THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Towards interoperable information and communication systems for manufacturing operations

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Cover: The research approach for this thesis.

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ABSTRACT

Mass customization and the demand for flexible manufacturing systems have increase focus on the human workers. Diversity and complexity of the products that manufacturing operators have to handle is constantly on the rise. It is believed that the recent advances in information and communication technology can assist the manufacturing organisations to manage these challenges. As a matter of fact, if organisations manage to implement the systems correctly, the productivity is thought to increase to such an extent that it will give rise to a new paradigm in production, the fourth industrial revolution. However, as it stands now, there is a large gap between the exiting technology and what is actually used in the manufacturing industry. If organisations are to close this gap they need to manage several challenges. The problem addressed in this thesis is how to design and structure the information and communication systems that need to handle the new technologies, and particularly those designed for manufacturing operators and the automation systems. This thesis aims to aid the manufacturing operations organisations to configure their information and communication systems and this has been done regarding interoperability. Interoperability is the ability for systems to communicate and exchange data which is crucial to enable many different systems to co-exist and work together. The information and communication technologies that manufacturing operators use have been connected with several areas of interoperability research, which enable a useful discussion about the implementation and design choices of the technology.

Keywords: Interoperability, Industry 4.0, Information Systems, ICT, Manufacturing operators.

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1 Introduction

This chapter presents the background, aim, and objective of this thesis. Research questions are formulated and delimitations stated.

1.1 Background: a new paradigm

Workers in future production systems need to handle more situations that will be more complex than they are today. High level of product customisation is a reality and is the current production paradigm for many products (Fogliatto et al., 2012). Mass customized and complex products leads to a greater need of information and more flexible automation solutions (ElMaraghy, 2005). This flexibility and more advanced information handling requires more intelligence in the system and that it is designed for the human workers, it requires smart factories (Zuehlke, 2008). Implementing such smart factories requires affordable technology that is able to interact with both humans and machines. It is believed those requirements are now fulfilled and that this, when implemented correctly, will lead to a new paradigm often referred to as the fourth industrial revolution or Industry 4.0. The name Industry 4.0 is inherited from a strategic program from the German Government ("Industrie 4.0 Plattform," 2015) that was released 2011. Hermann et al. (2015) found four concepts that are crucial for this new paradigm: Cyber Physical Systems, Internet of Things, Internet of Services, and the Smart Factory (Figure 1). In CPS the real, physical, world is merged with the virtual world by connecting humans, machines, and products together with sensors and actuators. The Internet of Things (IoT) concept is that objects may be uniquely identified and autonomously interact with other objects or systems. Internet of Services allows for new types of business models. If resources and processes can be acquired on-demand as services the system can become more flexible and scalable (X. Xu, 2012). CPS are enabled with IoT and embedded systems (Schuh et al., 2014). Services are reliant on cloud computing technologies (X. Xu, 2012). With the help of CPS and services it is possible to aid humans and machines with more specific and context-aware information, which is crucial when implementing the Smart Factory (Hermann et al., 2015).

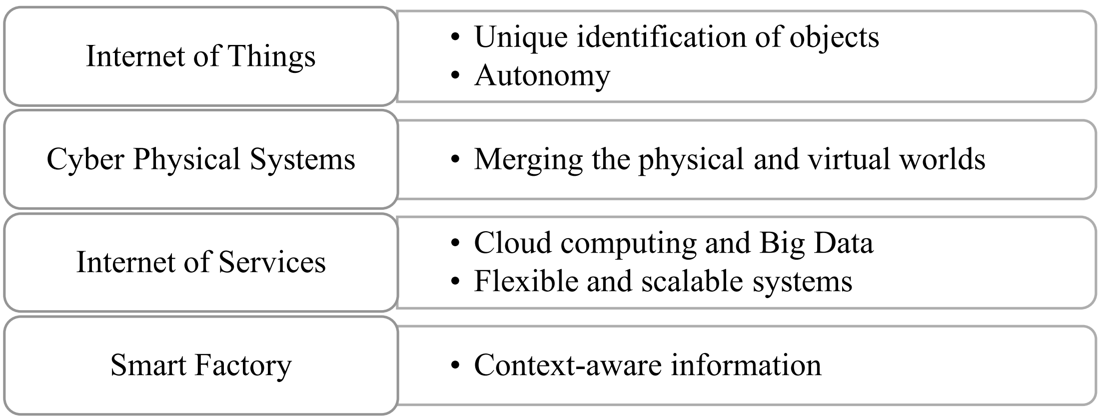

Figure 1. Important concepts of Industry 4.0. (Hermann et al., 2015).

1.2 Problem layout: interoperability

Industry 4.0 promises a lot regarding productivity, cost reductions, revenue growth, and increasing employment in the production area (Rüßmann et al., 2015). However, challenges exist with new technology, information structure and within the organisation. Context-aware information requires a system that acknowledges the need of individuals and can provide the right information at the right place in the right time (Kagermann et al., 2013). In order to do that the system must be integrated both horizontally and vertically across different systems and organisations (Bauernhansl et al., 2014). For the organisation such integration may lead to better collaboration between different roles and functions (Schuh et al., 2014). Increased knowledge sharing and co-operation can also decentralise decision-making and increase the autonomy of individuals (Mattsson et al., 2014). Furthermore, system integration is an enabler to implement IoT, CPS, and Smart Factories (Hermann et al., 2015).

Successful systems integration requires good strategies in managing system heterogeneity, component autonomy, and software distribution (Hasselbring, 2000). Both CPS and Smart Factory suggest higher autonomy and decentralisation of decision-making, of both humans and technology. Services are inherently autonomous which is part of their strength, however combining many services might become difficult to manage. Distribution of new systems or components will become more of an issue with larger and more diverse systems.

All of the new concepts are affecting the areas where systems integration issues do occur. The reason that it is thought to be manageable to combine these concepts is the great advancements of information and communication technology (ICT) in recent years. Internet technologies, wireless systems, storage capacity, programming paradigms, web services, embedded systems etc. have managed to solve many problems of system integration (Fuggetta & Di Nitto, 2014; Koussouris et al., 2011). Simplified solutions enable interconnection, or interoperability, between systems. However, new technology, higher complexity and difficulties to handle legacy systems put new focus on systems integration (Madni & Sievers, 2014). Therefore, it is important to identify the gap between the current state of information and communication systems for manufacturing operations and what is required to achieve the future interconnected heterogonous systems of autonomous entities.

1.3 Aim and objective

The aim of this thesis is to enable manufacturing operations organisations to understanding how they should configure their information and communication systems. In order to advance towards that aim, an objective has been formulated, which is to connect information and communication technologies with the back-end systems by providing a framework that aids the discussion regarding potential issues and opportunities of interoperability.

1.3.1 Research questions

The objective is divided into two research questions (RQ) as illustrated in Figure 2. The first RQ connects manufacturing operations with information and communication technologies. The second RQ broadens the view and includes the back-end information and communication systems.

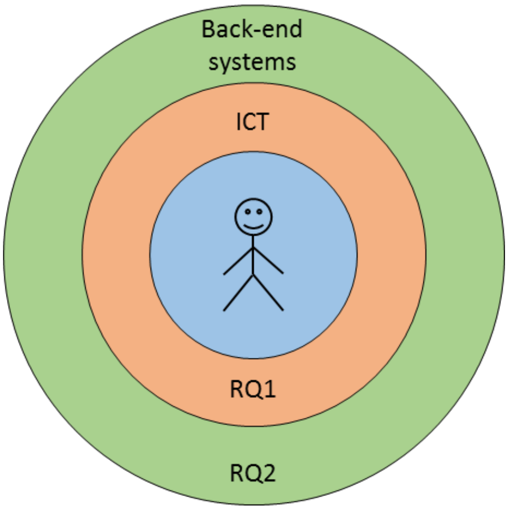

Figure 2. Thesis approach to the objective.

RQ1: How can digital information and communication technology assist manufacturing operators in their work?

There are many scenarios described within CPS and Smart Factory etc. where information and communication technologies are supposed to hugely improve the system (Lorenz et al., 2015). The intention of this question is to examine how manufacturing operators can, and/or do, use ICT in their work and how that is, or could be, beneficial for the manufacturing process.

RQ2: What challenges exists in designing an information system that enables horizontal and vertical system integration for manufacturing operations?

Systems and equipment in manufacturing organisations vary in age and what protocols and standards they utilise. The reasoning behind this question is to identify where to put the effort when creating or changing the requirement of the information system from the manufacturing operations perspective.

1.4 Delimitations

The following topics are considered relevant to the topic by the author but are delimited from the scope of this thesis.

- Cognitive processes: How humans make decisions and what affects their behaviour.
- Human factors: Graphical interfaces, choice of technology, workstation design, ergonomic aspects, etc.
- Manufacturing processes: Optimisations, line balancing, process layout, etc.
- Organisational: Management Strategies, knowledge management.
- Security: information privacy, legal issues, data encryption.

1.5 Outline of the thesis

No	Chapter	Description
1	Introduction	Presents the background, aim, and objective of this thesis. Research questions are formulated and delimitations stated.
2	Theoretical framework	The theoretical framework is divided in four parts. The first part describes the production system. The second part provides a generic background and models of software and communication systems. Then, in the third part, the manufacturing specific information and communication systems are explained with the Automation Pyramid. The last part describes how the Automation Pyramid will change in the near future.
3	Research methodology	This chapter describes the research methodology for this thesis. It includes the research projects, the research context, and the authors approach and design of the research.
4	Summary of appended papers	Presents the appended papers and highlights the important contributions towards the aim.
5	Discussion	Discusses the theory and the appended papers and how they contribute to answering the research questions. Furthermore, some interesting opportunities for possible future research are presented.
6	Conclusions	Concluding remarks. A revisit of the research questions, objective, and aim.

2 Theoretical framework

The theoretical framework is divided in four parts. The first part describes the production system. The second part provides a generic background and models of software and communication systems. The third part explains the Automation Pyramid model. The fourth and last part include theory about the information and communication systems that is thought to change future manufacturing.

2.1 The production system

This subchapter describes the production system. It is a mix of generic important theory and important findings from the body of work produced at Product and Production Development at Chalmers University of Technology.

A manufacturing enterprise consist of at least one production system with one or several production facilities. The production facility, or factory, is host to the manufacturing processes that transforms the input material into refined components or products and waste. Manufacturing processes can be divided into two main categories: processing and assembly operations. Processing operations include physical reshaping or enhancing the material. Assembly operations refer to the process of joining or fastening components together. (Groover, 2016).

Manufacturing facilities should be designed so that the manufacturing processes can be achieved in an effective and efficient manner. What layout to choose depends on the production volume and product variety (Groover, 2016; Slack et al., 1998). The main categories of layouts are: fixed-position layout, process layout, cell layout, and product layout. The material flow is another aspect of manufacturing process design. The two extreme examples are the Job Shop and flow line. In a Job Shop, highly skilled workers design new customised components on-demand using general-purpose tools. In a flow line, the material is continuously moved between the processes e.g. an assembly line. Figure 3 show how the concepts of process layout, product variety, production volume, and the importance of flow interconnects.

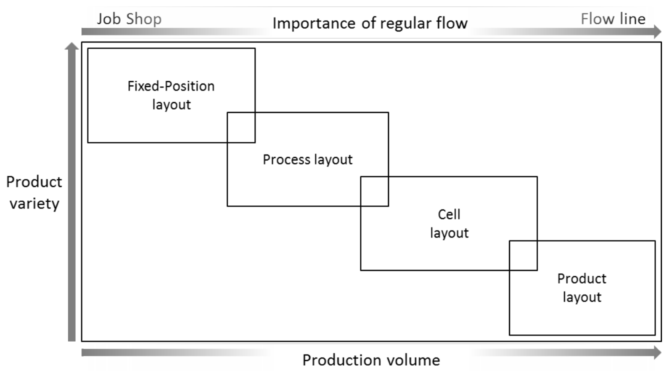

Figure 3. Relationship between product variety, production volume, manufacturing process layout, and the importance of regular flow. (Groover, 2016; Slack et al., 1998).

2.1.1 Operators and Automation

Manufacturing operators are the workers that do the value adding work of the manufacturing process. Besides the manufacturing processes, there are many other tasks that operators do, such as deciding production order, maintaining equipment, monitoring automation systems, teaching new operators etc. An example of how these tasks can be categorised is the operator´s action space (Table 1) that consists of seventeen types of tasks (Fast-Berglund & Stahre, 2013). The tasks are divided into five main operator roles: plan, teach, monitor, take over (intervene), and gain understanding (learn) (Sheridan, 1980, 1992).

Table 1. Operators action space, or role allotment, adopted from Fast-Berglund and Stahre (2013).

<table>
<tr><th>Plan</th><th>Teach</th><th>Monitor / Perform</th><th>Intervene</th><th>Learn</th></tr>
<tr><td rowspan="2">Process planning and production engineering</td><td>Programming for a new product</td><td rowspan="2">Manual assembling</td><td>Lack of material</td><td rowspan="2">Continuous improvements</td></tr>
<tr><td rowspan="2">Material handling</td><td rowspan="2">Small disturbances</td></tr>
<tr><td rowspan="2">Long time planning (>2 w)</td><td rowspan="2">Monitor machines</td><td rowspan="2">Learning new working tasks</td></tr>
<tr><td rowspan="2">Order handling</td><td rowspan="2">Large disturbances</td></tr>
<tr><td rowspan="2">Short time planning (1-2 w)</td><td rowspan="2">Maintenance</td><td rowspan="2">Teach new operators</td></tr>
<tr><td>Set-up</td><td>Quality check</td></tr>
</table>

Operations, workstations, or entire flow lines, can be automated. An automation system can be divided in the technical system, the control system, and the human (Frohm et al., 2008). The function of the technical system is mechanisation, which is the use of machinery to aid in physical tasks. Mechanisation has been around for a very long time since the wheel is an example of it. External power was added to mechanised systems in windmills and watermills but they could only operate at the speed of the water or wind. It was with the invention of the throttled steam engine 1785, which became the first type of control system, proper automation was a possibility (Groover, 2016). The next leap in automated systems was when the control system became programmable, as with the Jacquard loom. However, it was with the introduction of computerised control that automation started to become affordable and widely spread. Two types of automation equipment connected with computerised control are CNC (Computer Numerical Control) machines and industrial robots (Groover, 2016). CNC machines are programmable systems where a machine tool is controlled to process a part. According to the ISO standard of robots and robotic devices and industrial robot is an “automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be wither fixed in place or mobile for use in industrial automation applications” (ISO, 2012, p. 3). The manipulator, in this definition, is the actual robot arm.

Frohm et al. (2008) described mechanisation as the function of the technical system and computerisation as the function of the control system, in regards to the human. Another way to describe it is that mechanisation assist the human with physical tasks, computerisation assist the human with cognitive tasks. This way of dividing the functions of an automation system was developed into a taxonomy of different Levels of Automation (LoA) (Frohm et al., 2008). lists the seven different levels of both mechanisation (physical automation) and computerisation (cognitive automation).

Table 2 lists the seven different levels of both mechanisation (physical automation) and computerisation (cognitive automation).

Table 2. Levels of physical and cognitive automation. Adapted from Frohm et al. (2008).

