SOA was adopted as a solution to the WWW problems with Web Services. A Web Service is an implementation of SOA with Web standards like HTTP, XML, and JSON (JavaScript Object Notation) (W3C Working Group, 2004). A common web service design is the REST API (Representational State Transfer Application Programming Interface) model. REST uses stateless interactions and a hierarchical resource representation among other features to emphasise scalability, interface uniformity, and more (Fielding, 2000).

IoT technologies

Internet of Things is the merge of three visions: internet-oriented, things-oriented, and semantic-oriented (Atzori et al., 2010). These visions are realized by middleware (often utilising SOA), sensors and identification technology (e.g. RFID), and object abstraction. According to Gubbi et al. (2013), any IoT application consists of three parts: hardware (things), middleware (storage and computing tools), and presentation (accessible visualisation and interpretation tools). The number of IoT technologies, meaning software tools that aids development of IoT applications, is increasing rapidly. There are different ways of categorising these technologies (Gubbi et al., 2013; Ngu et al., 2017), often referred to as IoT Platform. The most profound difference is in the layout, centralised (cloud- or service-based systems) or decentralised (actor-based) (Ngu et al., 2017). In the extreme case of a centralised structure, we have a high-performing service-based platform. Such systems create a digital model of connected things and connect them using services. Thingworx, which is mentioned in appended paper IV, is an example of a service-based platform. On the other end of the scale, actor-based systems allow the software to be distributed over different hardware. This allows for end-to-end connections, unlike with a service-based platform. Since they allow a decentralised architecture, actor-based IoT middleware works well with limited hardware that can be placed close to the data-source, like sensors or smart watches. This distributed way of building IoT applications are also known as edge-computing (Shi et al., 2016), fog-computing (Giang et al., 2015), or 'swarmlets' (Latronico et al., 2015). Calvin (Persson & Angelsmark, 2015) is an actor-based platform mentioned in appended paper V.

Cloud Computing

Cloud computing is a paradigm that promotes sharing of computational resources. Scalability is a major benefit of cloud computing but other benefits include flexibility, better resource utilisation, and simplified management (Armbrust et al., 2010). The most shared definition of cloud computing has been defined by NIST and is stated here below (Mell & Grance, 2011).

'Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. This cloud model is composed of five essential characteristics, three service models, and four deployment models.'

The five characteristics are listed in Table 4 and they explain different ways in which resources and capabilities are distributed.

Table 4. Characteristics of Cloud Computing systems (Mell & Grance, 2011).

1	On-demand self-service	The consumer can acquire more capabilities when needed and without further interactions with the service provider.
2	Broad network access	The capabilities can be reached by standard mechanisms.
3	Resource pooling	The consumer has a sense of location independence of the physical resource.
4	Rapid elasticity	Capabilities can be rapidly increased and reduced, possibly even automatically with current demand.
5	Measured service	The system automatically measures the delivered service capabilities in an appropriate way.

Service business models

Cloud computing enables service-based business models and there are three main models for cloud services: Software-as-a-Service (SaaS), Platform-as-a-Service (PaaS), and Infrastructure-as-a-Service (IaaS).

Deployment models

The four deployment models are public cloud, private cloud, hybrid cloud, and virtual private cloud (Zhang et al., 2010). In a public cloud, service providers offer their resources publicly. Private clouds are exclusively used by one organisation, managed by the same or an external service provider. A hybrid cloud uses a mix of the public and private deployment model. And finally, the virtual private cloud is a virtual platform that runs on top of a public service and is accessed through a virtual private network (VPN).

Cloud computing technologies

For service consumers, cloud computing is convenient since it removes or reduces the need to manage the software and hardware needed, depending on the chosen business model. For service providers, there are several technologies available today that enable the cloud computing paradigm. Basically, cloud computing is built on one or several data-centres, which are centralised hubs with thousands of computers, switches, and routers. The architecture of data centres is very important but that topic is out of scope for this thesis, more information can be found in (Al-Fares et al., 2008). When the data centres are set up, technologies are needed that can distribute data between the different hardware nodes. The open-source project Apache Hadoop contains several software tools that enable reliable and scalable distributed computing ("Apache Hadoop,"). One of them, Hadoop Distributed File System (HDFS[TM]), is mentioned in the appended papers. HDFS and Hadoop MapReduce are based on technologies from Google. The distributed file systems divide files into chunks and spread them out over multiple devices to achieve reliability and high capacity while MapReduce is used to distribute computational work (MapReduce jobs) (Zhang et al., 2010).

Database technologies are also important in a cloud infrastructure. Because of great flexibility and scalability, so-called NoSQL databases (reads "Not only SQL", SQL - Structured Query Language) have been increasing in popularity ("NoSQL,"). A NoSQL database is generally a database that does not use the language SQL to query the database. According to Moniruzzaman and Hossain (2013), there are four types of NoSQL databases: key-value stores, document databases, wide-column stores, and graph databases. In this thesis, the document database type is mentioned (MongoDB). A

document database contains collections of documents of arbitrary and nested data formats, usually encoded using web-standards like XML or JSON.

When a large amount of data from different sources needs to be distributed quickly between different applications it is done through data streams (Namiot, 2015). Apache Kafka is an example of a distributed streaming platform that is used to stream data in appended paper V for a Big Data application.

Big Data

Big Data is a paradigm that comes from utilising the data enabled by IoT and cloud computing technologies and creating value from that data with analytics. This enables data-driven decisions instead of relying on the highest paid person's opinion ('HIPPO's') (McAfee & Brynjolfsson, 2012). This value of data is one of the four V's that make up the Big Data vision: value, volume, velocity, and variety (Gantz & Reinsel, 2011). Volume is the large volume of data that is now accessible, velocity is the speed of data generation (real-time data), and variety refers to the different types of data that can be collected in a heterogenous environment.

Any Big Data system requires the following six subsystems: data generation, data acquisition, data transportation, data pre-processing, data storage, and data analytics (Figure 10) (M. Chen et al., 2014).
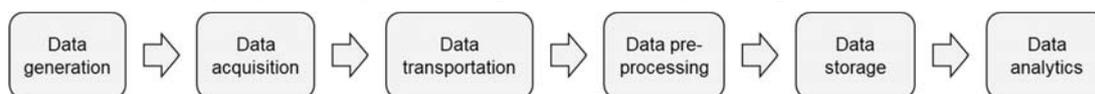

Figure 10: Components of Big Data applications *(M. Chen et al., 2014)*.

MAS

For completeness, it is important to state that the idea of a more decentralized architecture in production is not new with Industry 4.0. In 1985 Hatvany proposed cooperative heterarchies, as opposed to the typical hierarchical structure for which we in the western world have an internal bias (Hatvany, 1985). The rationale behind pursuing a holonic manufacturing model is to support important business requirements e.g. reconfigurability (Stefan Bussmann & McFarlane, 1999). A way to implement holonic-based systems is with the agent-based approach or Multi-Agent Systems. An agent is an autonomous, intelligent (they are pro-active and reactive), and co-operative piece of software and a multi-agent system is a collection of interaction agents (S. Bussmann et al., 2004). MAS is a promising technology for many important features of CPPS, this especially applies to modularity, autonomy, simulation, and artificial intelligence (Leitao et al., 2016).

Important standards

OPC UA	OPC UA was released in 2008 as a replacement of the old OPC that was the most common way to access automation and control systems data from IP networks. OPC UA adopts SOA and includes five distinguishing concepts ("Unified Architecture,"): 1. All previously existing functions (from OPC) are mapped to UA. 2. Unlike its predecessor, it is platform independent. 3. Security features. 4. It is extensible, meaning the protocol can be extended with new functionality for future interoperability. 5. An information model can be added on top of the data to add semantic value.
IO-Link	IO-Link is a standard (IEC 61131-9) for smart sensors and actuators. IO-Link devices are connected via an IO-Link master that manages the connection ("Apache Hadoop,"). There are several advantages of using IO-Link. One is that since the master manages the connection to the actual sensor, it also remembers all the settings for the specific sensor, which means that a sensor can be replaced and automatically

	configured identically to the previous one. Another advantage is the ability to communicate in multiple ways to the IO-link master, and thereby reach the data from all its connected devices.
AML	Automation ML (AML) is a standard that aims to simplify the exchange of automation engineering information. In AML it is possible to describe an automation system including details like plant topology, geometry and kinematic, behaviour etc. (Drath et al., 2008).
MQTT	MQTT is a publish-subscribe protocol designed for low energy devices and IoT implementations.

4 Summary of appended papers

This chapter presents a short summary of each of the six appended papers.

4.1 Paper I

Title: Introducing Customized ICT for Operators in Manufacturing

Short description

A one-year case study of the introduction of a mobile application for communication and decision support. The study was limited to one department managing a heat treatment facility. The department works in five shifts with five to six operators in each shift. The mobile application consists of several functions (see Table 5) and the mobile phone's general functions such as making calls or taking pictures were also included in the assessment. Both quantitative and qualitative data were collected. Qualitative data in form of semi-structured interviews and surveys, and quantitative data in the form of logs from the system and other databases.

Table 5: Functions examined during the case study in Paper I.

Function	Type
Phone calls	Smartphone function
Camera	Smartphone function
Disturbance reporting	Generic function
Chat	Generic function
Work instructions	Generic function
Production overview	Department specific function
Preventive maintenance checklist	Department specific function

Results

There were some inconclusive results such as the fact that many operators were positive about the system but did not seem to use it that much. The manager of the department was very positive and could early see several benefits such as better communication with colleagues and the ability to see status without being at the site. In general, it was optional to use the mobile application but for the preventive maintenance checklist, it became mandatory after some time. This change gave immediate results as can be seen in the maintenance database where a clear increase of reports of smaller issues can be observed (Figure 11).
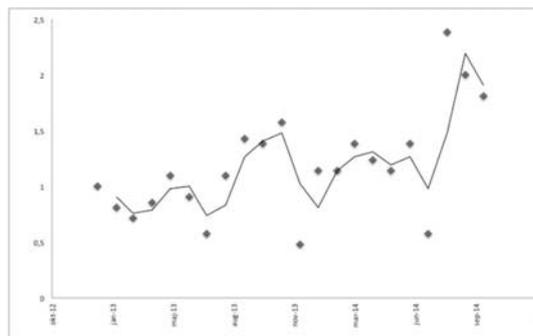
Figure 11: Reported issues in the maintenance database. When it became mandatory to use the digital system for preventive maintenance tasks, a clear increase in reports of smaller issues could be observed.

Discussion and conclusion

Results are discussed with respect to using the mobile application as cognitive automation and for information sharing. The most notable discussion is about using a system where the users themselves provide the content and where no one is using the system because of the lack of content. In all the conclusion is that the system introduced helped the operators and that the project was a success.
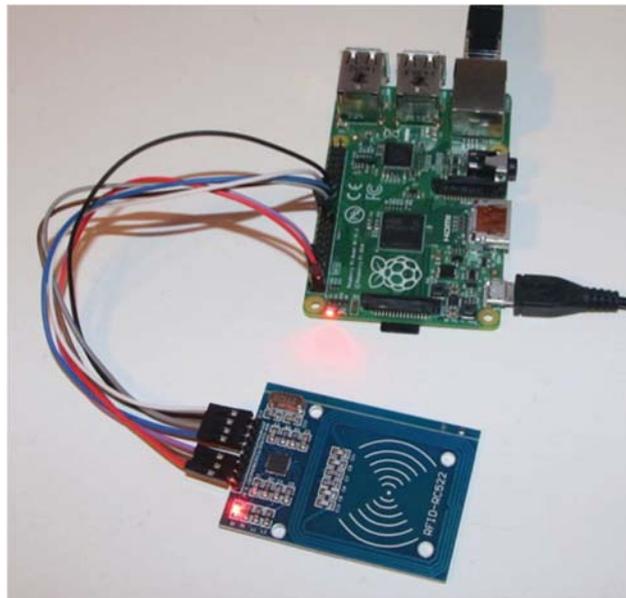
4.2 Paper II

Title: Interoperability for a Dynamic Assembly System

Short description

The paper describes the IT architecture for an assembly system built for mobility and with dynamic automation. The assembly system is built as a lab experiment but with the aim to assemble a real product, a coupling part of a quick connection for pneumatic applications. To manage future equipment diversity, a constraint was that every station had to be designed with PLC and HMI equipment from different suppliers. The assembly system contains three workstations where two are supported by collaborative robots. A pallet system with RFID tags supplies each workstation with the right components or subassemblies.

Results

From the entire system, two implementations are of interest. The RFID implementation and a web application for automation management. Because of the constraints of using different suppliers for PLC systems, it became difficult to implement RFID readers that would be the same for each station. Therefore, Raspberry Pi computer was chosen instead of the traditional PLC solution. An RFID reader was connected to a Raspberry Pi (Figure 12) and implemented with the aid of free and open software from the programming community.

Figure 12: A Raspberry Pi with an RFID reader (MFRC522 board) attached (paper II).

A web application was also introduced as a novel way of sharing information about the automation system among operators and engineers. This application was built using the Play framework which makes it accessible by other systems, as a web service, aligned with the REST paradigm. The innovative feature for this system is that it uses the AML standard to create its hierarchy, which

enables a common view between users and the automation system designers (if they use AML during the design phase). This system is now released as free and open software on GitHub called (https://github.com/MagnusAk78/mogas).

Discussion and conclusion

The system overview can be seen in Figure 13. OPC UA and HTTP is used to connect the operational level with the control level. Below the control level, different standards are used depending on what is supported by the supplier.
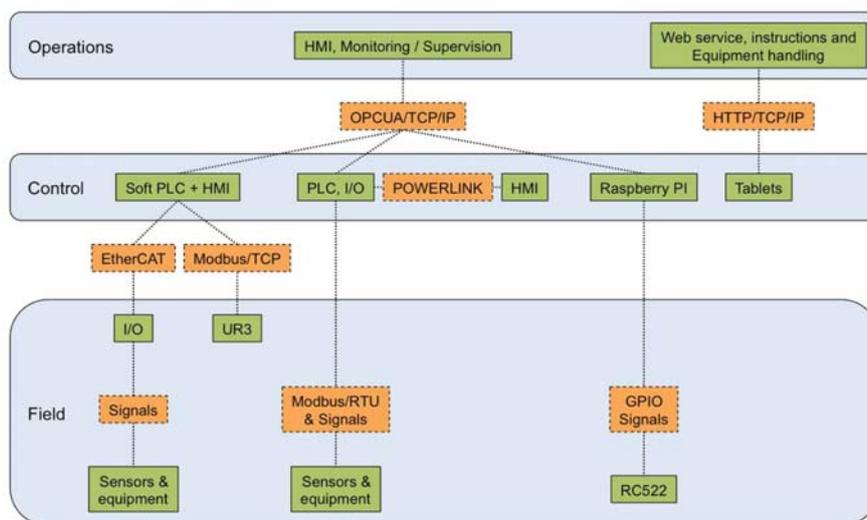
Figure 13: IT system overview of the assembly system (paper II).

4.3 Paper III

Title: Interoperability for Human-Centered Manufacturing

Short description

Paper III presents an interoperability framework for human-centred manufacturing. This framework combines two separate views into a matrix that can be used to identify and/or evaluate shop floor IT from a human perspective. The first view is a novel way of framing production workers' use of ICT. The second is first granularity level of areas for enterprise interoperability issues (data, process, rules, objects, software, and cultural) presented by Koussouris et al. (2011) (see Figure 7).

Results

The view of how operators use ICT is summarised in Figure 14. Future factories will rely heavily on increased collaboration between humans and machines (computers) (Moghaddam & Nof, 2017). From a human perspective, ICT can be used to collaborate with either humans or computers. In the human-human collaboration, it is important to be able to collaborate both internally and externally. In a human-computer collaboration scenario, the human can actively look for information or control machines, or she can be guided by the computer which is cognitive automation.

Figure 14: Production workers use of ICT at the shop floor (paper III).

The combination of operators' use of ICT and the first granularity level of interoperability areas makes a matrix which is the interoperability framework (Figure 15) that can be populated by technologies, standards, or issues.