LoA	Physical automation	Cognitive automation	LoA
1	**Totally manual** Hands and muscle power.	**Totally manual** Own knowledge and experience.	1
2	**Static hand tool** Static tool and muscle power.	**Decision giving** Information on what to do.	2
3	**Flexible hand tool** Adjustable tool and muscle power.	**Teaching** Information on how to do the task.	3
4	**Automated hand tool** Handheld tool that add physical force.	**Questioning** Verification of performance.	4
5	**Static machine/workstation** Automatic work with a machine designed for one or few specific tasks.	**Supervision** Information on events of interest.	5
6	**Flexible machine/workstation** Automatic work with a generic machine designed for many different tasks.	**Intervene** Automatic correction of deviations.	6
7	**Totally automatic** Autonomous systems, automatic work by a system that can reconfigure itself.	**Totally automatic** Autonomous systems manages all information and control	7

Figure 4 shows a visualisation of a production facility, shop floor, with different layouts, manufacturing processes, operators, and automation.

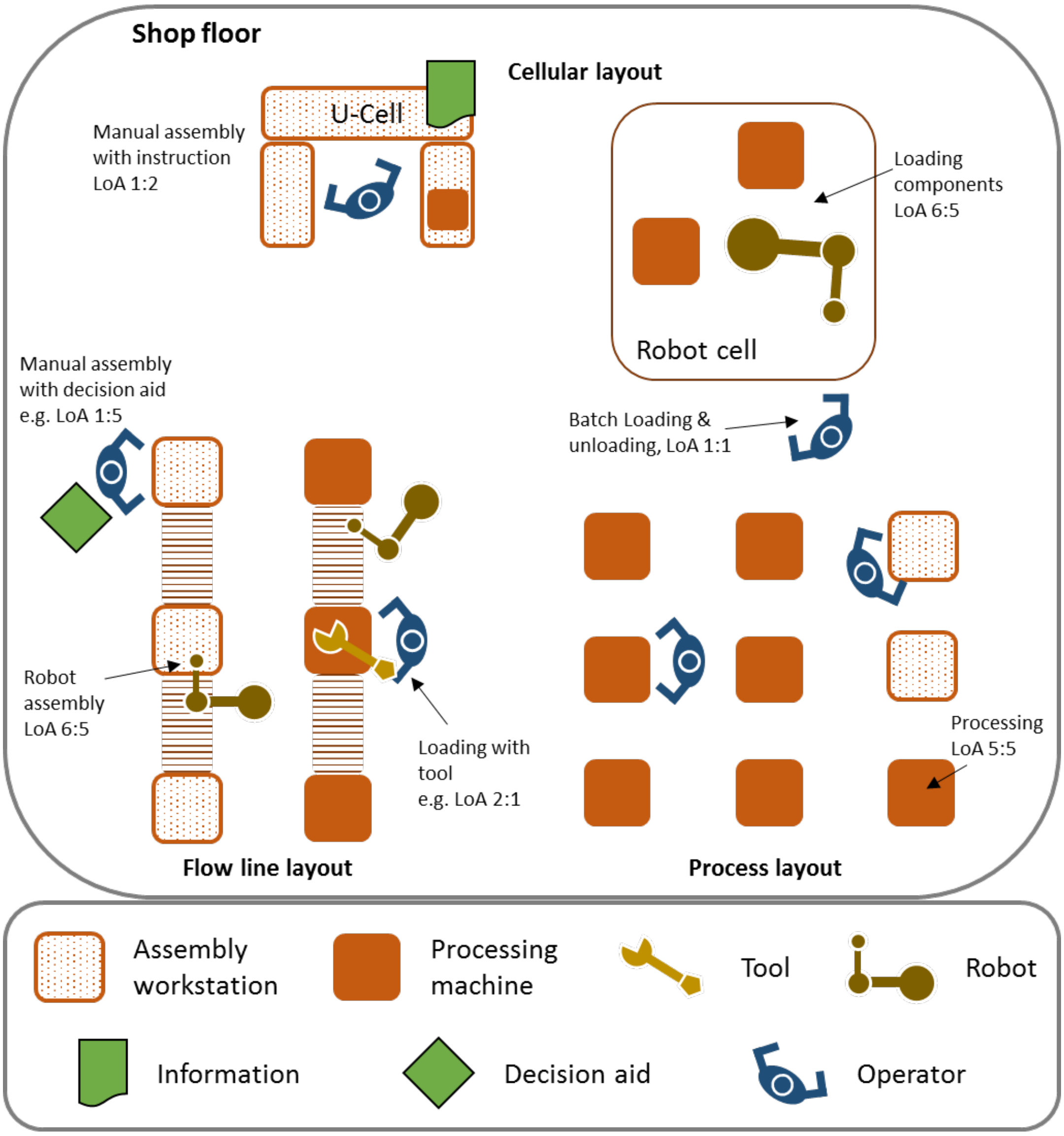

Figure 4. Visualisation of a manufacturing facility with manufacturing processes in different layouts. Operators and automation are doing tasks at different LoA.

2.1.2 Challenges of Automation

At some point during the design of a manufacturing system it has to be decided what to automate and how. Higher levels of automation do not equal a more efficient system. When an operator enters and leaves different roles she need to adapt and manage new situations. Fully automated systems can keep the operators from fully understanding the process which makes it difficult for them if a manual takeover is needed. This is known as out-of-the-Loop problem and relate to faults in the implementation of the automation system (Endsley & Kiris, 1995). Bainbridge (1983) describes two common design mistakes, or "*Ironies of Automation*", that stems from the fact that the system designer view of the operator is that she is unreliable, and should be eliminated if possible (Figure 5).

Irony 1	Actual faults in the design are the major source of problems in the operation.
Irony 2	The designer intended to eliminate the operator but failed to do so for some tasks.

Figure 5. Ironies of Automation. (Bainbridge, 1983).

The second irony of automation (Figure 5) might lead to monotonous work of leftover automation, like packing, loading or unloading. Or that the operator just monitors the automation and end up out-of-the-Loop. The point of the ironies is that a system should be designed with focus on the human operator so that they are utilised to greatest potential. These potential issues are the basis of the DYNAMO++ method that aims to aid the system designer in choosing a suitable automation solution (Fasth, 2012). In this method, the production system is measured before and after implementation of a suggested new system, in which every task should be designed within a range of LoA.

During the change process it is important to remember that physical automation, or mechanisation, is not the only way to assist the operator. Cognitive automation can increase situation awareness and this is increasing in importance with higher product variety and complexity. Mass customization is the current production paradigm, meaning that production companies create large amounts of very different types of products, which requires both flexible and productive manufacturing systems (Fogliatto et al., 2012). These shifts of paradigm do not happen overnight and production flexibility have been in focus for decades and still is.

There are many types of flexibility of manufacturing defined in the literature. One important distinction of flexibility is static vs dynamic (De Toni & Tonchia, 1998). In a system with static flexibility it has been designed for a fixed set of parameters while a system with dynamic flexibility is designed to adapt and change its configuration. For this reason, the previous system paradigm of Flexible Manufacturing Systems (FMS) is changing towards reconfigurable or changeable systems (Wiendahl et al., 2007). The type of changeability required depends on what level of the production that need to handle change. As shown in Figure 6 Wiendahl et al. (2007) define five classes of changeability: Changeover ability, configurability, flexibility, transformability, and agility. The focus towards more dynamically flexible manufacturing systems have also increased the focus of humans role in the system (ElMaraghy, 2005).

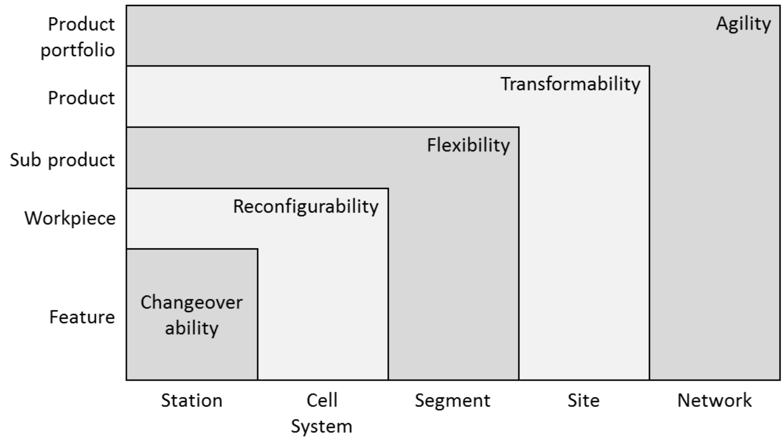

Figure 6. Five classes of changeability. Adopted from Wiendahl et al. (2007).

Because of recent advances of information and communication technologies (ICT) and with the increased focus on human operators and flexibility of manufacturing systems, it is a tempting proposition to increase the utilisation of ICT as cognitive automation for manufacturing operators (Karlsson et al., 2013). One way to view ICT is that of carrier and content of information (Fast-Berglund et al., 2014). Information content is how the information is presented and the information carrier is how the information is transferred. Smartphones and tablets are now very affordable and is a natural choice as the information carrier for many applications. Furthermore, the few existing and used cognitive automation in assembly systems are very restrictive in its implementation, while mobile smartphones can easily be individualised (Fässberg, 2012). Other technologies are being researched and will soon be available on the market to further increase the options of automation. Smart glasses can be utilised as a carrier to allow the operator free movement. Smartboards are utilised in the educational environment and could be a valid replacement for the whiteboards used so extensively in the industry today (Fast-Berglund, Harlin, et al., 2016). Augmented Reality (AR) is a way of presenting information directly connected to physical objects or improve interaction between the environment and information (Figure 7). Another upcoming automation technology is collaborative robots, or Cobots, that allow operators to work together or side by side with industrial robots (Andreadis, 2015).

Figure 7. An example of AR used in a remote guidance scenario. The device shows the reality from the camera view with an overlay of the hand of an expert that can remotely both explain and simultaneously show what to do.

2.2 Software systems and communication networks

This part describes models of software systems and communication networks.

Any enterprise needs systems to manage the information flow through processes and the organisation. Enterprise engineering was popularised in the 1990's and is the art of improving an enterprise as a complex system by systematically improving its models and their implementations (Lim et al., 1997). Another term is enterprise architecture, that describes the information system architecture and its integration and organisational alignment (Richardson et al., 1990; Tamm et al., 2011). The technical aspects are a combination of software systems and communication networks (Figure 8). The software systems architecture is concerned with how the system components should be organised, including their external connections (Nan et al., 2013). A common view of software systems is that they are organised in logical layers that run on computational machines, or tiers. Different tiers are separated physically while layers are separated by logic or function. There are many different models for multi-layered architecture but the most basic is that of presentation, domain, and data source layer (Fowler et al., 2002). A presentation layer is the interface with the users, the domain layer is the logical (core function) component, and data source communicates with other systems or manages persistent data (e.g. a database system).

A communication network is the communication infrastructure for system components. Its structure is often directed by the limitations of the interfaces and protocols involved. A network is a structure of different data connections that transfers data over some medium like copper wires, optical fibres, radio waves etc. The Open Systems Interconnection (OSI) model is a generic layering model that defines the different communication functions (Zimmermann, 1980). It is a reference model, and an international standard, based on seven logical communication layers (ISO/IEC 7498-1, 1994). The two lower layers, physical and data link, can be used to define how data is sent over the physical medium, e.g. single bit representation and frame size. The network layer defines how to setup a multi-node layer, this includes addressing and routing, the Internet Protocol (IP) belongs in this layer. The next two layers, transport and session, can be used to describe data reliability and communication sessions, e.g. retransmission and keep alive messages. The top two layers, presentation, and application, can be used to define higher abstraction of data transfer, e.g. compression and encryption and that what which concerns the specific systems involved. Figure 8 illustrates the concepts of the enterprise information system as described in this section.

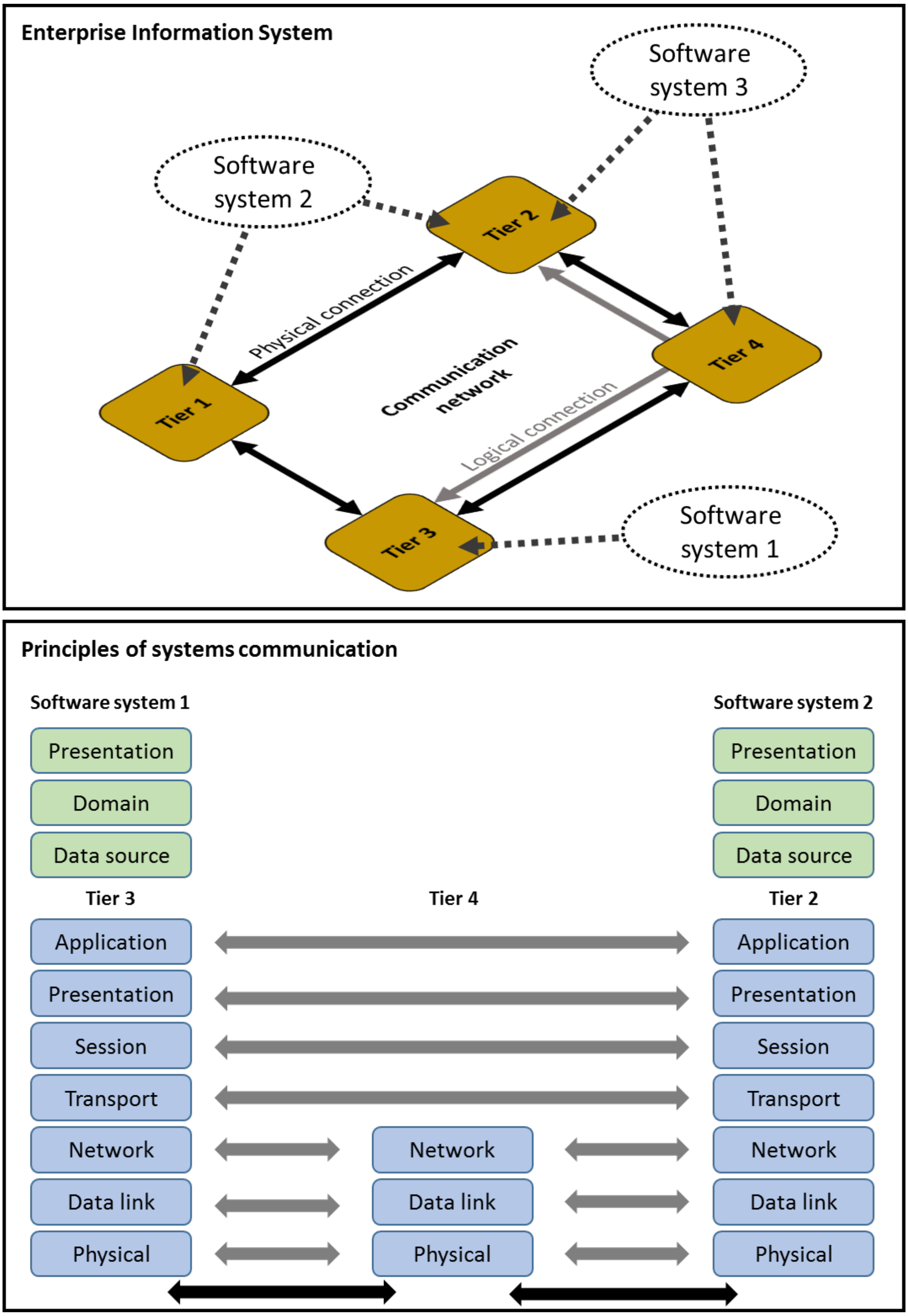

Figure 8. The enterprise information system with focus on the technical aspects and basic layer models (Fowler et al., 2002; ISO/IEC 7498-1, 1994).

2.2.1 Software architectures

The Open Management Group (OMG) is a standards consortium founded 1989 that strongly advocates Models Driven engineering (MDE) (OMG, 2015a). Standards like UML and SysML are developed within OMG. With SysML different applications can share UML developed models (OMG, 2015b). The Unified Modeling Language (UML) allows the designer to raise the level of abstraction by visualising the system by using standardised graphical models (OMG, 2005). MDE is important so that the correct architecture models are chosen for a software system. For many applications data is "distributed over a multitude of heterogeneous, often autonomous information systems, and an exchange of data among them is not easy" (Hasselbring, 2000). Main strategies against this problem of data exchange are either to integrate systems, meaning making them more uniformed, or to make them more interoperable, which means that they can co-exists as autonomous systems but still interact seamlessly (Chen et al., 2008). The chosen strategy is implemented in the models and in the architecture of the software system. Nan et al. (2013) mention five relatively recently proposed types of software architectures to advance industrial applications: domain specific EISs, distributed real-time control, embedded and dependable systems, agent platforms, and the service-oriented architecture (SOA). The type of architecture that best suits a system depends on the type of system and business generic requirements, or quality parameters, e.g. scalability, reliability, performance etc.

SOA allows for loosely coupled systems that enables interoperability without forcing homogeneity (Vernadat, 2007). At its core, SOA, consists of service providers and consumers. The model also requires two specialised types of services that either find other services, aka service locators, or publish them, aka service brokers (Endrei, 2004). 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 a SOA with Web standards like e.g. HTTP and XML (W3C Working Group, 2004). The service-oriented model does not define the interface of various services. It is important to have a uniform style of the interfaces to simplify interactions. The RESTful style of interface architecture includes these concerns in its design. REST (Representational State Transfer) uses stateless interactions and a hierarchical resource representation among other features to emphasise scalability, interface uniformity, and more (Fielding, 2000).

Agent platforms, or multiagent systems, consists of many, more or less autonomous, interconnected and interacting computing elements, known as agents. There are several reasons for building multiagent systems but they can be condensed into a purpose of achieving some larger goal by utilising individual agents that operate on more simple rules, or intelligence. (Wooldridge, 2002).

2.2.2 Interoperability

System integration and interoperability are different sides of the same coin and the concepts are often used interchangeably. Interoperability is often described in the levels technical, syntactical, semantic, and organisational (Rezaei et al., 2014). Technical interoperability considers the physical aspects of interconnection and low-level communication protocols. The syntactical level focuses on the structure of data. Semantic interoperability can involve both technology and humans and explains how the data should be interpreted. Organizational interoperability and business integration are more holistic aspects. A basic model of system integration is an enterprise system model where different organisational units, horizontal integration, are coupled with technological levels, vertical integration (Hasselbring, 2000). Combining this view with the basic levels of interoperability, see Figure 9, shows how similar these concepts are.

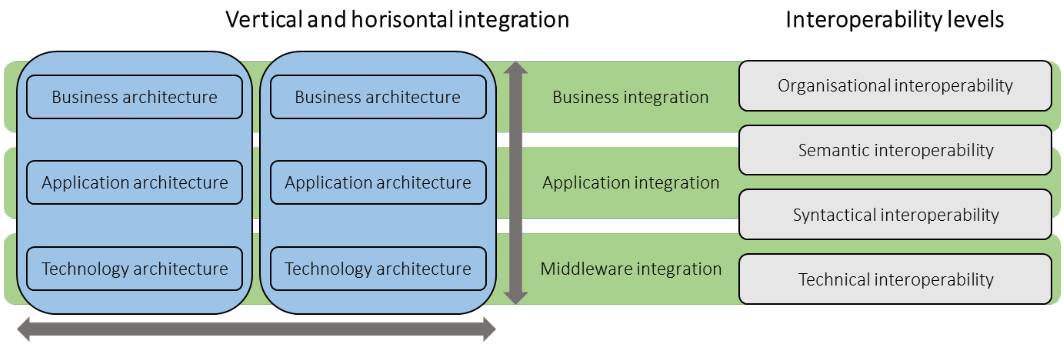

Figure 9. Vertical and horizontal integration (Hasselbring, 2000) connected to levels of interoperability (Rezaei et al., 2014).

One way to understand why interoperability is important is to investigate what happens when systems are not interoperable. In a whitepaper describing ETSI's approach to technical interoperability Van Der Veer and Wiles (2008) summarise non-interoperable systems, on a technical level, with the answer to three questions (Table 3).

Table 3. Issues of technical interoperability (Van Der Veer & Wiles, 2008).

Question	**Meaning**	**Possible reasons (Not complete list)**
Where are you?	A system does not acknowledge the existence of the communicating part.	Faulty communication standard or internal error in one of the entities.
What did you say?	Data is transferred but not correctly interpreted by the receiving part.	Wrongly implemented or incomplete standard.
Why did you do that?	Completely unexpected behaviour or unwanted side effects.	Ambiguous standards or misinterpretations.

Interoperability has been extensively researched, especially in parallel with the increased interest of enterprise integration during the 1990's. Several models have been developed for evaluating interoperability of current systems (Rezaei et al., 2014). Levels of Information Systems Interoperability (LISI) is a model that combines five levels of complexity with four system attributes (C4ISR, 1998). The LISI model was also generalised and expanded into the C2 framework that also focuses on organisational interoperability (Clark & Jones, 1999). C2 stands for Command and Control and relates to the fact that these models were developed within the US Department of Defence. The enterprise interoperability maturity model, a result of the European research project ATHENA IP, is a system that measures maturity levels on defined interoperability indicators. (Rezaei et al., 2014). These three models (Table 4) have similarities in approach but they differ in point of view, no doubt inherited from the respectively field of interest.

Table 4. Comparison between three maturity models to measure interoperability. (C4ISR, 1998; Clark & Jones, 1999; Rezaei et al., 2014)

Model	**LISI**	**C2 Framework**	**Enterprise interoperability maturity model**
Maturity levels	Enterprise Domain Functional Connected Isolated	Unified Combined Collaborative Ad Hoc Independent	Optimising Interoperable Integrated Modelled Performed
Areas of concern	Procedures Applications Infrastructure Data	Preparedness Understanding Command Style Ethos	Enterprise modelling Business strategy & Processes Organisations & Competence Products & Services Systems & Technology Legal, Security, & Trust

Koussouris et al. (2011) investigates interoperability from a different perspective. Their aim was to find different research areas that can connect interoperability with the enterprise system and include inter-organisation communication. They suggest six fundamental areas: data, process, rules, objects, software systems, and cultural that can connect to new interdisciplinary areas in higher levels (Figure 10).

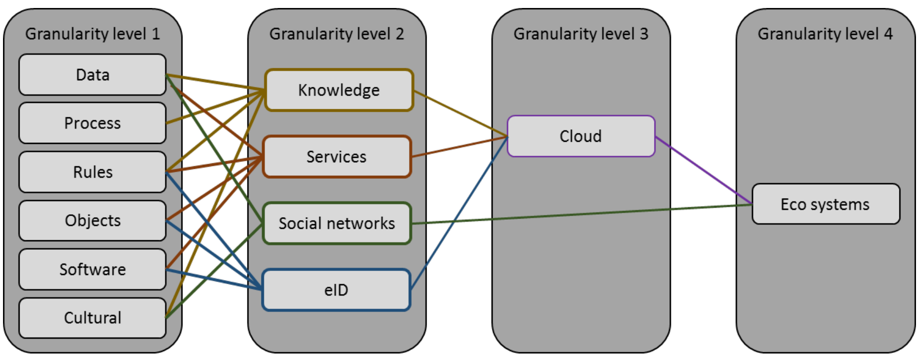

Figure 10. Enterprise interoperability research areas divided in granularity levels (Koussouris et al., 2011).

The higher granularity levels include the fundamental areas but defines new disciplines where the distinct difference between previous concepts becomes more difficult to detect. Table 5 lists all the individual areas with a short description.

Table 5. Enterprise interoperability research areas.

Interoperability research area	Short description
Data interoperability	Data should be accessible, understandable, and reusable by all parties.
Process interoperability	Describes how aligned different processes are between different entities. Such alignment enables those entities to work together more seamlessly.
Rules interoperability	Business rules and legal rules do sometimes dictate processes. Such rules must be integrated in the system to support the overall process.
Objects interoperability	Identification and interconnection of objects.
Software systems interoperability	The ability for two different software systems to work with each other.
Cultural interoperability	Cultural interoperability relates to traditions, languages, social norms, localised rules etc.
Knowledge interoperability	The ability for entities to share intellectual assets, use it, and create new knowledge trough collaboration.
Services interoperability	Service interoperability is the ability to utilise external services
Social network interoperability	The ability of an enterprise to utilise social networks for coloration purposes.
Electronic Identity interoperability	The ability to utilise eID systems.
Cloud interoperability	The ability to utilise cloud services.
Ecosystems interoperability	Ecosystems are groups of interests such as common core business that cross the enterprise borders. Ecosystem interoperability deals with interconnections within and between these ecosystems.

2.3 The automation pyramid

This part of the theory describes the current model of information and communication system of a manufacturing enterprise.

During the seventies a discussion started about how to structure the information systems at an enterprise level and how the systems could be better integrated with each other. These discussions resulted in a few generic theories or models describing how to structure and or classify different types of communication for an enterprise information system within the research field of computer-integrated manufacturing (CIM) (Doumeingts et al., 1995). A common feature of all models of enterprise architecture was the hierarchal structure that would be known as the automation pyramid (Sauter et al., 2011). For industrial implementations, the most promising models were combined into the standard ISA-95. ANSI/ISA-95 is an enterprise architectural standard model consisting of five levels that represents where in the enterprise certain information belongs. Figure 11 shows the traditional Automation pyramid with the levels inherited from ISA-95.

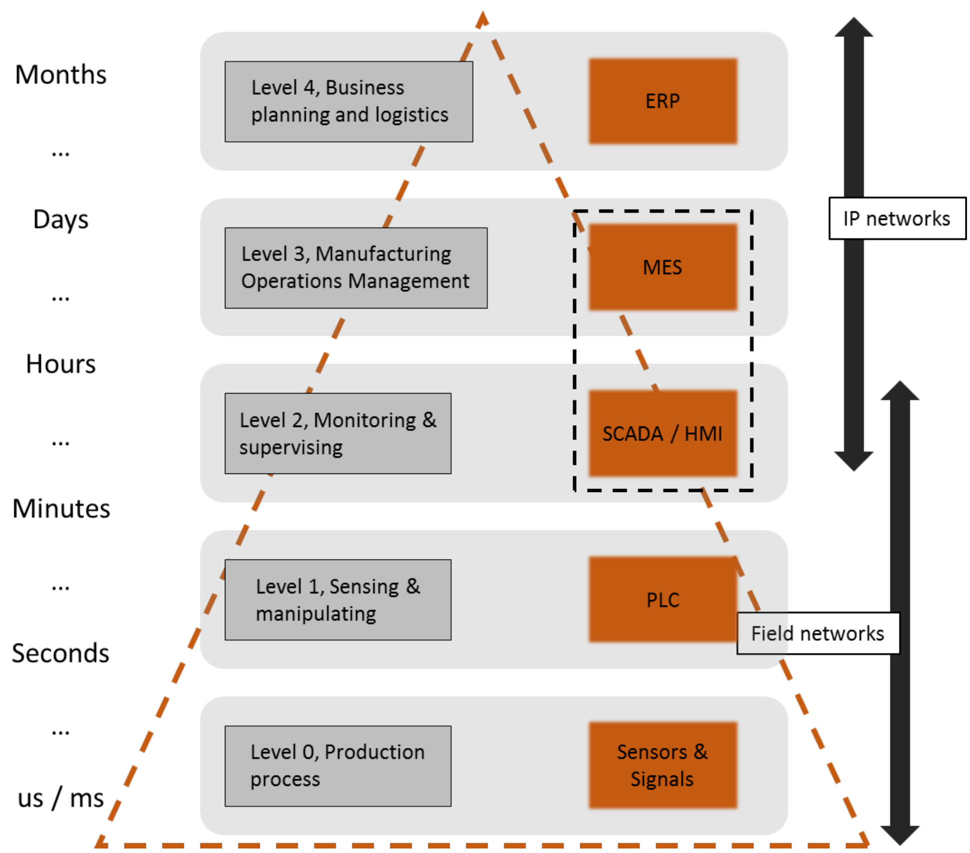

Figure 11. The automation pyramid with levels from ISA-95.

ERP systems deals with the entire business and links the functions as they are required. Today's ERP software is highly modularised and the selectable functions are continuously growing. (Jacobs & Weston, 2007). Since SOA and Web-services enable loosely coupled systems it has been the norm for ERP systems since 2000 (Vernadat, 2007).

2.3.1 Operations management, monitoring, and control

Resources, operators and automation, require information to be able to execute the manufacturing process. A system that is dedicated to manage this type of information is called a Manufacturing Execution System (MES) (Ugartea et al., 2009). An examples of MES responsibility could be providing instructions and other documentation to the operators. The solution could range from dynamic digital instructions to a document that has to be printed and taken to the workstation.

The Manufacturing Enterprise Solutions Association (MESA) is an organisation that wants to improve the operations information systems by developing best practices and sharing knowledge between its members (MESA International, 2016).

Table 6. Principle MES functions according to MESA. Adopted from Ugartea et al. (2009).

MES functions	Data acquisition
Operations scheduling	Performance analysis
Resource allocation and status (people, machines, tools and materials)	Labour management
Dispatching production units (materials or orders)	Maintenance management
Document control	Process management
Product tracking	Quality management

MESA defines eleven types of MES functions as described in Table 16. Because if this large diversity of functions and potential information, MES is sometimes split up, either in modules, or separated so that some MES functionalities are integrated in the ERP system and some are implemented in a Supervisory Control and Data Acquisition (SCADA) system. MES and SCADA have followed the same path towards flexibility and scalability through Web Services and open standards as other systems. There is an XML standard called B2MML to integrate the business and operations layers of the ISA-95 model, which beneficially can be combined with the Web-Service approach (Karnouskos et al., 2007). Since these systems exists in the border between shop floor systems and office IP networks vertical integration was, and still is, a large obstacle. OPC was released in 1996 as a solution to this problem ("Opc Foundation,"). The OPC acronym stands for OLE (Object Linking and Embedding) for Process Control. OLE is a Microsoft specific technology and OPC was tightly connected to the Windows platform. OPC quickly became the de-facto standard for vertically integrating automation equipment.

2.3.2 Shop floor systems and field level networks

Automation equipment, sensors and actuators, on the shop floor are connected in a field level network. The field level network differs from IP-based local area networks (LANs) because the technology and systems have been developed with a different set of requirements (Table 7) (Galloway & Hancke, 2012).

Table 7. Major differences between conventional networks and those for industrial monitoring and control, adopted from (Galloway & Hancke, 2012).

	Industrial networks	**Conventional networks**
Hierarchy	Deep	Shallow
Failure severity	High	Low
Reliability required	High	Moderate
RTT (Round Trip Times)	250us – 10ms	~50ms
Determinism	High	Low
Data composition	Required	Not required
Operating environment	Hostile	Clean

The history of field level networks can be divided into three generations where two of them, fieldbus systems and Industrial Ethernet, have gone through conformation phases of standardisation while the third, wireless field-level network, is in its beginnings (Sauter, 2010). Fieldbus systems were individually developed at first and the lack of international standards was a concern acknowledged by the International Electrotechnical Commission (IEC). The international standard IEC 61158 was released in 2000 and it is a multiprotocol standard defining a family of fieldbus systems (Galloway & Hancke, 2012). Industrial Ethernet protocols are the result of trying to close the vertical gap and integrate IP-based networks with fieldbus systems. Ethernet doesn't close this gap completely, not all protocols support IP for instance but it is a start. Since IEC 61158 included many different protocols another standard, IEC 61784, has been released and is constantly updated in an attempt to clarify the field. IEC 61784 also includes Industrial Ethernet protocols.