Discussion and conclusion

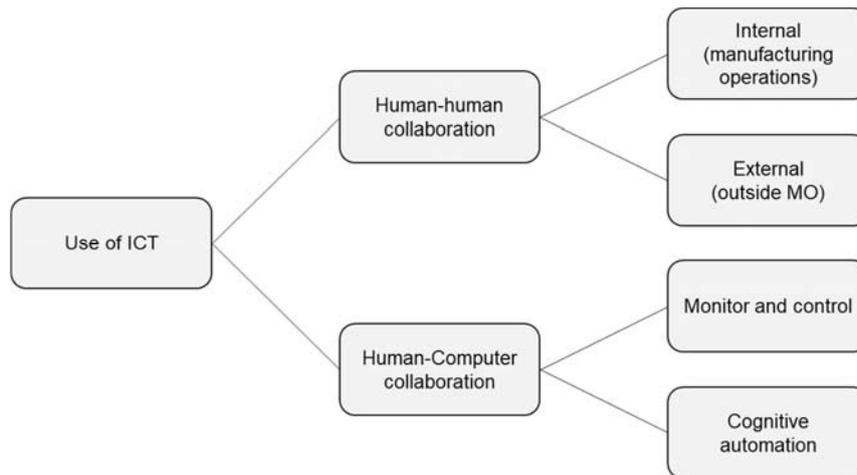It is not defined how the framework should be used but several examples are described in the paper. The system from paper I and the two described implementations from paper II are also used to exemplify how the framework can be populated. This is visualised in Figure 15 which is a simplified version from paper III that contains more examples.

Interoperability areas for enterprise systems	Manufacturing operators use of ICT			
	Human-human collaboration		Human-computer collaboration	
	Internal	External	Monitor and control	Cognitive automation
Data		AML (Paper II)		
Process	Preventive maintenance (Paper I)			
Rules				
Objects				
Software			OPC UA (Paper II)	
Cultural				

Figure 15: Interoperability framework for human-centred manufacturing (paper III).

The automation management platform described earlier can be used as an example of how to populate the framework. Since it utilises Automation ML to create a common view between operators and engineers, it connects the external human-human collaboration with the data interoperability area. The same system also includes a REST API that simplifies connectivity with other systems, which connects to the software interoperability area. Paper III includes several more examples of how this framework can be populated. The framework is the first step towards a method; by categorising technical solutions this way it is possible to either identify generic solutions for a specific purpose or area or find gaps where a holistic technology is lacking a good solution. Either way, it is a novel way of framing information and communication technology at the shop floor.

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4.4 Paper IV

Title: Modularized assembly system: a digital innovation hub for the Swedish Smart Industry

Short description

Paper IV describes the IT architecture for Chalmers Smart Industry Hub, which is now also known as Stena Industry Innovation Lab (SII-Lab). The goal is to spread knowledge to companies of any size about new technologies. This lab focuses on the complex assembly context in an Industry 4.0 environment. The goal of the architecture is to achieve a modular system that can cope with many different types of products, flows, automation, and people.

Results

The architecture revolves around a backbone module of connectivity and an IoT platform that deals with the interconnection of the attached modules. Three core modules, the assembly system, an ERP system, and analytics functionality, are common for most applications and extensions can be added directly to the backbone or to other modules (Figure 16).
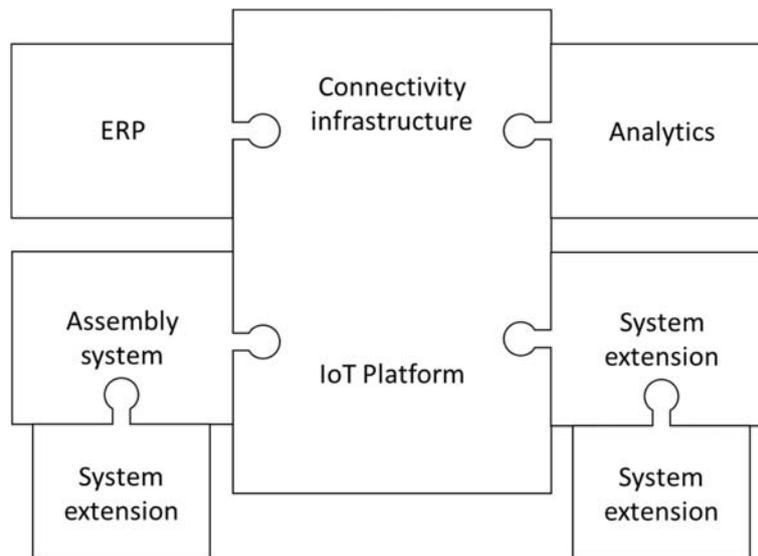
Figure 16: The modular architecture of the CSIH assembly system. A backbone with connectivity infrastructure and an IoT platform connects modules with or without extensions.

The backbone, core modules, and several system extensions are already defined with systems and industrial partners. Ericsson LTE network, that provides the connectivity infrastructure, and PTC Thingworx, which is the IoT platform, make up the backbone. The current ERP is provided by IFS and analytics from Axxos etc. All the different modules can be seen in the second figure of paper IV. By connecting a module to the backbone is sufficient to demonstrate some functionality but the real value comes from combining modules into a more advanced scenario.

Discussion and conclusion

The idea of the modular architecture is to promote decentralised autonomous decisions while still maintaining a simple structure by centralising connectivity logic in the IoT platform. An IoT platform can function as a middleware between the different modules that simplify interoperability. Thingworx can communicate with the industrial network, web services, propriety systems, and with IoT protocols like MQTT. A fundamental difference of an IoT architecture compared to a traditional control system is that it is event-driven. In an event-driven system, entities or modules react to events that occur as

opposed to running in an infinite loop. This makes it more difficult to foresee the exact behaviour of the system but in a heterogeneous environment, the complexity can be significantly reduced.

4.5 Paper V

Title: Technical interoperability for machine connectivity on the shop floor

Short description

The fifth paper goes into depth of the technical aspects of interoperability and discusses them using the learning outcomes from connecting a grinding machine to a private cloud in the Vinnova project 5G-Enabled Manufacturing (5GEM), which was a collaboration between SKF, Ericsson, and Chalmers. The theory is divided into two parts. The first part presents the general technological paradigms that are needed to implement CPPS´s and connects them with the Industry 4.0 maturity model (Schuh et al., 2017), see Figure 17. The second part describes technical interoperability and technologies that can be used to achieve it.
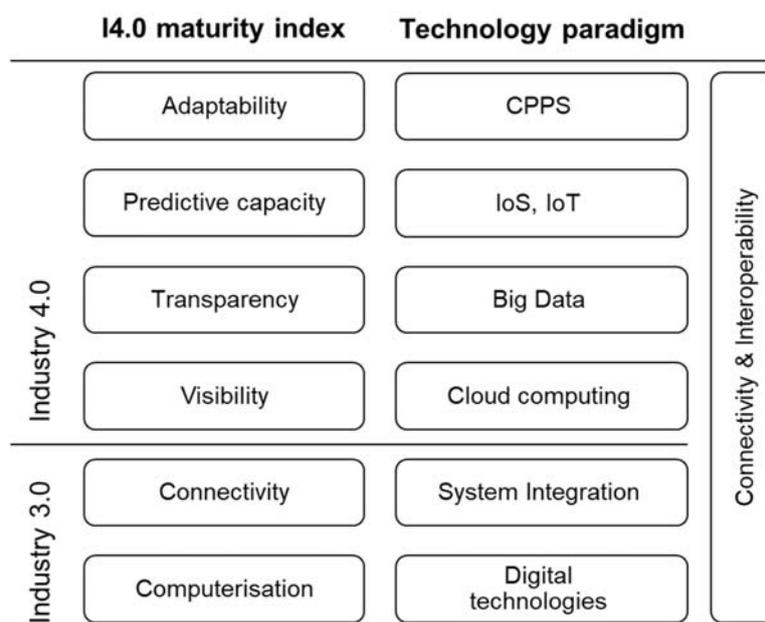
Figure 17: Industry 4.0 maturity index model with connected technologies.