Table 8. IEC 61131-3, programming languages for PLC programming adopted from John and Tiegelkamp (2001).

Language	**Type**	**Description**
SFC Sequential Function Chart	Graphical	Ability to break down the program into smaller parts that can run both in sequence and parallel.
LD Ladder Diagram	Graphical	Resembles circuit diagrams with Boolean logic. Can be structured in parts called networks.
FBD Function Block Diagram	Graphical	Connections between function blocks divided in networks.
IL Instruction List	Code	Low level machine instructions.
ST Structured Text	Code	High-level, more abstract, programming language.

Automation equipment are commonly controlled by specialised computers or PLCs. A PLC, Programmable, Logic Controller, is programmed using specialised types of programming languages (Table 8), where the practitioners can be guided by IEC 61131-3 in which the five classic methods are described.

Another important standard is IEC 61499 that defines architectures, tools, and other information for developing industrial systems (Vyatkin, 2013). It is a reference architecture of Function Blocks FB, extended from IEC 61131-3. The standard includes extensive support for code generation, which means that it could be possible to write entire projects in IEC 61499 and then generate the code instead of using the traditional PLC languages (Vyatkin, 2011).

2.4 Towards free communication

This part describes the concepts of Cloud computing, Internet of Things, and Cyber Physical Systems that are the cornerstones of the Industry 4.0 paradigm. Furthermore, it will dive into some new technical systems that can enable implementation of these ideas together with current automation systems.

The automation pyramid is a valid model for most current production systems and their information and communication systems. Table 9 summarises the explained topics and exemplifies some aspects of the automation pyramid with enterprise and software systems and communication networks.

Table 9. Description of enterprise information system with software system and communication network components. General aspects and models are described and then exemplified from the perspective of the manufacturing industry.

System	**Enterprise Information System**	**Software system**	**Communication network**
Description	Entire enterprise information system. Organizational domains and technical systems.	One specific software system with defined functions.	Data transfer system between tiers.
Structural model	Enterprise Engineering / Architecture	Software architecture	Network structure
Common model view	Organizational hierarchies and domains, information types, responsibilities, processes	Tiers, layers, and logical interfaces	Data transferring medium, protocols, physical interfaces, and logical layers (OSI model).
Generalisations	CIM, ISA-95, Automation Pyramid	ERP, MES, SCADA, Automation control	WAN, LAN, Fieldbus systems
Implementation	Unique combination of systems	MRP, SAP R/2, PLC program, Robot programs	Ethernet, TCP/IP, Modbus, Profinet, EtherCAT

As explained in the introduction, the manufacturing industry is anticipating a new paradigm: Industry 4.0. A forerunner to Industry 4.0 is the SmartFactory^{KL} (Zuehlke, 2008). It is a project to realise new ideas about connectivity and distributed computing in a laboratory environment. Zuehlke (2010) describe a system where SOA is implemented with B2MML to transfer business information. Wireless technologies are implemented for monitoring and some sensor data, and a RFID system guides the process control.

The five different software architectures, that Nan et al. (2013) described as important for new industrial applications, are not directly tied to a specific type of implementation and several architectures may be mixed within one software system. However, with the exception of domain specific enterprise systems, they are tightly connected with emerging paradigms regarding information and communication systems that are all important for future manufacturing systems.

- Domain specific EISs → Modern ERP systems
- SOA → IoT, Cloud Computing
- Agent platforms → IoT, CPS
- Distributed real-time control → IoT, CPS
- Embedded and dependable systems → CPS

Service Oriented Architecture is involved in some way in almost any modern system because of the success of Web Services. The SOA model has also given rise to a new concept, Cloud Computing, in which more than data transfer is considered as services (Armbrust et al., 2010). In the Internet of Things paradigm objects are connected with data and to use services is an excellent way of implementing such connections (Song et al., 2010). Furthermore, distributed objects could also inherit behaviours, which can be implemented through multi agent system (Alexakos & Kalogeras, 2015). The CPS paradigm takes the concept of decentralised decisions connected to objects and environment even further. When real time requirements are added to the equation, the currently existing engineering models need to be adapted (E. A. Lee, 2008).

2.4.1 Cloud computing

Cloud computing is the concept of utilising different services to build a system. According to NIST (National Institute of Standards and Technology) there are three main models for cloud services: Software-as-a-service (SaaS), Platform-as-a-Service (PaaS), and Infrastructure-as-a-Service (IaaS). Furthermore, cloud computing is also defined by five characteristics (Table 10). (Mell & Grance, 2011).

Table 10. 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.

Most private consumers utilise cloud services today especially regarding social networks, e-mail, search engines, e-commerce, and storage etc. One of the main drivers for enterprises original interests in cloud computing was the business driven requirement of lowering initial investments (Alali & Yeh). This scalability is a major benefit of cloud computing but other benefits include flexibility, better resource utilisation, and simplified management (Armbrust et al., 2010).

2.4.2 IoT

Internet of things is a concept, or paradigm, that allows objects in our immediate surrounding to, with individual addressing and identification, communicate with each other and therefore cooperate and achieve common goals (Atzori et al., 2010). IoT combines three aspects, or technological visions, which are visions of things, internet, and semantic (Atzori et al., 2010). The semantic visions relate to the understanding of data, standards and technology to use, to reach interoperability when the objects interact. As the name suggests, visions of things are central to the IoT concept, and objects need to be uniquely identified. Early implementation of this is the RFID system, that identifies objects with radio signals and connect them with an uID, unique identification. There are several options of wireless technologies to choose from (Table 11), the best suitable depends on the implementation. An RFID solution does not include every aspect of IoT. Internet visions imply that IoT platforms either are Internet, meaning objects have their own IP address, or can seamlessly communicate with the Internet.

Table 11. Wireless communication technologies. (Li et al., 2015).

Communication protocol	Transmission rate	Range
RFID	424 kbps	~50 cm - ~3 m
NFC	100 kbps-10 Mbps	-
ZigBee	256 kbps/20 kbps	10 m
Bluetooth	1 Mbps	10 m
BLE	10 kbps	10 m
UWB	50 Mbps	30 m
Wi-Fi	50-320 Mbps	100 m
Wi-Max	70 Mbps	50 km
UMTS, CDMA, EDGE, MBWA	2 Mbps	~

IoT platforms can either focus on data and services in an 'Internet centric' model or focus more on the physical objects in a 'Things centric' model (Table 12). In an Internet centric model, objects contribute data but the intelligence of the system is provided by services and cloud computing platforms (Gubbi et al., 2013; Li et al., 2015; Tao et al., 2014; L. Xu et al., 2014). The RFID solution in the Smart Factory, described by Zuehlke (2010), would lean towards an Internet centric IoT implementation. Sánchez López et al. (2011) describe a Things centric model as similar to a multi-agent model where Smart objects communicate with each other. These objects are also assumed to have sensors connecting to the real environment, which is a description that resembles a CPS.

Table 12. Two types of IoT implementations, Internet centric (Li et al., 2015) and Things centric (Sánchez López et al., 2011).

Internet Centric	Things Centric, Smart Objects (SO)
Interface layer: Users or applications interacts with services.	SO possess a unique identity
Service layer: Manage services required for various applications.	SO are able to sense and store measurements made by sensor transducers associated with them.
Network layer: Ensures a connection between things.	SO are able to make their identification, sensor measurements, and other attributes available to external entities such as other objects or systems.
	SO can communicate with other SOs.
Sensing layer: Consists of the physical objects.	SO can make decisions about themselves and their interactions with external entities.

2.4.3 Cyber-Physical Systems

In Cyber-Physical Systems, physical processes and software systems are completely integrated and constantly interacts through feedback loops (CHESS: Center for Hybrid and Embedded Software Systems). This means that a software system can be both dependant and in control of one or several physical systems and vice versa. This added complexity creates a new type of engineering problem which derives from the engineering models that different disciplines use. Each component in a CPS will be modelled in a different way and the sum of the system will be very difficult to overview and impossible to predict (Derler et al., 2012).

Other aspects of CPS are the heterogeneity of networks that they imply (Shi et al., 2011). A system could potentially be connected with all possible types of wired and wireless technology e.g. Bluetooth, WLAN, mobile networks, etc. Furthermore, many components of a CPS will have time constraints that apply real-time requirements on the system. In a Cyber-Physical system many things happen at the same time, which requires a good model and platform for embedded systems that can manage concurrency, e.g. actor oriented systems (E. A. Lee, 2008). Some characteristics of Cyber-Physical Systems are also their benefits. Since they are so complex they need the ability to automatically and dynamically adapt to changes, and they need to be reliable and secure (Shi et al., 2011).

In a later iteration of the Smart Factory, Kolberg and Zühlke (2015) discuss a CPS to enable Lean principles in the SmartFactory. However, it is clear that not everyone would define their system description as being CPS.

A platform to implement CPS in manufacturing systems is suggested by J. Lee et al. (2015) in a five layer structure they call a 5C architecture (Figure 12). The five layers: Configure, Cognition, Cyber, Conversion, and Connection represent different abstraction layers, organised similar to the automation pyramid, of a manufacturing CPS. The connection layer represents individual sensors but also data acquisition from systems or services. The conversion layer is where the data becomes useful information with algorithms for different data analytics. The conversion layer provides a sense of self-awareness to the machines. In the cyber layer all information from individual components is combined so that more holistic analytics can be made. In this layer, the system can compare machines to each other and adapt accordingly. Cognition is the representation layer for human users such as operators. The top layer, configure, is the feedback to the physical system and acts to prevent problems and correct deviations. (J. Lee et al., 2015).

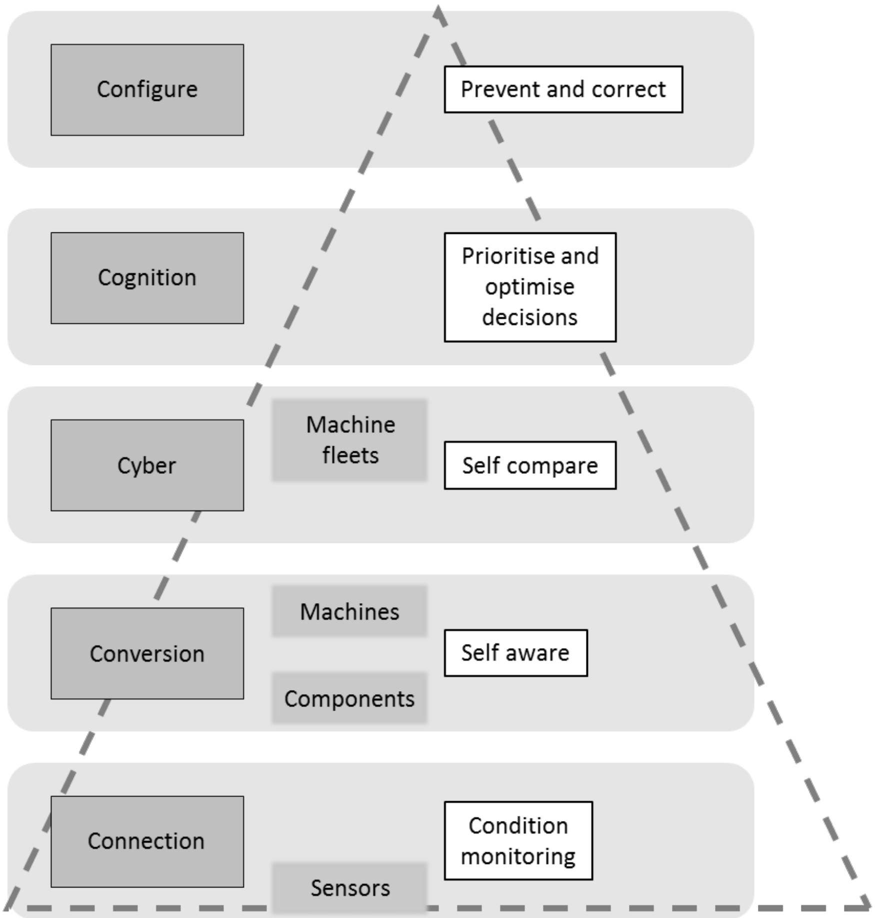

Figure 12. A framework for CPS in manufacturing (J. Lee et al., 2015).

2.4.4 Automation engineering

UML and SysML are tools for model-driven software engineering while IEC 61499 with its function block models provides similar approaches for developers of automation systems. However, UML and SysML provides a lot more help in the beginning of the development cycle while IEC 61499 is more focused on the finishing details (Vyatkin, 2011). Several attempts have been made in combining these frameworks to improve engineering work for industrial systems with varying result, interested readers are referred to Vyatkin (2013) for more information on this. In short, the way industrial automation systems are designed today will most likely change in the near future and a merge of traditional frameworks, with both old and new techniques from the automation area, may occur. The standards or concepts described below are some of the important parts in figuring out in which direction software automation engineering will turn. They are OPC UA, Automation ML, and IoT-Platforms.

OPC UA

When the importance of open standards and platform independence started to become clear, the popular OPC standard started to feel very outdated. The OPC foundation, that was managing the standard, developed an updated version OPC Unified Architecture released 2008. OPC now stands for Open Platform Communications to emphasise that OPC is now platform independent. ("Opc Foundation,").

Communication is achieved using either XML, from Web Services, or binary code over TCP, called UA native. This allows for a scalable solution where the UA native protocol can be utilised for limited embedded systems with smaller data bandwidth. (Hannelius et al., 2008). This scalability allows OPC UA to be implemented for a wide range of applications and suitable for at least some aspects of the IoT paradigm (Imtiaz & Jasperneite, 2013).

Automation ML

CAEX, Computer-Aided Engineering eXchange) is an internationally standardised file format, which provides an object-oriented structured meta-model. The Automation ML (AML) data format is built on the CAEX model (Vyatkin, 2013). AML aims to simplify information exchange between tools used during the automation engineering process. It supports storage of plant topology, geometry and kinematic (COLLADA), behaviour description (PLCopen), references, and relations. Automation ML consists of class libraries and a concrete instance hierarchy. (Drath et al., 2008).

Implementing IoT

IoT and CPS are based on connectivity and interoperability between small and intelligent physical objects. The two things needed to achieve this are: a protocol that can handle potentially low bandwidth for communication and a system to distribute software to many, small and potentially limited, devices. Furthermore, for the manufacturing industry, the system must also meet the specific requirement of manufacturing systems such as timeliness. There are some promising platforms to build these systems and today there are plenty cheap hardware options to utilise when testing them.

Communication

In distributed multi-tier software systems components communicate over a network structure using a message transfer system. Two common message transfer patterns are request-response and publish/subscribe. In request-response communication the requestor initiates the communication, which can be very inefficient in an event-based system of distributed physical objects since it requires that the requester polls the other nodes to ask if there is anything to request. A publish/subscribe method is more efficient since events trigger a publish and the message gets distributed to subscribing nodes (Zeng et al., 2011).

HTTP is a request/response protocol. A HTTP request message contains a method, commonly the GET method, and an identifier e.g. www.chalmers.se. Simple and standardised HTTP messages can be sent using JSON (Java Scrip Object Language) or XML. However, HTTP requires that every layer of the IP-stack is implemented and could add too much overhead for some implementations. There are alternatives like CoAP and MQTT-SN (see Figure 13).

CoAP (Constrained Application Protocol) works well with HTTP but requires less overhead (Colitti et al., 2011). It is also a request/response protocol but it does have a built-in publish/subscribe support (Zeng et al., 2011). Other advantages are that it utilises a RESTful style interface and is based on UDP (Shelby et al., 2014). MQTT, Message Queuing Telemetry Transport, is a lightweight, best effort, publish/subscribe message protocol (IEC/ISO 20922). There is also an extension for sensor networks MQTT-NS (Stanford-Clark & Truong, 2013). MQTT-SN takes it a step further than CoAP in that it does not rely on IP. HTTP has been extensively developed and when going down in layers to reduce overhead there is naturally a trade-off in functionality and interoperability (Roth, 2014).

JSON / XML	Message	Message
HTTP	CoAP	
TCP	UDP	
IP	IP	MQTT / MQTT-SN

Figure 13. Simple comparison of HTTP, CoAP, and MQTT protocols.

Connecting Things

To decide what data to transfer between Things in large distributed IoT systems can be very complex. There are systems that focus on managing and visualising this data flow to simplify management. For this purpose, Blackstock and Lea (2014) point to two systems, WoTKit and Node-RED, as being of special interest. Both utilise a graphical system where data flows are created by connecting nodes together in sequences, (pipes). WoTKit is more centralised and focuses on aggregating sensors web data while Node-RED can be deployed on limited devices and accesses the sensors locally (Blackstock & Lea, 2014).

Calvin is another system, that goes one step further in integrating data flow and software distribution (Persson & Angelsmark, 2015). Like WoTKit and Node-RED, Calvin manages and visualises data flows with nodes and connections. Nodes operate as actors in an actor-model approach. An actor represents reusable software that can communicate with other actors, in Calvin the communication is achieved by passing tokens over specific ports. A Calvin node, or actor, can run on any device with a Calvin runtime instance that also has the support that node requires. To exemplify, a device might have a temperature sensor attached that reads temperatures in the form of integers. If the same device also has an instance of the Calvin runtime that device could host a Calvin node that reads integers, which would in this case represent the local temperature. One strength of Calvin is the potential to dynamically distribute software components anywhere on a Calvin-platform, which could include cloud based implementations (Persson & Angelsmark, 2015).

Raspberry Pi - hardware for testing

Raspberry Pi is a minimalistic computer with digital I/O signals to control various electronics. The creator of the Raspberry Pi, Eben Upton, noticed around 2005 when he, as the director of studies in computer science at St. John's College in Cambridge, noticed that new students dropped in numbers and lacked skills and knowledge that former students had. The abstraction levels of computers had increased since the 1980's to such an extent that new students never had the opportunity to play with the simple stuff, they didn't know what was happening inside the computer. The development of creating a small and simple computer started but it was the community users that started to use the Raspberry Pi to control other equipment and build home automation systems. (Severance, 2013). Today there is a range of Raspberry products from the very low-cost Raspberry Pi Zero to more advanced versions. There are a lot of supported technology, a large community, and educational material ("Raspberry Pi,").

3 Research methodology

This chapter describes the research methodology for this thesis. It includes the research projects, the research context, and the authors approach and design of the research.

3.1 Research projects

The research has been conducted within four different research projects funded by the Swedish agency of innovation VINNOVA.

3.1.1 Operator of the Future (UDI-2)

Oct 2012 – Dec 2014

The research project Operator of the Future aimed at developing information and communication tools specifically designed for an operator of the future Swedish factory. The next generation of operators was exemplified using three different personas that had different needs in terms of information and communication support. Information needs were mapped and compiled into ten different groups or general functions.

The author's role in this project was to participate in the studies and needs analysis, develop digital tools to test and demonstrate, and aid discussion with the different stakeholders. Three global Swedish manufacturing companies were visited by the author and had a direct influence on the knowledge and conclusions: AB Volvo (Trucks), Sandvik Coromant, and SKF.

3.1.2 MEET - Meeting the Future: Communication, Organization, and Competence in Next Generation Work Places (P2030)

Oct 2013 – Sep 2016

The focus of the MEET project is on meetings in the production environment. Meetings in this context are referred to as situations of information sharing. The project aims to improve the information sharing situations by considering both organisation and the information system.

The main role of the author was to test and develop tools and systems that contribute to knowledge sharing and/or improve the meeting environment. A web-service that promotes collaboration over different functions is presented in this thesis. All four external companies have added valuable contributions to the results. Two are large global manufacturing companies: Volvo Cars Corporation (VCC) and Volvo Penta, and two are smaller painting subcontractors: Skelack and Laray.

3.1.3 Dynamite - Dynamic human-automation interaction (P2030)

Dec 2014 – Dec 2016

The Dynamite project aims to integrate humans and automation in creative and collaborative environments. The objective is to increase the number of dynamic features in the production system.

This project involves several academic partners and companies and there are several different approaches towards the aim. The author focuses on a specific assembly system at one of the external partners, CEJN AB, which is a global manufacturing company that makes couplings for pneumatic and hydraulic applications. This study is ongoing and this thesis provides valuable input when establishing future results. The studied assembly system is also the target of a smaller parallel project called MOTION.

3.1.4 MOTION - Mobile and digital automation (P2030)

Nov 2015 – Mar 2016

MOTION is a practical project in a laboratory environment and is as a deepening of one of the studies from the Dynamite project. The aim is to show that automation system integration is possible using equipment from different suppliers and different levels of automation. This project also involved students from a course in automation.

Three different mobile assembly workstations were designed and the author's contribution to this project was to design the information flow of the system and the communication between the different workstations. CEJN contributes with products and technical details and two external partners, AH Automation and B&R, have contributed to implementing the automation solutions.

3.2 Research context

All the organisations part of the research presented in this thesis handles discrete batch production. However, the product size, batch size, and variety differ. Table 13 lists the different processes the author has had the opportunity to study. At CEJN, for example, there is both manual assembly for smaller product volumes and batches as well as highly automated machines for mass production.

Table 13, types of manufacturing processes that have been part of the research projects.

Manufacturing process	Facility layout	Work tasks	Batch size (Approximate)	Context
Final assembly	Flow line	Manual work Robots	1	Operator of the Future
Heat treatment	Flow layout	Highly automated	50-300	Operator of the Future
Machining	Cellular layout	Robot cell	50-200	Operator of the Future
Final assembly	Cellular layout	Manual work	100	Operator of the Future
Painting	Flow line	Manual work	10-300	MEET
Machining	Process layout	Manual loading Automatic processing	1	MEET
Final assembly	Flow line	Manual work Robots	1	DYNAMITE
Machining	Process layout	Manual loading Automatic processing	10-300	DYNAMITE
Final assembly	Cellular layout	Manual work	10-300	DYNAMITE
Final assembly	Flow line	Specifically designed automation equipment	>1000	DYNAMITE

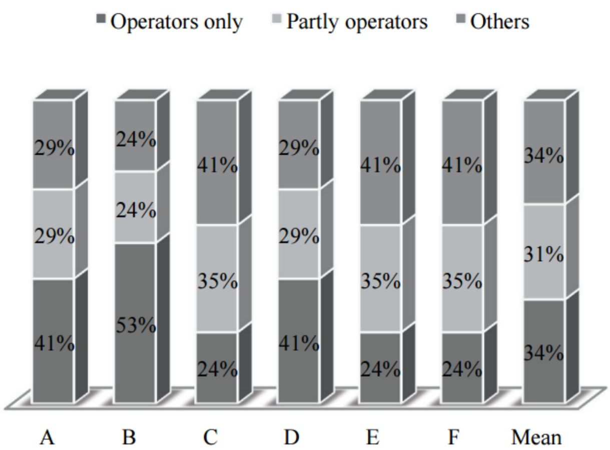

Figure 14. Tasks done by operators or other functions, six industrial case studies based on the operators' role allotment. The study was part of the project Operator of the Future. (Mattsson et al., 2014).

The actual responsibilities of the manufacturing operations department vary between the companies. Within the project Operator of the Future a study showed (see Figure 14) that there are many tasks the operators can't perform without help from other functions (Mattsson et al., 2014). Increasing the autonomy and decision-making abilities for the operators is the main driver for applying digital technology and cognitive automation. For many tasks at the visited companies, the main carrier of information is a static piece of paper (Table 14).

Table 14. Use of cognitive automation, including information carriers and content, for some of the visited companies.

Manufacturing process	**Information source**	**Carrier(s) of information**	**Content of information**	**Research project**
Final assembly	MES	Papers Screens	Component list Pictures	Operator of the Future
Heat treatment	MES	Screens Beacon Lights Speakers	Process overview Alarms	Operator of the Future
Machining	Order system	Papers	Product quality parameters	Operator of the Future
Final assembly	Order system	Papers	Product quality parameters	Operator of the Future
Painting	Order system	Papers	Product parameters Pictures	MEET
Machining	Order system	Papers	List of operations	DYNAMITE
Final assembly	Order system	Papers	List of operations	DYNAMITE

3.3 Research approach

Basic research - systematically look for new knowledge without specific application.

Applied research - systematically looking for new knowledge based on a specific application.

Production systems are complex and include many different aspects. This thesis focuses on information and communication systems and their connection to ICT for manufacturing operators. The research area connected to the information and communication systems could include fields such as systems architecture, requirement engineering, software engineering, data communication and more. Researchers within production systems and manufacturing operations may focus on operations management, automation, production simulation etc. Combining different disciplines requires the researcher to consider the different philosophical worldviews of the different fields and that different methods are typically used to answer various research questions.

For a pure technical system, such as the information system, the worldview of the positivist is common. This worldview stems from the traditional form of scientific research and is sometimes referred to as science research (H. W. Creswell, 2014). In this research tradition, objectivity is both crucial and reasonably possible to achieve, which puts more emphasis on quantitative research methods. Systems including humans are more unpredictable and overemphasising objectivity and quantitative methods often puts unreasonable limits on the research method. For this reason, including the tradition from previous research, most research studies are industrial case studies. These studies imply a more pragmatic worldview where every specific problem is individually assessed and methods are chosen by practicality and usefulness. The overall approach to the research areas was to first acquire required knowledge about production systems, the field least known by the author. This was done by exposure to the production environment with the first research question in mind. Early approaches were based focused on human interactions and automation, which proved valuable for knowledge building. The research design then changed towards more technical aspects, more delimited in scope. Figure 15 illustrates the overall research approach and Figure 16 shows the timeline with projects, studies, and activities.

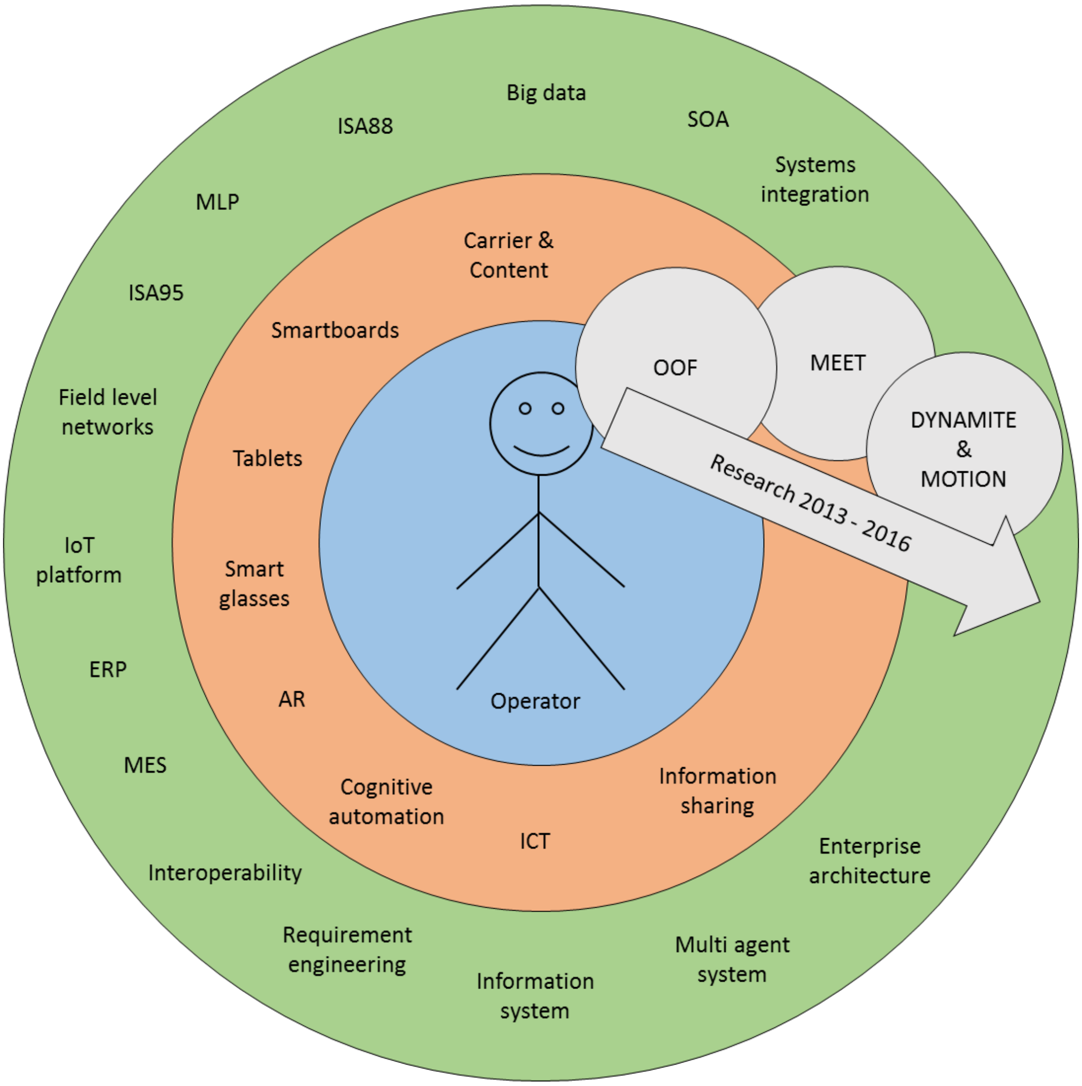

Figure 15. The research approach connected to the research questions.

3.4 Research design

The pragmatic worldview applies to both open and closed questions and often implies both qualitative and quantitative methods. (H. W. Creswell, 2014). The goal of quantitative research is to objectively analyse variables to conform to or disprove theories. In qualitative research, data needs to be interpreted and complexity often needs to be taken into account with a holistic perspective.

Most of the manufacturing related studies presented in this thesis can be described as case studies (Table 15). Simply put, a case study is an investigation of a phenomenon, with an unclear connection to its context, in its real environment (Yin, 2014). It's important to note that some researchers don't agree on this loose definition. Merriam and Ebrary (2009), as an example, think that it is the defined boundaries that make the case in a case study. However, some of the studies presented here do not start with a clear scope and that implies that several types of data need to be triangulated in order to find new results.

Table 15. The studies part of the research.

Paper	Study	Type of study	Time frame	Purpose
I	A|B	Case study	Weeks	Investigate how companies think regarding ICT for manufacturing operators.
II	C	Usability case study	Days	Investigate the possibility to use an usability study to find previously undiscovered needs of information.
III	D	Case study	A year	Investigate the actual change to the manufacturing system after introducing ICT for manufacturing operators.
IV	E	Case study	Year	Investigate possibility to increase automation of final assembly without reducing flexibility.
IV	F	Laboratory test	Months	Implantation and test of mobile assembly stations and interconnecting them with an interoperable information system.

3.4.1 Activities

Important activities in case study research are the company visits where empirical data is collected. It is important to plan these visits to ensure a good structure of the results and minimise the time of disturbing the system. Included in this planning phase could be preparing interview structure, choosing study participants, time of visit, designing a survey, observation method, usage of data collection equipment etc.