The methodology follows the design science approach and the artefacts of interest are software and hardware that was developed to acquire data from the grinding machine and transmit it to a private cloud and further to data analytics and mobile operator support system. This is enabled by a connectivity infrastructure, see Figure 18, which consists of an LTE radio network with 5G technologies deployed at the SKF factory and a centralised private cloud environment. The private cloud has technologies to store data in NoSQL databases (MongoDB) and distribute data in large data streams using Kafka ("Apache Kafka: A distributed streaming platform,").
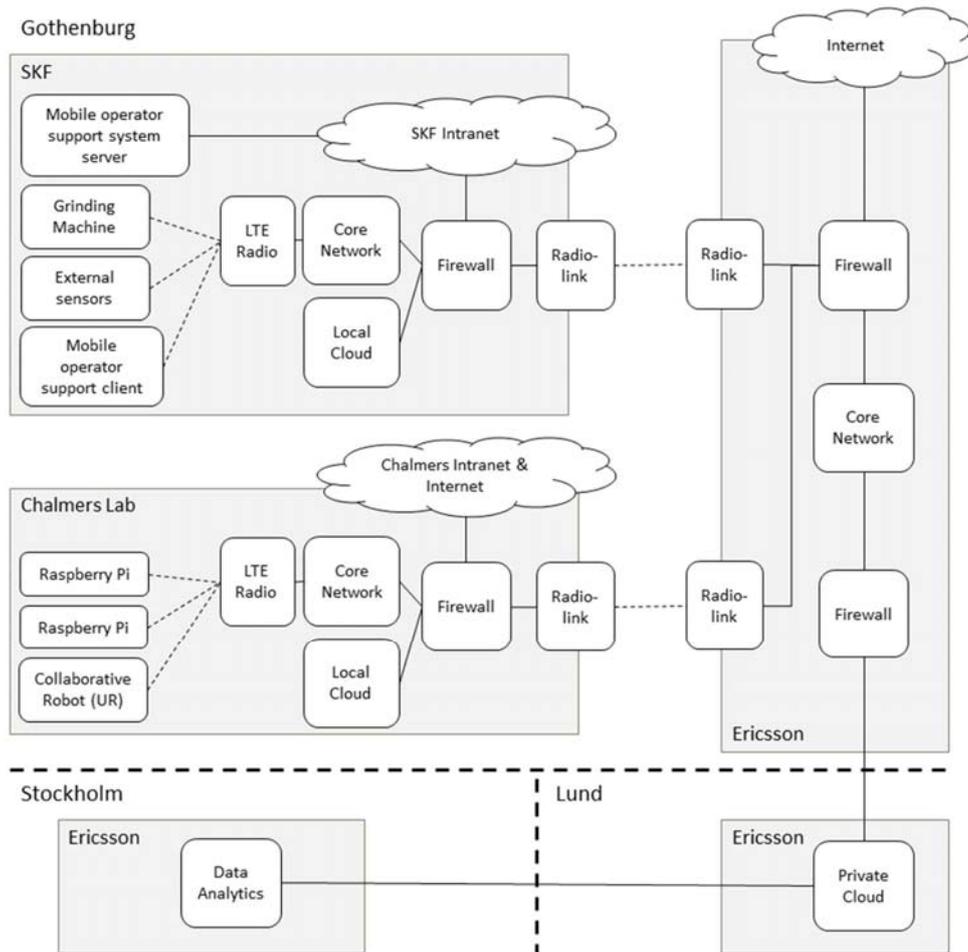
Figure 18: The connectivity infrastructure of the 5GEM project. Visualises how different technologies are connected from the SKF factory and Chalmers laboratory to Ericsson's cloud and data analytics centre.

Results

Data is collected from the machine onboard computer and from external sensors. The external sensors are in turn connected to three different systems: a vibration measurement system called IMX, IO-Link sensors, and an embedded sensor. IMX collects vibration data from sensors mounted on the machine and transmits a spectrum result. Both the onboard computer and the IMX system transmits the data over OPC UA. IO-Link is a standard for smart sensors that allows data to bypass the PLC through a propriety TCP connection. To simplify the communication with the IO-Link gateway, a separate REST API was developed. The embedded sensor is a temperature sensor directly connected to a Raspberry Pi. Data is collected and transmitted using distributed software deployed on the Calvin ("Calvin - Lets Things Talk to Things," 2015) IoT middleware. Figure 19 visualises the Calvin application that has function blocks, or actors, deployed in three separate locations. Functions blocks are software that enables Calvin to e.g. communicate with external systems or do calculations. They can communicate with each other seamlessly across logically and physical borders. Three Calvin runtimes, called calvinsys, hosts functions blocks that read, write, and transmits data from the grinding machine and to three separate systems: a database, an operator support system over MQTT, and to the data analytics centre over a Kafka stream.

Figure 19: The Calvin application. It is distributed over three physical locations: The Raspberry Pi, the local cloud, and the centralised cloud.

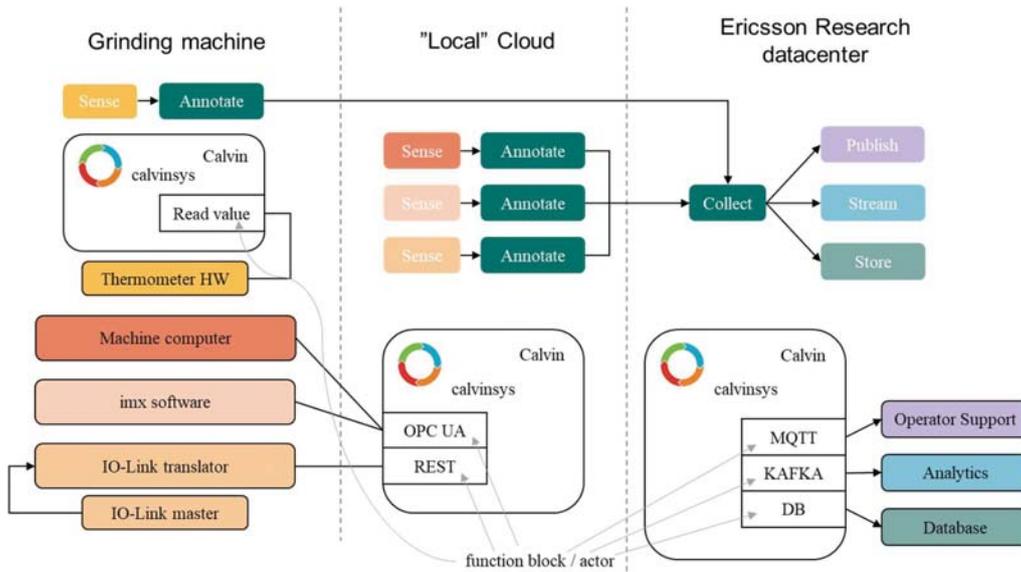## Discussion and conclusion

There does not seem to be any obvious solutions to practically connect generic machines on the shop floor. The solution described is one way to achieve this but there are several aspects to consider when implementing such a system. The paper discusses the results with respect to the three areas: system layout, communication standards, and open systems. System layout refers to two choices. The first choice is what sensor systems to use i.e. the onboard computer or external system. The second regards the software architecture and deployment. In this case, the choice was a decentralised implementation using an IoT middleware but other design choices can and should be considered. It is important to follow well-established communication standards. However, this work showed that even doing so does guarantee a problem-free implementation. For example, since OPC UA is self-certified, every implementation can be slightly different which can create problems. Another noteworthy discussion regarding communication standards was the fact that a new IO-Link gateway has been released since this implementation was finished. This new gateway includes an IoT port that shares the data over a Web service and REST API. This is the same solution that was developed for this case and shows that, even if technological development is moving fast, it does not have to be a problem if sticking to proven methods and de-facto standards. Finally, the paper discusses the importance of open-source systems that was crucial for this implementation.

4.6 Paper VI

Title: Challenges Building a Data Value Chain to Enable Data-Driven Decisions: A Predictive Maintenance Case in 5G-Enabled Manufacturing

Short description

Paper VI describes the different challenges observed when building a Big Data application for predictive maintenance in the 5G-Enabled Manufacturing project. The paper focuses on the complexity and the need of interactions between different domain experts at every link in the data value chain. The data value chain is defined in five steps, shown in Figure 20, which combines some of the theoretical steps of a generic Big Data application (see Figure 10).
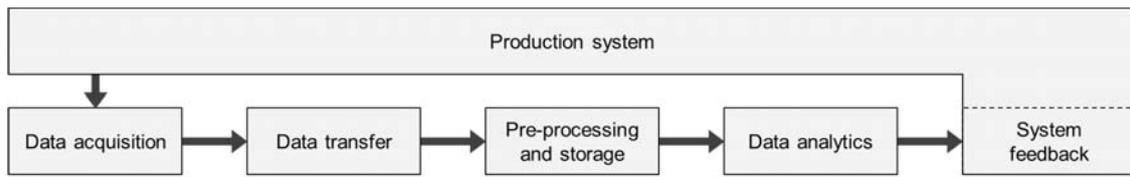
Figure 20: Data value chain as explained in Paper VI.

Results

The paper starts with a comparison between Big Data applications and models for CPPS and Industry 4.0 in terms of analytics. As can be seen in Figure 21, in CPPS models, data analytics are placed in the middle of the architectures and several more steps are required to make the system function. This is different from the Big Data perspective that focuses on the data analytics and its algorithms.

Figure 21: Comparison between three models of CPPS and Industry 4.0 and where they include analytics.

Data is acquired in two main ways, from an onboard machine computer, and from externally mounted sensors. The challenge here is to understand the alternatives that exist and weigh them against current resources, which requires detailed knowledge of the machines as well as different sensor systems.

It is in the data transfer where the manufacturing domain and the computer science domain first meet. Data is transferred in three different ways: OPC UA, IO-Link with connected web service, and from direct sensor access. All data is also converged using the Calvin platform. Here, the challenges are to understand the requirements of the data transfer and what limitations might exist with different options.

In the pre-processing and storage step, one challenge is to understand how to handle the data variety. This is usually done with metadata, which adds information about how the data is connected to the process.

Data analytics is the difficult part regarding different expert knowledge domains. To know what approach to aim for requires deep knowledge of the manufacturing process.

The system feedback is a crucial part of the application. This is where the human aspect comes into play. In this implementation, it was never possible to show analysed results since that work never reached the point that it provided useful data to machine operators. Nevertheless, implementing simpler functionality based on real-time data provides similar challenges, which is related to how the information should be visualised to be helpful.

Discussion and conclusion

Paper VI concludes that it is difficult not to underestimate the knowledge gap, and the implication of it, that exists between different domains involved when building Big Data applications. Furthermore, this challenge exists at every step of the data value chain. Four suggestions are given that could simplify the process of closing this knowledge gap.

- Agile work cycle. Meaning that there should be very short iterations between new data acquisitions, analysis, and utilization. This includes following the entire value chain for every new data source. Adding everything at once can create too many questions at every step of the chain, halting any progress.
- Know which parts of the process are self-comparable, and which parts are not relevant. In a discrete manufacturing flow there are lots of different phases, some are just idle and simply cannot influence the process.
- Connect the data to relevant metadata depending on the specific production process, e.g. products, components, machines, batches, or product families etc.
- Experiment with the data but let the manufacturing process experts guide these experiments, do not suffice with letting them comment on results.

5 Answers to the research questions

This chapter answers the research questions by discussing the results from the appended papers and theory.

RQ1	What aspects are important when implementing a shop floor IT according to Industry 4.0?
RQ2	How can a shop floor IT be implemented to enable an Industry 4.0 environment?
RQ3	What are the effects of implementing a shop floor IT according to the Industry 4.0 paradigm?
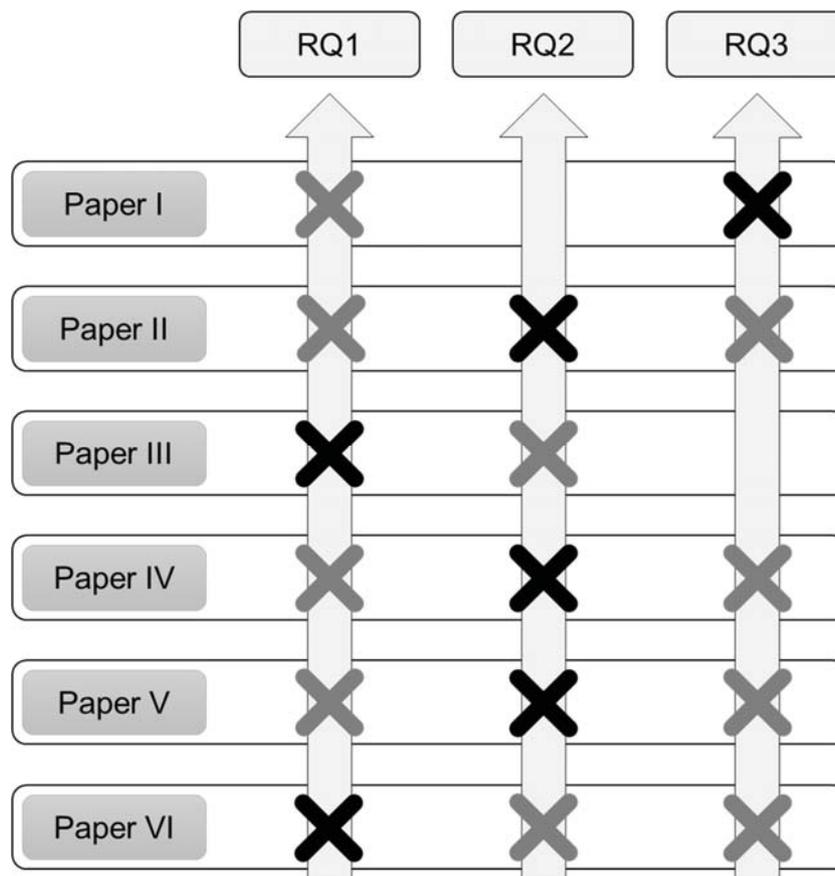
Figure 22: How the appended papers contribute to each research question.

5.1 Results related to RQ1

RQ1: What aspects are important when implementing a shop floor IT according to Industry 4.0?

Human-centred production

The need for flexibility and the ability to make customised products has increased focus on the most flexible resource, the human worker (ElMaraghy, 2006). More complex and autonomous systems require good support to aid humans with cognitive tasks (Fasth-Berglund & Stahre, 2013). The notion that it is important to build systems for humans needs instead of the other way around has always been an integral part of the Industry 4.0 vision (Lasi et al., 2014; Zuehlke, 2010). However, to enable effective cognitive automation requires an interconnected shop floor IT (Fast-Berglund et al., 2014).

Paper I, II, and III are all related to the human aspects of production. Paper I describes a case study of introducing a customised ICT, with communications and decision support capabilities, to operators and managers at a heat treatment facility. In paper II, a novel automation management platform is introduced that aims to enable a common system understanding by utilising the Automation ML (AutomationML) standard. Paper III presents a human-centred interoperability framework with worker's use of ICT that includes both a technical and a human aspect.

Technology

Obviously, there are technical aspects of implementing shop floor IT in an Industry 4.0. Paper IV and V are mostly related to these aspects but it is also touched upon in paper II. In paper II, a constraint for the implementation is to use different suppliers to emphasize heterogeneity. This is also mentioned in paper IV through the difference in the different modules. Managing heterogeneity is important since, in an Industry 4.0 environment, new and old equipment have to function side by side (Stock & Seliger, 2016). Paper IV presents an IT architecture, which is a generic layout of the IT system. This aspect is also brought up in the discussion in paper V. It is already clear from the literature that the hierarchical automation pyramid will change (Monostori et al., 2016). However, there are different ways to achieve this change such as utilising different types of IoT Middleware (Ngu et al., 2017), for either a centralised cloud solution (Derhamy et al., 2015) or a decentralised edge network (Shi et al., 2016). Paper IV and V include the aspect of connectivity, even if not going deep into the subject. Connectivity is an extremely important aspect of future manufacturing systems. The number of connected sensors, equipment, and devices will rise exponentially and that adds to the requirements on the connectivity infrastructure (Papakostas et al., 2016).

Knowledge gap

Paper VI is about the knowledge gap that can be identified through the entire data value chain, from data acquisition to system feedback. The problems that arise from these knowledge gaps does not come as a surprise and the need to educate for IT skills was highlighted by Kagermann et al. (2013) as a recommendation for implementing Industry 4.0 in Germany.

Table 6: How the answers to RQ1 relate to the appended papers.

	Paper I	**Paper II**	**Paper III**	**Paper IV**	**Paper V**	**Paper VI**
Human-centred	X	X	X			
Heterogeneity		X		X		
System layout				X	X	
Connectivity				X	X	
Knowledge						X

5.2 Results related to RQ2

RQ2: How can a shop floor IT be implemented to enable an Industry 4.0 environment?

Standards

Standards are usually mentioned as the solution to solve issues of technical interoperability (F. B. Vernadat, 2010). However, standards can also contribute to the higher levels of interoperability. In paper III, AML is connected to data and human-human communication across the organisation. Since OPC UA, as opposed to its predecessor OPC, support complex information modelling, it is possible to find synergies and use that to connect the semantic and technical levels (T. Sauter & Lobashov, 2011). These synergies could even be interconnected AML and OPC UA specifically (Henßen & Schleipen, 2014).

OPC UA does not solve every situation of shop floor connectivity. As discussed in paper V, since OPC UA is now open and self-certified, there are no guarantees that different implementations will work together. Paper V also brings up IO-Link and MQTT that both play a crucial role when interconnecting the system. IO-Link is used to connect to smart sensors and it allows for data acquisition by bypassing the PLC. MQTT is used to send data to the operator support system.