Research studies can also include development of prototypes to test or systems that are needed wither as a research result or as a tool to collect research data. Most of the studies part of this thesis include testing, verifying, or integrating various technology. This has sometimes required a certain amount of development work. Some of this work has proven to be interesting for the actual research studies and will probably be subject for analysis in future work. The author has developed three systems described in the results. A mobile checklist, an automation management platform, and a RFID-reader with OPC UA support.

3.4.2 Data collection and analysis

Much of the analysis from the industrial case studies is from semi-structured interviews. Furthermore, surveys, observations, information mapping, and stored log data have also been collected (Table 16). A semi structured interview starts with a defined structure where the interviewer asks the same questions to all interviewees. Then the interview changes to the unstructured format, which is more similar to a conversation (Merriam & Ebrary, 2009). The most common interview setup has been face-to-face with one interviewee and one or two interviewers.

Most interviews were recorded but some were documented by taking notes. Observations can be problematic as a data-collection method because of selective perception and the subjective nature of the observed phenomenon. However, it is possible to train yourself in being a better observer, including conveying the essential empirical data to other researchers (Merriam & Ebrary, 2009). In studies C and E some direct observations of operators' work and their environment were recorded and analysed. For most industrial studies, especially for studies A and B, observations and interviews were tightly connected where one was a result of the other and vice versa.

Table 16. Data collection for the different research studies.

Study	Activities	Data collection	People involved
A|B	Company visits	Unstructured interviews Observations information mapping	Operators production managers maintenance engineers
C	Company visits prototype development implementation	Semi-structured interviews observations.	Operators
D	Company visits survey creation	Semi-structured interviews surveys observations log data	Operators production manager maintenance coordinator system developers
E	Company visits	Unstructured interviews observations information mapping	Operators production managers production engineers
F	System development System implementation	Observations experience	Research group production engineering students production engineers

In a mixed method study, the researcher chooses to rely more on the qualitative and quantitative data (J. W. Creswell & Clark, 2011). Studies A to E are leaning more towards the qualitative data such as interviews and observations. Analysis has been focused on understanding or deepening already known or suspected phenomena. Yin (2014) describes this analysis technique as pattern matching, which can show strong internal validity. The three case studies A, C, and D were conducted in the same environment, with increasing pre-knowledge, time period, and consequently, with increasing structure, and therefore its validity.

Sometimes the phenomenon that you want to study is elusive or inaccessible in a real environment. In study F, which is a laboratory study, the data collected is represented by the experience gained and the systems produced. Here, the quantitative data is valued to a larger extent since the usefulness of an implementation or approach can be easily valued, at least by an experienced practitioner. It was also studies E and F that generated the most questions that then formed the literature review and the major part of the theory presented.

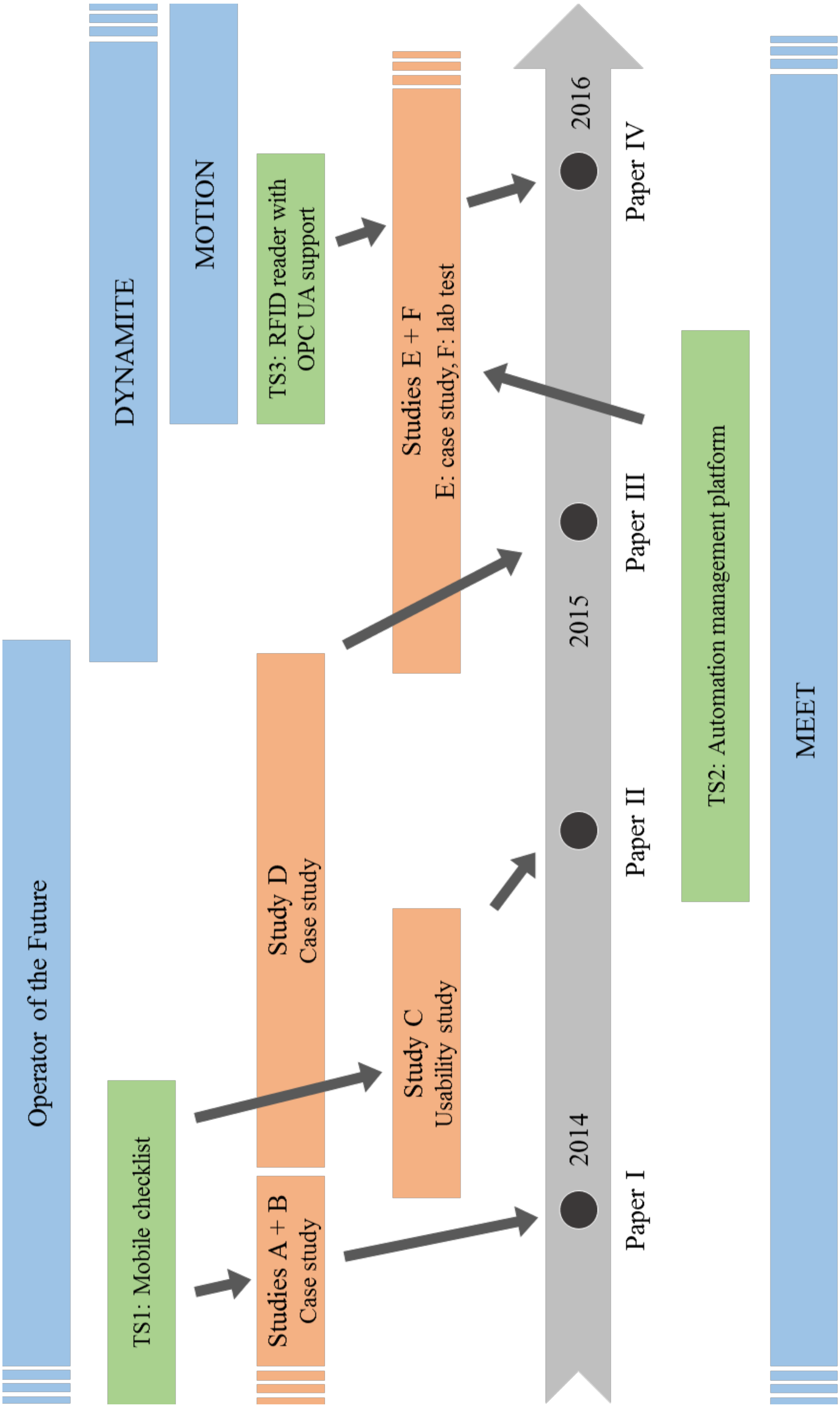

Figure 16. The research process timeline.

4 Results

This chapter presents the results of the research activities as developed systems and appended papers with important contributions highlighted.

The results are presented as three technical solutions and the four appended papers. The first technical solution, the mobile checklist, is used in studies A and B. Studies A, B, and C, presented in paper I, II, and III, have been conducted in sequence and their results are tightly connected to RQ1. The industrial study E is overarching the laboratory study F, which include technical solutions 2 and 3. Figure 17 visualise these connections.

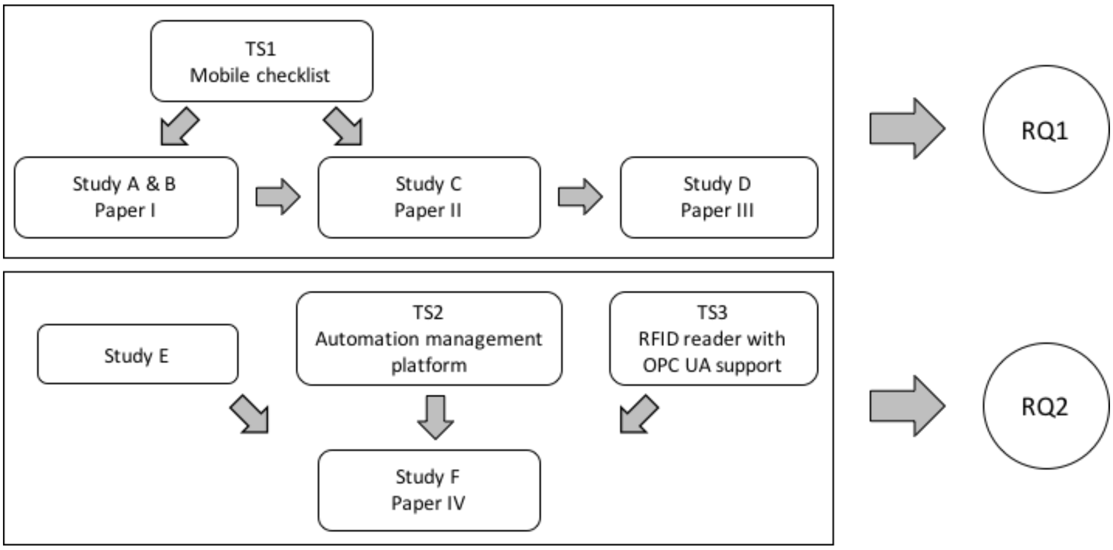

Figure 17. How technical solutions and studies connects to the appended papers and how their results help to answer the research questions.

4.1 TS1: Mobile checklist

The mobile checklist is an application that was developed for studies A and C. The general functionality of the system is a checklist that can be dynamically managed and used remotely with a mobile smartphone or tablet (Figure 18). The client application, built on the Android platform (Google), consists of a list view and details view. The list view presents information on what tasks are more urgent while the details view presents an instruction and allow the user to complete the task with a new status. Checklist management is done through a Web interface that is designed in the Web Application framework called CouchApp, which is a feature of the object database platform Couch DB ("Couch DB,"). The CouchApp was developed with a set of tools called kanso ("kanso npm,").

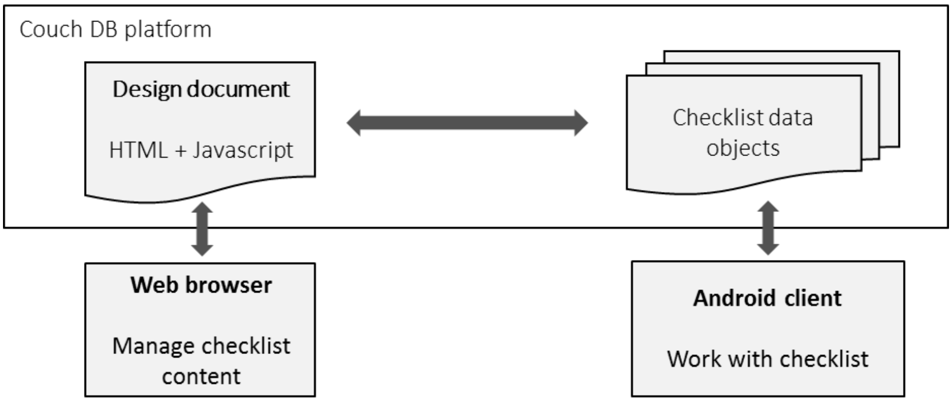

Figure 18. Mobile checklist system architecture.

4.2 Paper I

Cognitive Automation Strategies - Improving use-efficiency of carrier and content of information
(Fast-Berglund et al., 2014)

Paper I presents how cognitive automation is viewed upon in the industry in the two case studies A and B. The cases are presented with both current and future states, where the future state for study A is partly tested with the mobile checklist application.

Case study A describes to a preventive maintenance work task that the operators at a heat treatment facility do every morning. The current state is a paper checklist that the maintenance department have created in Microsoft Excel. Since the paper doesn't change unless someone edit the Excel document and print new versions and inform the operators, this solution very static. The future state involves a dynamic system using digital technology (TS1). A limited test was conducted and some positive results could be concluded. Study A is also continued in studies C and D below.

The second case, study B, regards a planning task where operators need to decide in which order to load batches in a manufacturing cell. In this cell a robot automatically loads and unloads a milling machine. A large batch could run through the night without supervision. The problem is that there are many parameters to account for wen deciding which batch to run through the night. This is currently tacit knowledge that operators gain by experience but no one really knows if the current decisions are correct. A digital rule-based system would help both novice and experienced operators to choose the batch order, furthermore, a digital solution could measure the outcome that could be used to further improve the rules.

Connecting to this thesis, interesting results can be summarised in three parts. The cases themselves show how easy it can be to identify and implement digital information support for many operator tasks. This relates to RQ1, finding opportunities for ICT usage does not imply that they should be implemented but it is a start. The second part is the fact that companies do not seem to have a well-defined strategy for cognitive automation. These two observations lead to a conclusion that the lack of strategy is the reason why there are no digital systems despite that they are so easy to identify. It is also the difficulty of integrating such technology with current existing systems, which leads to the final part, disconnected, or stand-alone systems, does not seem to be acceptable. These conclusions align with the assumption that there are problems of systems integration.

4.3 Paper II

Title: Refining the needs: an exploratory study through usability testing
(Åkerman et al., 2014)

Paper II presents a usability study that is a direct continuation of study A. Usability studies are usually, as the name suggests, a way to test a product, prototype, or graphical interface in regards to users' perception of their usability. The mobile checklist (TS1) was further developed into a high fidelity prototype. The prototype was an android application that was installed on three tablets of separate sizes (4,3"; 7"; 10"). Figure 19 shows how the prototype looked like on two of the devices. The aim of the study was to let the operators, which are the intended users, use the prototype in their real work environment. The purpose was not to optimise the usability of the prototype but to use it as a mediating object to elicit new requirements or other interesting, previously missed aspects.

The results from the study were mainly about the actual method and how it works for the intended purpose. As for the actual observation two notable things came up. First was that the tested technology was not aligned with the operators' current safety regulation. Clothing and walking habits were often inconvenient and sometimes dangerous in combination with the tablets inside the heat treatment facility. Second was the fact that operators weren't able to pick the preferred size before the test. Or, more correctly, many changed the preferred size after testing. As for the evaluation of the actual method, the conclusion was that it is useful if conducted with a limited understandable scope, in an orderly fashion, and with ecological validity.

The results relate mostly to RQ1 and indirectly to RQ2. Part of understanding how ICT can be useful for the operators is to observe and question the ideas. To some extent it is also part of investigating implementation. However, the checklist is a standalone prototype and does not connect to any other systems in the organisation.

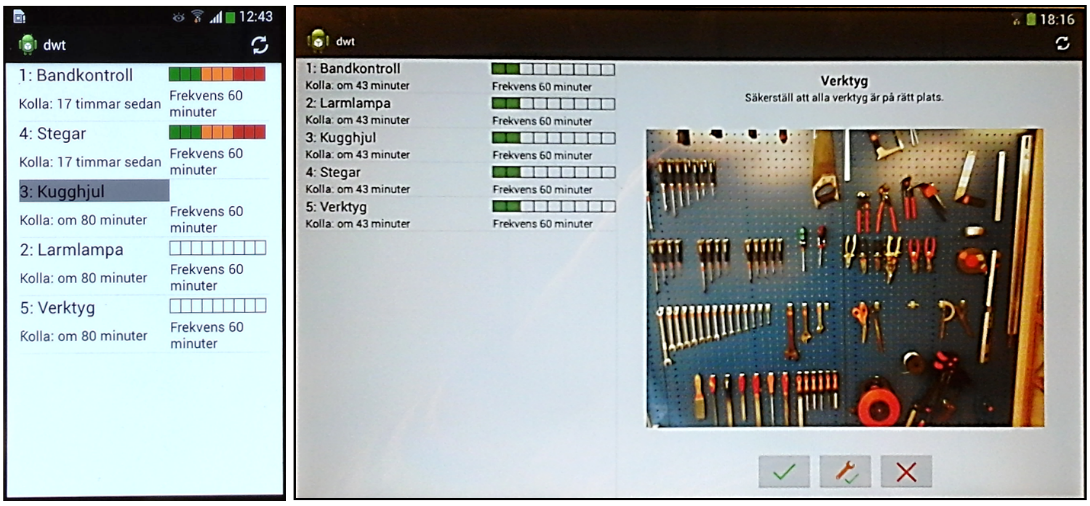

Figure 19. Mobile checklist client on a 4.3-inch smartphone (left) and a ten-inch screen tablet (right).