5G

The 5GEM project that paper V and VI are based on is based on the idea of introducing 5G connectivity on the shop floor. In the project, an LTE network with 5G technologies is installed. Real 5G networks do not exist yet but aim to hit the commercial market around 2020. 5G networks are mentioned as an enabler for Industry 4.0 (Varghese & Tandur, 2014) and will most likely soon enter the domain of industrial control networks (Wollschlaeger et al., 2017). With more scalable and flexible networks, with cellular and Wi-Fi networks tied together, it will be much easier to build large interconnected networks of connected things (Andrews et al., 2014). In the 5GEM project, only one stationary machine was connected to the LTE network, which never utilised the advantage of scalability. If all the machines, new and old, are mounted with sensors the network needs to be able to manage the many connected devices, the large volumes of data, and preferably, without lots of cables.

Open systems

Open systems is an important characteristic of systems in an Industry 4.0 environment (Wang et al., 2015). Paper II describes a solution for a PLC free RFID reader. Two problems needed to be solved for this hardware to work with traditional automation equipment, one was getting the RFID hardware to work on the Raspberry Pi and the other was the communication with a PLC. Both problems were possible to solve with free and open Python libraries, one for the MFRC522 and another for OPC UA. Similarly, in paper V, the image processing application relies on OpenCV, which is an open image processing library for Python and Java ("Open CV (Open Source Computer Vision Library),").

The cloud solutions in paper V also rely heavily on free and open software solutions like the open-source platform Apache Hadoop ("Apache Hadoop,"). Calvin, that is the IoT middleware used in paper V, relies on users adding more modules and functionality. This is common for all similar systems and it's a strategy that relies on accessibility and trust.

IoT Technologies

Both paper IV and V include the use of different IoT technologies. In paper IV, the Thingworx IoT platform is proposed. Thingworx can function both as the middleware between different modules and as a way to add functionality, in the form of software applications, to the system. In paper V, a Calvin application (Figure 19) acts as a middleware between machine data acquisition and data storage. This application includes modules that interact with different external interfaces such as OPC UA, for the machine onboard computer and the IMX system and a web-service (REST API) that translates IO-Link sensors to JSON.

SOA is central in IoT implementations, which enables decoupling to manage heterogeneity (L. Xu et al., 2014). This is also the idea of both the Thingworx and Calvin implementations, to create a common middleware. Still, they are not interchangeable. Thingworx is a cloud-based commercial framework (Derhamy et al., 2015), IoT Platform, while Calvin is an actor based IoT middleware (Ngu et al., 2017). Calvin combines actor model and flow-based computing into a system that can run on multiple units and can hide from the application, which enables distributed computing (Persson & Angelsmark, 2015).

Cloud Technologies

Cloud computing technologies become crucial when scaling up systems and/or when working with a multisite environment like in paper V. In that case, Ericsson's data centre in Lund hosted the private cloud that was used for the project. Now, there is no need to host a cloud environment yourself, thanks to the different cloud service models (IaaS, PaaS, SaaS) (Mell & Grance, 2011). But no matter how, technologies are needed to enable data storage and distribution. In paper V, MongoDB is used for storing the data, which is a document-based NoSQL ("NoSQL,") database. One reason for choosing a document-based database is to manage heterogeneity of data since there are no fixed columns as in a relational database. Dealing with large volumes of data also requires technologies to distribute that data where and when it's needed, Kafka ("Apache Kafka: A distributed streaming platform,") that was mentioned in paper V, is a platform for that purpose.

Way of working

Even though the need for more knowledge and skills in software and IT is known, new implementations are limited to the systems and people that currently exist. In paper VI, four suggests are made with the hope to more quickly deal with the known knowledge gap that exists between different domains. The ideas are influenced by the agile ways of working that have been popularised in the software development community (Beedle et al., 2001), which has had a documented successful impact on projects in the past (Serrador & Pinto, 2015).

Table 7: How the answers to RQ2 relate to the appended papers.

	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI
Standards (semantic)		X	X			
Standards (technical)		X	X	X	X	
5G				X	X	X
Open systems		X	X		X	
IoT Technologies				X	X	
Cloud Technologies					X	
Way of working						X

5.3 Results related to RQ3

RQ3: What are the effects of implementing a shop floor IT according to the Industry 4.0 paradigm?

Supported workers

Augmented work is an important benefit of Industry 4.0 (Lorenz et al., 2015). In Paper I, the mobile application that was introduced to the shop floor workers was proven successful for some tasks. In the case of preventive maintenance, trust between manager and operators went up when more issues were reported in the system. It was an appreciated tool for most of the operators and the manager was very positive.

Dynamic automation

The assembly system in paper II was built with regards to dynamic automation. Meaning, the levels and type of automation can be easily altered depending on the situation. Collaborative robots are examples of automation equipment that can be quickly mobilised when needed. This requires the shop floor IT to be very flexible and manage both diversity and mobility.

A way to solve the diversity or heterogeneity is to have less hierarchical systems (Lasi et al., 2014). In paper IV, the described architecture is built for modularity and is based on event-driven principles, which enables decentralised logic. Decentralisation, along with modularity, are important design principles for Industry 4.0 components (Hermann et al., 2016; Marques et al., 2017). Event-driven control architectures are also crucial future self-organising cyber-physical production systems (Wang et al., 2015).

In paper II, the assembly stations have mobility as a requirement because the stations need to be moved to where and when needed. In paper V, 5G connectivity provides high-speed connectivity for mobile equipment and devices.

Industry 4.0 maturity

In the Industry 4.0 maturity index model (Schuh et al., 2017), the third step, visibility, is the first step in the Industry 4.0 environment. In paper IV, V, and VI, the ability to collect and share information has been solved and discussed. The next step is to add value to the data collected, which is discussed in both paper V and VI where data analytics are applied to the data. To be able to reach higher levels of maturity, according to the maturity index or the similar 5C model (Lee et al., 2015), requires that these technologies are applied on a larger scale and that the results are utilised to improve the system.

Table 8: How the answers to RQ3 relate to the appended papers.

|	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI
Worker support	X					
Dynamic automation		X				
Mobility		X				
Modularity				X		
Visibility				X	X	
Transparency					X	X

6 Discussion

This chapter discusses the answers to the research questions with regards to the aim of the thesis. It also includes a reflection of the research in terms of contributions and quality.

6.1 Shop floor IT in an Industry 4.0 environment

The aim of this thesis is to aid decision makers in the manufacturing industry to implement a shop floor IT according to the Industry 4.0 paradigm. The aim indicates a practical approach (implement shop floor IT) for a large and undefined topic (shop floor IT and Industry 4.0). Three research questions were formulated to aid in reaching the aim. The questions were answered in chapter 5 by combining the results from the appended papers and theory. The answers show both the practical and holistic approach that is indicated in the aim. The continuation of this chapter will discuss the answers to each research question and relate them to theory and each other.

Aspects

We know from previous literature, see chapter 0, that the scope of shop floor IT has grown to include both automation control and enterprise systems. The reason for this change comes from the goal of Industry 4.0, which is to build cyber-physical production systems that can sense and adapt to its environment. In that context, the shop floor IT needs to be integrated horizontally, vertically, and throughout the value chain (end-to-end integration) (Monostori et al., 2016). Research and technologies for vertical integration are more developed than for horizontal integration (Marques et al., 2017). End-to-end integration, in turn, requires both vertical and horizontal integration. From a shop floor IT point of view, vertical integration strongly relies on the interconnectivity of heterogeneous devices of sensors, machines, and systems. When mixing this connectivity with enterprise systems, the system architecture (layout) becomes increasingly more important. The human-centred aspects are not directly derived from the system integration goal, meaning that it is not dependant on integration but rather a goal itself, and can be dated back to before and through Industry 4.0 (Kagermann et al., 2013; Zuehlke, 2010). In paper VI, the knowledge aspect is connected to building a data value chain, which in a shop floor IT perspective is related to connecting the entire value chain (end-to-end integration). Figure 23 shows the connections from the vision, or goals, of Industry 4.0 and how they connect to the answers to RQ1.
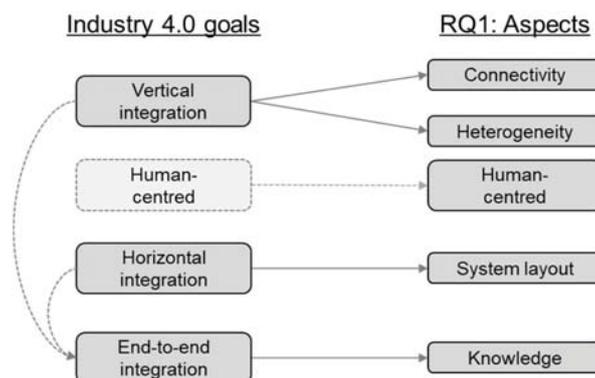
Figure 23: How the answers to RQ1 can be connected to the goals of Industry 4.0.