4.4 Paper III

Title: Introducing customized ICT towards operators in manufacturing
(Åkerman, Fast-Berglund, Karlsson, et al., 2016)

The third paper is a longitudinal case study and the third and last study from the heat treatment facility described in studies A and C. This case study is based on an in-house developed product including similar functionality from the previously described prototype and much more. A similar checklist functionality for preventive maintenance is included along with other functions.

The solution that the company chose was a smartphone with a customised application, which means that normal smartphone capabilities also had to be considered as new functionality. Most operators at the facility were already sometimes using their personal smartphones for work but it could not be assumed. Furthermore, the functionality within the customised application was of different levels of customisation, where a specified function had to be customised to fit a specific process or production area. The existing functions can be seen in Table 17.

The functionality was not all present or only partially functioning at the beginning of the year-long study period (Nov 2013 to Nov 2014). Qualitative data was collected through surveys and semi-structured interviews. Since the application required that the operators logged in it was possible to get quantitative data about the real usage over time.

Table 17, ICT functionality in case study D.

Function	Type	Description
Phone calls	Smartphone	Normal calls over the public the mobile network.
Camera	Smartphone	Inbuilt camera in the smartphone.
Disturbance reporting	Generic	A type of newsfeed where anyone could make a quick remark concerning things they consider an anomaly.
Chat	Generic	A normal chat where users can send messages directly to each other.
Work instructions	Generic	Instructions that are tied to specific documents, the instructions can be ticked off while you do them to simplify the workflow.
Production overview with alarm info	Customised	This is a from-above-view of the facility and it is possible to see what the machines are doing and if there are alarms or other problems.
Preventive maintenance checklist	Customised	A list that the user checks off and each checkpoint has an instance of work instructions to guide the user. Checkpoints are also physically connected with QR codes.

In general, very few negative remarks about the technology were made during the interviews. However, the actual usage didn't reflect this overwhelming optimism. A few committed and interested operators used it regularly and made almost all contribution of new content. The department manager was also very positive and used the technology to distribute information to encourage more usage. The most conclusive result from the study regards error reporting. To use the smartphone was optional during this introduction phase except for one specific task. Since the preventive maintenance checklist had been part of previous studies and in focus for a longer period of time, the digital version was simply much better than the previous paper version. Furthermore, the digital checklist was always up to date and easier to change. With that in mind the manager made it mandatory to use the digital checklist from the later part of the study. Shortly after that the number of logged errors in the error report system is significantly increased. After analysing the data, it seems like the increase is not a sudden increase in new errors but simply an increase of focus from the operators, and an understanding that it is important to log everything in the system.

The paper presents the different functionality to exemplify cognitive automation and information sharing for operators in manufacturing. It also discusses a more holistic view about technology usage and commitment. The organisation and general understanding should not be underestimated when considering new information technology. These results are direct input to RQ1 since they show how ICT can be used by manufacturing operators and that it can assist them in different way.

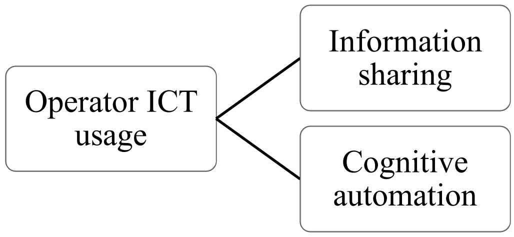

Figure 20. Different ICT usage for manufacturing operators, paper III.

4.5 TS2: Automation management platform

The automation management platform was developed within the MEET project and presented as part of the systems solution for the assembly system in study F. It is a full Web application built with the Play Framework ("Play Framework,"). With Play it is possible to build dynamic web solutions by utilising generic the high-level programming languages Scala ("Scala,") or Java. The application consists of a database representing the automation system components. Each component can be connected with disturbances and instructions. The interesting feature of this particular system is how the database is created. The system allows several different organisations and users. Each organisation can have one or several manufacturing systems and each system have an automation equipment hierarchical structure. This structure is automatically generated from an Automation ML file (AutomationML). If the file is updated, it is possible to regenerate the structure with maintained system information.

Automation ML files can be generated from other systems with such support or created with a specialised editor. As implemented now only the names, structure, and unique identification that are extracted from the file. Figure 21 shows the assembly system from the Motion project represented in an Automation ML editor. Figure 22 shows part of the same information in the Web interface. The pictures have been added to the Web application and are not connected in the Automation ML file.

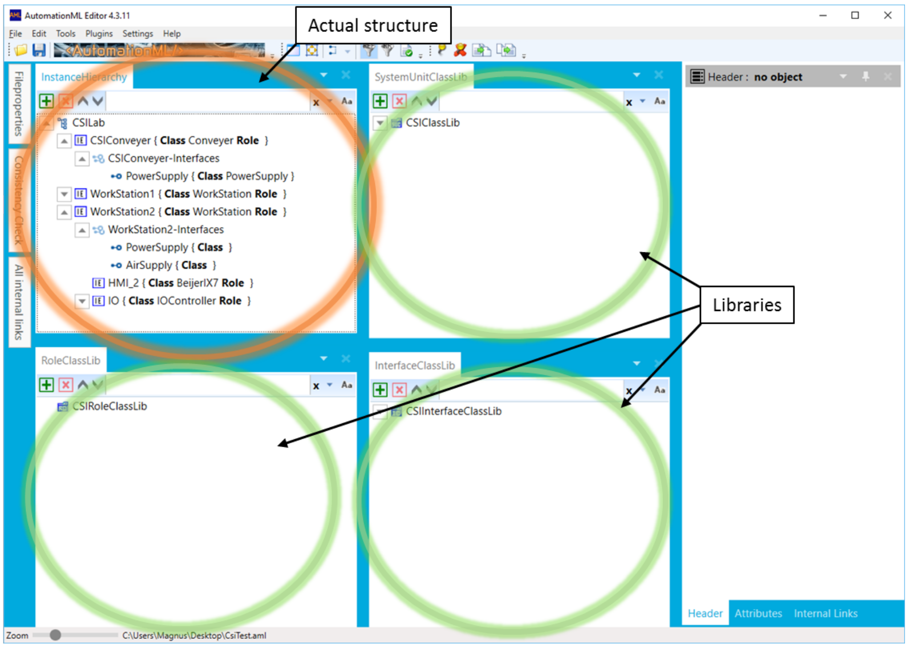

Figure 21. Automation ML Editor with the structure from the MOTION project. CSILab, which is the facility, is at the top structure and it consists of CSIConveyer, Workstation1, and Workstation2.

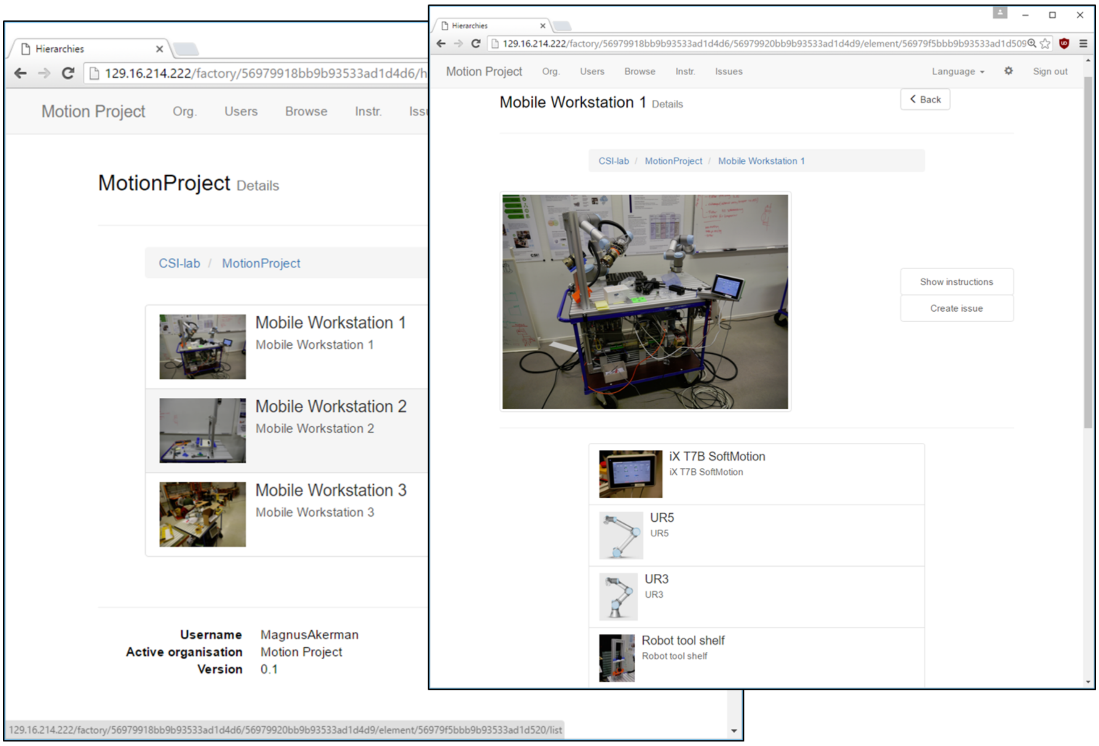

Figure 22. The automation management platform here exemplified with the Motion project.

4.6 TS3: RFID reader with OPC UA support

Part of Study F a solution to read RFID tags was developed. The traditional solution for this is that the PLC is directly connected to an RFID reader. This solution replaces the PLC and is based on the Raspberry Pi connected to an RC522 RFID reader (Figure 23). Communication with other industrial equipment is done with the OPC UA protocol. In Figure 24 the architecture of the system is shown. The system consists of two separate threads where one manage OPC UA communication and the other manages the RFID communication. External Python APIs for both systems were found free to use which greatly simplified the implementation process.

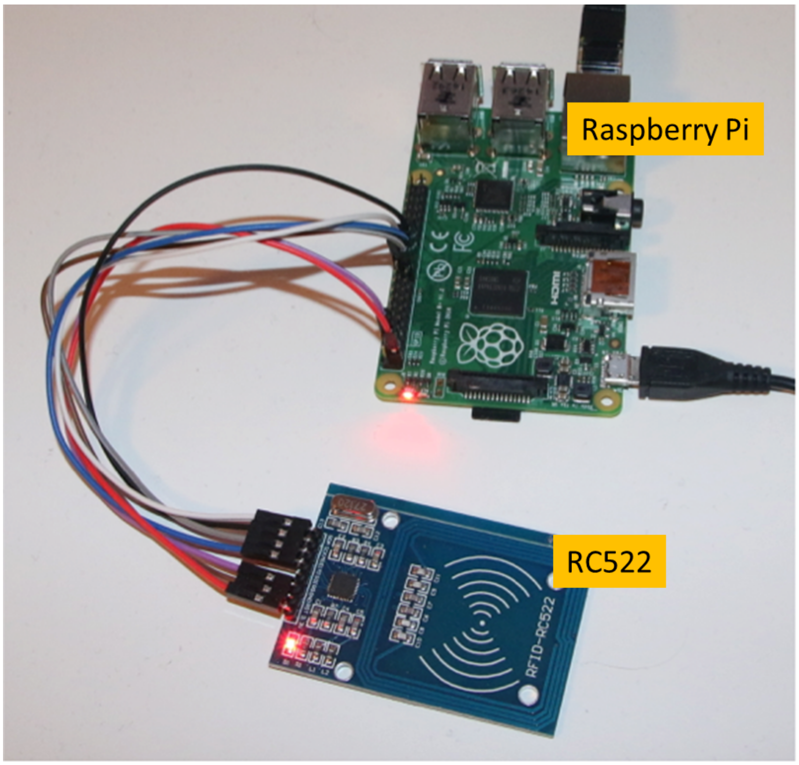

Figure 23. A Raspberry Pi connected to the MF-RC522 reader.

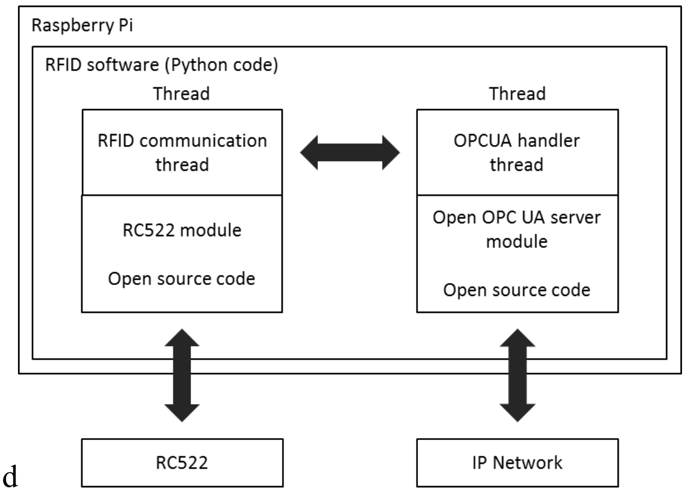

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Figure 24. The internal software architecture of the RFID OPCUA server.

4.7 Paper IV

Title: Interoperability for a dynamic assembly system
(Åkerman, Fast-Berglund, & Ekered, 2016)

The research project MOTION had the intention to build a flexible and automated assembly system. Flexibility was achieved by utilising mobile workstations and preferably less specialised automation solutions. Cobots were utilised since they allow high level of automation without reducing the flexibility (Fast-Berglund, Palmkvist, et al., 2016). The product to assemble is a quick-connection for pneumatic applications see Figure 25. This product has many small components and their assembly is notoriously difficult to automate, for lower volume production, such as springs and O-rings. The automation solution providers were predetermined so that the workstations utilised different systems, which increased the heterogeneity and the challenge to implement interoperable communication. Paper IV describes how the information system was designed and implemented to connect these mobile assembly stations with different systems. The automation management platform is presented as a solution for disturbance reporting, maintenance, and instructions. The connection to AML is important in a system that may be rebuilt and reconfigured often so that the data can be up-to-date.

Figure 25. Quick connection from CEJN, product to assembly in the assembly system built during the MOTION project (CEJN).

The solution utilises RFID tags in palettes for the main information carrier regarding components and status between the stations. RFID solutions are the de-facto standard for object identification in manufacturing today. If RFID-tags that can store data are chosen, they also provide a backup communication channel in case the connectivity is lost for the mobile workstations.

Beijer Electronics and B&R delivered the automation control systems that were used at the different workstations. Beijer electronics is connected with the systems IX developer for their HMI development and CODESYS for PLC programming while B&R have their own system called Automation Studio. Connecting RFID readers to the PLC requires low level programming of its functions in these various systems. How this programming should and can be done differs case to case. For this reason, the system utilises a more generic solution for the RFID reader. This solution connects a reader to a Raspberry Pi computer, and the Raspberry Pi connects to the PLC with the OPC UA protocol. The actual implementation utilises free open software and this approach allowed for a generic and simple implementation of the RFID reader.

OPC UA was also chosen for any communication above the automation at each workstation, e.g. overall monitoring. It has become a de-facto standard and with its open and platform independent approach it seems aligned with the future of interoperable information system.

Finally, paper IV introduce a web service that can be utilised by operators, maintenance engineers, and automation engineers to get information and keep track of the automation equipment and their status. Most production facilities separate these three functions with disconnected systems. The solution also includes Automation ML as a flexible way to create and update the automation system also at this semantic level.

The system presented in paper IV and the work of designing and implementing it is valuable input to answer RQ2. When choosing relevant standards, which fulfil needed requirements, it can benefit many parts of the system.

5 Discussion

This chapter discusses the theory and the appended papers and how they contribute to answering the research questions. Furthermore, some interesting opportunities for possible future research are presented.

Many manufacturing companies understand the importance of utilising more digital technology. However, the organisation, legacy systems, current level of knowledge, etc. seem to have limiting effect on the possibility for change. From paper I we can see that it is often easy to find scenarios where ICT would benefit the system, however, the way to implement and integrate such technology is not clear. Manufacturing operations are responsible for the manufacturing processes and that includes all the tools, equipment, power sources, operators, automation etc. The information needed to connect, manage, control, and monitor this system is growing in size and complexity. In order to help manufacturing operations to configure and manage their information system it is important to understand how the technology, organisation, and information systems relate.

5.1 ICT and manufacturing operators

Paper III shows that manufacturing operations can benefit from ICT usage. When operators actually use the technology and understands it's benefits, as with the case of preventive maintenance, the overall system understanding can increase. Papers I-III illustrates the whole chain of idea generation, testing, implementation, and introduction of ICT for operators. In the end of the case study, it was only for the preventive maintenance work that ICT-usage became mandatory, and therefore resulted in a predominate change of the system. The reason for this could be because of precious focus on this specific task that prepared both the system and organisation for a change. At least it is clear that it is important to understand many different parameters regarding operators' work tasks before introducing new ICT.

The appended papers have described several different ways of how information and communication technology can be used by manufacturing operators. From a cognitive perspective, operators action space, derived from Sheridan's five operator roles is a useful way to categorise the operators' tasks (Fast-Berglund & Stahre, 2013). However, within each task digital technology can be used in different ways. The operator action space is focused on human behaviour and reasoning. Another perspective is the focus of paper I, carrier and content of information (Fast-Berglund et al., 2014). This perspective perceives information technology from a human user perspective. Figure 26 illustrates what the different categorisations describe within a manufacturing system.

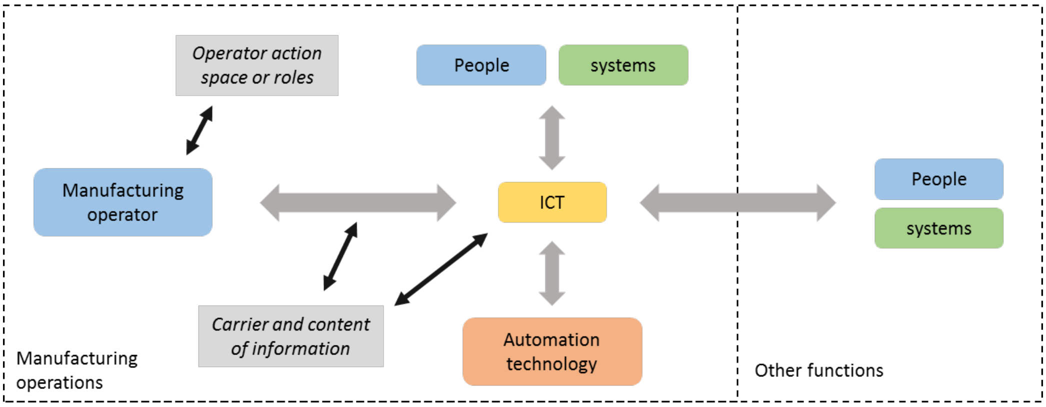

Figure 26. Manufacturing information and communication systems and how the operators action space and carrier and content of information relate to them.

Operators use ICT to communicate with, or transfer information between, other people, technology, and systems. There is one direct type of communication where the need derives from the current value adding work that is either in progress, e.g. monitor/perform, or will soon be in progress, e.g. a hint of next scheduled task or an alarm. Another type of communication is connected with the indirect work that operators do. This could be connected to meetings, learning/teaching new tasks, or information transfer between different shifts. This is similar to the viewpoint of paper III that separates generic information sharing from the cognitive automation (Figure 20).

One example of information sharing, described in paper III, is the disturbance reporting system. This system works almost like a newsfeed where operators add small anomalies they might see while doing other work. This example is about sharing information in the organisation. Another example is the web-service, from paper IV, based on the AML standard. The purpose of utilising this standard was to connect automation engineers, operators, and possibly maintenance functions.

Cognitive automation is more connected to operators' value adding work tasks, from the perspective of the manufacturing process. A digital mobile platform, in contrast to the paper checklist, that helps the operator in choosing where to go and in what order, also aids the operator to decide when preventive maintenance should be done and if all checkpoints have been visited. This type of decision making tool requires the system to dynamically adapt the information depending on previous events. Another type of cognitive automation is the process overview functions described in paper III and IV. A process overview can aid with monitoring tasks but also planning within a short time frame. Figure 27 shows the four types of operator ICT usage.

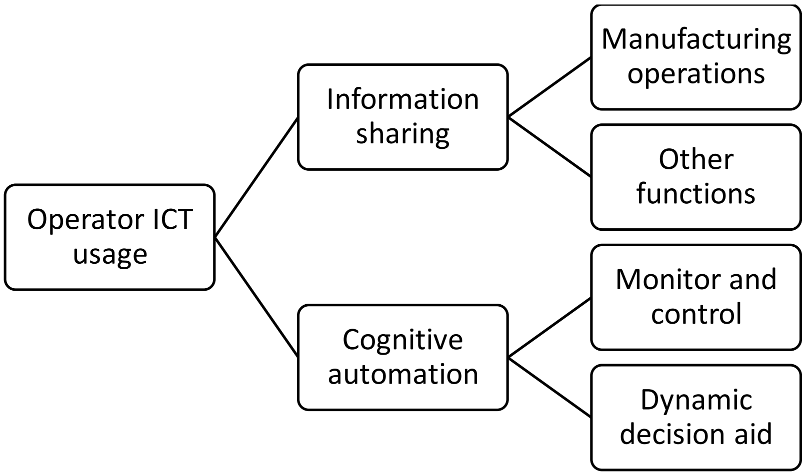

Figure 27. Manufacturing operators' different usage of ICT.

5.2 Challenges of system integration

With higher utilisation of ICT, IoT, Services, Big-Data analysis etc. the need for structure and efficiency of the information systems increases. Because of the increasing heterogeneity and complexity of the system, a federated approach with interoperability principles is the preferred approach to manage this problem. For internet technologies a lot has happened in the last decade or two and that has pushed interoperability issues up to semantic level and beyond. Automation systems and field level networks are still not fully compatible with IP networks, which suggests that interoperability issues are more on syntactical levels and concerns for low level protocols etc. The interoperability abstraction levels are useful for assessing specific connections but they do not help in more holistic reasoning about issues and opportunities of systems integration. The study of enterprise integration has identified that interoperability is affected by many different areas. The summary of the enterprise interoperability research areas by Koussouris et al. (2011) divides the field horizontally, rather than vertically like the abstraction layers. Together these formulate valuable input when discussing empirical data. The six fundamental areas data, process, rules, objects, software systems, and cultural will be exemplified with the results.

There are several examples in the attached papers that enable new data access for operators. The use of a mobile digital tool during preventive maintenance, as described in paper I and II, enables direct access to an updated checklist and its current status. The communication protocol OPC UA enables vertical integration and connects low level automation equipment with higher levels of the automation pyramid (Grossmann et al., 2008). This enables the operators a more direct access to automation technology. Automation ML is a standard that defines a structure and a tool to align information during implementation of automation (Drath et al., 2008). Utilising this standard to generate an automation equipment management platform for operators and maintenance simplifies their access to equipment information.

Process interoperability of the enterprise perspective is business driven, or the alignment between different entities and business processes (Koussouris et al., 2011). For manufacturing operators, the business process should be the concern of the manufacturing process. Most ICT solutions exemplified in this thesis have been built to improve manufacturing processes and thus become more aligned with them. The example of the automation management platform enables a common view of automation equipment between automation engineers and operators. If this provides more information to the operators or also eventually increases the knowledge of the engineers, or both, is for future tests and evaluations to decide. Either way, manufacturing processes are most likely to benefit from this knowledge sharing.

Objects interoperability is becoming increasingly important with the IoT concept. Bringing IoT to the semantic interoperability level is a current challenge (Atzori et al., 2010). As it stands now, and exemplified in the appended papers, technologies such as RFID and QR codes can be used to connect objects and information.

Software systems interoperability relates to how different autonomous systems communicate and interact between each other. As for the case of data interoperability, common standards are important. Furthermore, for systems that use similar architectures, standardised interfaces would simplify their communication. Like the case of SOA, which have proven invaluable for software interoperability with middleware systems. However, when many services are involved it will be important to also standardise their application programming interfaces (APIs). The automation management platform uses the Play framework to build the web application. It allows for an easy API setup and is RESTful by default, which among other things allows for an alignment of interfaces (Fielding, 2000). That open standards are important is a known fact, also within field level networks (Sauter, 2010). Not only do they simplify the connectivity between systems but they can also allow a broader spectrum of technologies. OPC UA is an open standard and someone in the global software community have developed a free python server implementation, which is a preferred programming platform for Raspberry Pi applications. The AML files are another example since they are designed to transfer information, in this case about automation system design, between different systems.

Cultural interoperability is related to language and cultural barriers. It could be argued that by increasing the communication between operators, as with the functions from paper III, the technology might help to reduce cultural issues. However, this is more related to the general organisational strategy and less specific to the system or technology itself. As an example, dynamic information could be connected to an operators preferred language or other form of representation. As with rules interoperability, cultural aspects are a topic for future research.

5.3 Towards interoperable systems

A combination of the interoperability research areas, at the fundamental level, and operators' use of ICT has been filled out with some of the examples that have been previously described (see Table 19). The idea is that this matrix can aid in the process of choosing implementation solutions regarding information and communication for the manufacturing operations organisation. However, the areas for enterprise interoperability were not considered specifically for manufacturing operations and can be difficult to apply without being specific. In order to know where a specific function belongs in the matrix a specific task or scenario should be defined. Furthermore, focus questions described in Table 18 were used for each of the chosen scenarios.

Table 18. Help questions to use regarding interoperability and ICT implementations.

Interoperability area	Question
Data	For a specific task, how do systems access, store or apply required data?
Process	For a specific task, how do systems align with the manufacturing process?
Rules	For a specific task, how do systems align with rules and regulations related to that task?
Objects	For a specific task, how do systems identify physical objects related to that task? (E.g. products, people, equipment).
Software systems	For a specific task, how are the different systems involved linked together?
Cultural	For a specific task, how do systems account for cultural barriers? (E.g. language, social contracts, etc.).

An important aspect for interoperable systems is standardisation, a known fact that also shows in the suggested model. OPC UA, and Automation ML are examples of standards that target different problems but share openness and simplicity as important features. With the results presented it is shown that one type of standards can improve interoperability for several different areas and use cases. According to Rezaei et al. (2014) it is important that an interoperability evaluation model is easy to use and that it considers every aspects of interoperability. The result matrix can be a step towards such a model.

Table 19. Thesis results related to interoperability areas and manufacturing operators' ICT usage.

Areas of interoperability research, RQ2		**Manufacturing operators ICT usage, RQ1**			
		Information sharing		Cognitive automation	
		Manufacturing operations	Other functions or organisations	Monitoring and control	Decision aid
	Data	Operator ICT continually store preventive maintenance status in a database.	The automation management system uses AML standard to apply the data object structure.		
	Process	Operator ICT uses its database to show trends and status of preventive maintenance.	Automation management platform aligns engineers and operators view of automation equipment.	Operator ICT shows alarm and status information visualised with the current setup and layout of the manufacturing process.	Operator ICT adapts timing and content of preventive maintenance round.
	Rules				
	Objects			Autonomous workstations use RFID on palettes to identify next assembly task.	Operator ICT uses QR codes to connect a physical area or object with checkpoints in a checklist.
	Software systems		Automation management platform is a RESTful web service and could easily be accessed by e.g. a maintenance system.	OPC UA enables connections between autonomous workstations and monitoring systems, it also connects RFID reader on Raspberry Pi with any PLC.	
	Cultural				

5.4 Future research

It is an exciting time to do research in information and communication systems in the manufacturing industry these days. Sometimes old discoveries seem to be brought back into focus, such as the interoperability models. Furthermore, since it is an interdisciplinary field, already tested and known concepts regarding e.g. software architecture need to be reiterated in the manufacturing field. At the same time, it is important to separate our theoretical knowledge from the practicalities of real manufacturing systems. Manufacturing operations do not have the knowledge nor the organisation to facilitate a discussion about the system setup. The author identifies four topics that would benefit from further study.

From several of the industrial case studies it has been implicitly shown that there is often a large knowledge gap between manufacturing operations organisations and the IT organisations, occurring in both directions. Connecting manufacturing operations and IT departments and facilitating a discussion between them e.g. by utilising some proposed framework should be most welcome and beneficial for the entire production system.

Investigating the use of IoT platforms together with current manufacturing systems with OPC UA and Industrial Ethernet. This is important in order to understand where the real problems are in building connected, interoperable, distributed, dynamic, and durable manufacturing systems. Also, how can this can be connected with Cloud computing.

The implementation of AML in manufacturing operations has clear potential and should be tested in a real environment. First order of business here is to actually use AML in the automation design phase otherwise there will be no information to upload to a system for operations or other functions. Furthermore, there are surely other standards or systems that could be connected to both increase usefulness and reduce complexity.

Implementing automation software systems on new devices such as Raspberry Pi may not only be a requirement for utilising IoT platforms but will most likely change the way automation systems are perceived by the manufacturing organisation. Open platforms and community-based development are crucial when building successful systems today. In the manufacturing industry, where robustness and security is important, such ways of working haven’t received much attention yet.

6 Conclusions

Concluding remarks. A revisit of the research questions, objective, and aim.

Manufacturing operations need information and communication systems that can handle many different situations. From the manufacturing operators' perspective those situations are how they use, and benefit from using, information and communication technology. Empirical findings showed that ICT usage can be categorised into information sharing in the organisation and cognitive automation that connect to the technical system. Three case studies that discuss, implement, and introduce a customized digital tool for manufacturing operators showed that an idea of such technology is relatively easy to identify and that, when implemented, do benefited the manufacturing system by assisting the manufacturing operators.

It is known that systems integration is important for future information systems in manufacturing. The systems are also becoming more heterogeneous as more things and services enable new smart and dynamic information scenarios in the factory. Interoperability principles enable free communication over organisational and system borders. In order for technology and humans to communicate there must be some common semantics. Communication protocols and standards have to fulfil that criteria. Furthermore, theory suggests that the challenges to achieve interoperable systems exists in many different areas. A framework of six interoperability categories connected to the model of an enterprise was adopted as a basic structure. The categories are: data, process, rules, objects, software systems, and cultural. The design choices of three different systems implemented for manufacturing operators have been applied to these categories and several challenges of horizontal and vertical systems integration have been identified.

The combination of the operators' ICT usage and the enterprise interoperability categories result in 24 specific discussion topics. The empirical findings visualised with these topics enables a discussion of interoperability and ICT usage. The implemented systems exemplified show that the use of one standard can increase interoperability in several areas. Furthermore, the framework can promote idea generation and comparisons of future system changes. The suggested future system changes must include practical solutions that increases the interoperability. If manufacturing operations, as an organisation, can formulate such suggestions it will form a stronger foundation for planning, implementing and managing the information and communication systems.

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