Implementation

There is no shortage of ideas of how to implement Industry 4.0. However, since different scientific areas are merging, there are also different perspectives. Figure 24 is a visual attempt that shows how the implementations described in this thesis can be connected to the aspects (RQ1).

Interoperability is a common denominator in the Enterprise Integration domain, which is the means to achieve integration (Romero & Vernadat, 2016). The natural way to structure interoperability issues is with the four levels: technical, syntactical, semantic, and organisational (Rezaei et al., 2014). Technical and syntactical interoperability is closely connected to standards and connectivity. The type of standards referred to then is the communication protocols that allows machines to communicate such as OPC UA or MQTT. Therefore, utilising well-defined communication standards is key to managing heterogeneity. As described in paper II, another crucial component for dealing with many different systems is to rely on open systems, which allow for flexibility and community-based solutions.

5G was discussed as an enabler for large-scale interconnectivity but, since 5G does not exist commercially and several challenges are still not solved, there are no guarantees that there will be any commercially available solutions ready for 2020 as planned. There are alternative technologies for wireless networks such as Wi-Fi, ZigBee, Bluetooth, and RFID but they all lack in some Quality of Service (QoS) indicator important for industrial applications (Li et al., 2015). To succeed in building large sensor networks, with high speeds, low latency, and low energy components, something like 5G is needed that combines the needed capabilities into one system (Wollschlaeger et al., 2017).

Higher levels of interoperability can also be connected to standards but then it's the type of standards that add value to the data, like with AML and OPC UA (with the extended information model) that has been previously mentioned. This is a way to connect to the human-centred aspect, with semantic interoperability standards. SOA is a concept often mentioned as a solution to interoperability. This is not explicitly mentioned among the answers to RQ2 but SOA is an integral part of internet technologies today (L. Xu et al., 2014).

The IoT technologies that have been used in the studies are Thingworx and Calvin. One is a centralised service-based platform while the other is a distributed actor-based IoT middleware and, between them, they cover many different connectivity related scenarios. There are many commercially available IoT platforms today (Derhamy et al., 2015) and which one to choose depends on the specific connectivity challenge. For most implementations, a centralised cloud platform is a natural choice, like the suggested solution with Thingworx in paper IV. Sometimes, computations need to be pushed closer to the devices, then a distributed platform is needed, like using Calvin to connect the grinding machine in paper V. There is also the possibility to use a combination of these technologies in more advanced solutions. Independent of the specific implementation, the IoT technology field is growing and will soon be an integral part of any shop floor IT system with an Industry 4.0 agenda.

In the studies described in this thesis, cloud technologies are introduced when building a Big Data application. But many IoT technologies also imply a cloud environment. In fact, it is difficult to separate cloud technologies from IoT technologies, since they are often used together. In paper V, the system used was designed for a large-scale implementation, even if only one machine was connected. When systems scale up, there is a need to utilise technologies that can manage the four V's of data, e.g. the MongoDB database and Kafka from paper V. There are other types of databases ("NoSQL,") which have different strengths and weaknesses and Apache Hadoop ("Apache Hadoop,") contains several open-source projects that all contribute to reliable and scalable distributed computing.

In paper VI some suggestions for the way of working when designing Big Data applications for maintenance and manufacturing was introduced. These suggestions are mostly spontaneous reactions from participants of the project and only implicitly derived from theory, like the agile methods. No doubt the methods and processes will be a large research focus in the future because clearly, the knowledge gap is a big hindrance here.
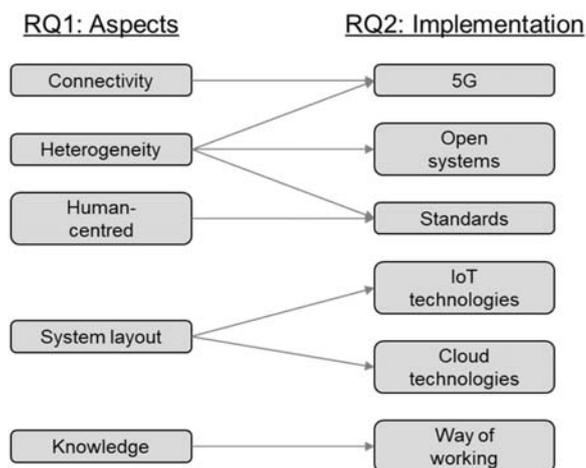

Figure 24: How the answers to RQ1 and RQ2 relate to each other.

Effects

The effects that are listed as answers to RQ3 regards the information system part of the production system. Typically, effects regarding production are evaluated in terms of known important KPI's such as throughput, quality, OEE, etc. Because of the already large scope and the practical research approach it was not realistic to find these connections directly.

Figure 25 shows how the answers to RQ3 can be derived from the implementation areas. The most straightforward evidence of system improvement is presented in paper I. The case study provides documented proof of increased trust and improved work effectiveness (more reported issues). This system used Wi-Fi but for scalability and performance reasons, 5G technologies would add to the mobility. Since 5G also aids the scalability of stationary and mobile devices on the shop floor, it is an enabler for IoT technologies.

As shown in paper II and III, open systems and the use of correct standards enables more dynamic automation, which in certain cases act as worker support. In paper IV, the goal was to design an event-driven modularised architecture, which was achieved using the IoT platform Thingworx and proper standardisation.

In paper V and VI, the goal was to enable a Big Data application that can predict failures in a grinding machine. By connecting a grinding machine, using Calvin and other systems, digitised (data) visibility of the system was achieved. By collaborating over domain borders, it is also possible to get more value from the data (information), which makes the system more transparent according to the Industry 4.0 maturity index (Schuh et al., 2017).
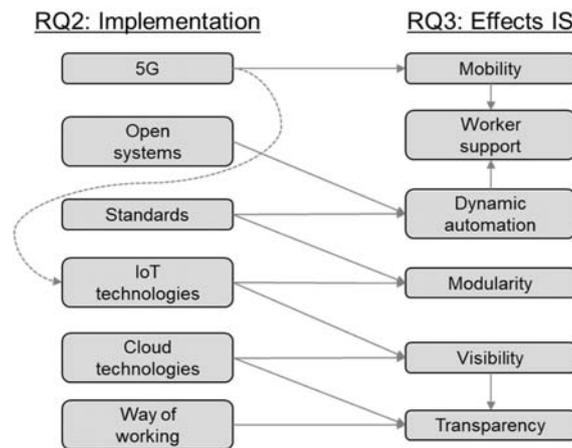
Figure 25: How the answers to RQ2 and RQ3 relate to each other.

Summary

If we summarise all the answers and connect them as visualised in Figure 26 a rather complex and interesting picture emerges. We want to achieve system integration and human-centred automation to build an Industry 4.0 environment. For discrete manufacturing companies, this can be achieved by implementing a shop floor IT considering certain aspects, using certain technologies to get certain effects. Worker support, mobility, and dynamic automation all contribute to more flexibility. Flexibility can mean many different things in a production system and here it refers to the task flexibility workers get by utilising proper communication and decision support. It refers to the geographic flexibility of mobile connectivity, and it refers to the task flexibility of automated systems that can adapt to sensory input. A modular architecture makes it easier to reconfigure the system set up by combining a decentralised event-driven architecture with more predictable subsystems (Wiendahl et al., 2007). Big Data applications that aggregate, compute, analyse, or simulate data into information provide data-driven decision-making, which is arguably better than the randomness of relying on the highest paid person (McAfee & Brynjolfsson, 2012).
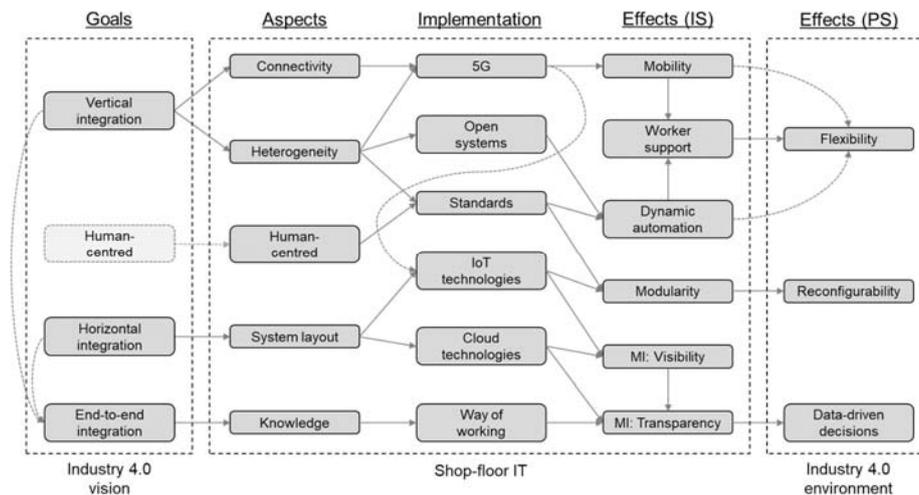

Figure 26: Summary of the answers to the research questions and how they relate to each other and goals and effects of achieving an Industry 4.0 environment.

Industry 4.0 as a buzzword

As discussed in chapter 0, what constitutes a shop floor IT has constantly grown from the first stand-alone CNC machines, to interconnected robot cells and MES systems, to today's merger with enterprise systems. This expansion is not only visible in manufacturing, the important OT/IT convergence discussion shows that this is a general trend that affects the whole society ("Gartner Says the Worlds of IT and Operational Technology Are Converging," 2011). This is also why the term Industry 4.0 has been expanding, and will probably soon be phased out. Today, it is more common to talk about the merger of cyber and physical worlds i.e. Cyber-Physical Systems. Many countries have started R&D programmes to promote this development. Germany created a huge buzzword, at least in Europe, with Industry 4.0. In the United States, Smart Manufacturing is the defining term (Mittal et al., 2017). In Japan, Society 5.0 was launched 2016 (*Report on The 5th Science and Technology Basic Plan*, 2015), a name that more clearly implies the effects on society. Even if the intentions of Industry 4.0 haven't changed, perhaps the buzzword has a limiting effect on the understanding and complexity of its implications (Granrath, 2017).

6.2 Reflections on the research

Design research in information systems contains three research cycles, the relevance cycle, the design cycle, and the rigour cycle (A. R. Hevner & S. Chatterjee, 2010). Figure 27 shows how they relate to the IS research framework (Figure 4). The relevance cycle provides the relevant context, the production system, to the design science activates. The rigour cycle bridges the activities with the relevant theoretical foundations, experience, and expertise in the Industry 4.0 field. The design cycle iterates the core design activates, develop and evaluate artefacts, that in this case constitutes the shop floor IT. These three cycles must be present and identifiable in any design research project (A. R. Hevner & S. Chatterjee, 2010).
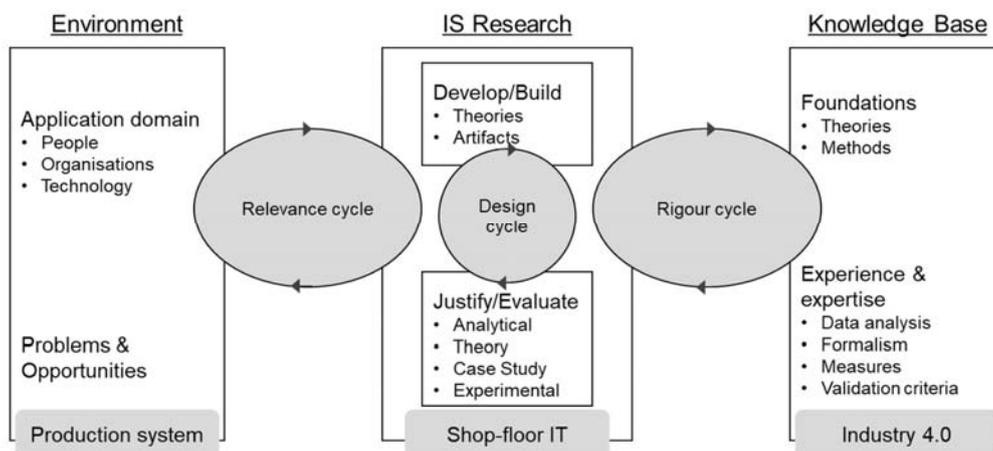
Figure 27: Design science and the three research cycles: relevance, design, and rigour, adapted from (A. R. Hevner & S. Chatterjee, 2010).

The aim, to implement a shop floor IT according to the Industry 4.0 paradigm, derives from a need in the production system environment which provides relevance to the design cycle activities. Combining the IS research framework and the summarised result model (Figure 26) paints a clear picture. The aspects, which are the answers to RQ1, are derived from the Industry 4.0 knowledge base. Implementation, answers to RQ2, constitutes the artefacts of the shop floor IT and the design cycle, and the answers to RQ3, effects, applies to the production system. The connections between the aspects and implementation provide rigour to the design cycle, and the connections between

implementation and effects provide usefulness to the production system. To close the loop are the additions to the knowledge base, which are the contributions, both to science and industry. Figure 28 visualises the relationships described above.

Contribution to industry

The practical use for the industry can be divided into two parts. The first part is the different answers to the research questions as related to aspects, implementation, and effect. These can be used as a checklist for the industry to look to when planning a strategy of change towards Industry 4.0. The second part is the practical implementations. These provide examples of technologies and equipment that can point towards a useful practical solution.

Contribution to science

Three scientific contributions have been presented. The first is the documented impact of using ICT as operator support at a heat treatment facility. The second is the interoperability framework described in paper III, which has a large potential of becoming a method. The final third scientific contribution is the holistic perspective of the shop floor IT. This perspective includes a definition of the shop floor IT as well as aspects, examples, and effects of practical implementations that are connected to both theory and industrial applications.
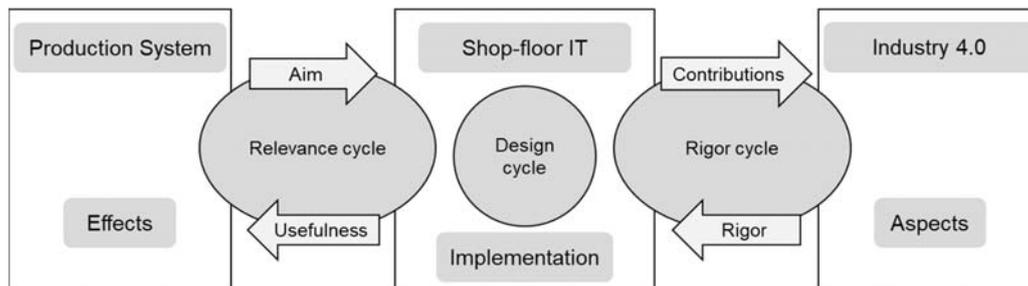

Figure 28: Description of how the design science approach connects to the aim, answers to the research questions, and scientific contribution.

7 Conclusions

This chapter presents the authors concluding remarks.

The aim of this thesis is to aid decision makers in the manufacturing industry to implement a shop floor IT according to the Industry 4.0 paradigm. Industry 4.0 started as a national R&D programme in Germany with the vision of digitizing the manufacturing industry and of creating cyber-physical production systems that sense and automatically adapt to the environment. The shop floor IT is defined as the merger of the enterprise and the automation control systems, a change that has been sped up by the introduction of Industry 4.0. To guide the research towards the aim, three research questions were formulated.

Table 9: Summary of the research questions.

RQ1	What aspects are important when implementing a shop floor IT according to Industry 4.0?
RQ2	How can a shop floor IT be implemented to enable an Industry 4.0 environment?
RQ3	What are the effects of implementing a shop floor IT according to the Industry 4.0 paradigm?

The answers to the research questions are summarised in Table 10. Answers to the first research question show important aspects that need consideration when implementing a shop floor IT according to Industry 4.0. These answers can be used to guide decision makers towards focus areas and to develop a general strategy. The second research question regards the practical implementation of a shop floor IT. The answers can be used as a checklist by the industry to measure against, or as inspiration for further development. Answers to the third research questions are the effects of the information system that can be expected by implementing a shop floor IT in an Industry 4.0 environment.

Table 10: Summary of the answers to the three research questions.

Aspects	Implementation	Effects
Human-centred	Standards	Worker support
Heterogeneity	5G	Dynamic automation
System layout	Open systems	Mobility
Connectivity	IoT Technologies	Modularity
Knowledge	Cloud Technologies	Visibility
	Way of working	Transparency

People that are about to start their journey towards a digitized and interconnected shop floor can feel overwhelmed, unmotivated, and hopelessly behind everyone else. The results presented in this thesis confirm the complexity behind these feelings by examining the aspects involved but it also provides hope. Consider the long-term effects that are needed and find implementation areas that are most important. Start with simple and practical implementations in small incremental steps and build new knowledge. With this new knowledge, it is possible to create new policies, requirements and processes that move the organisation towards an Industry 4.0 environment.

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