Adaptive Decision Support for Shop-floor Operators using Function Blocks

by

MAGNUS HOLM

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Magnus Holm (2017)

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Abstract

In manual and semi-automation production systems, flexibility and adaptability are affected by the shop-floor operators’ skills, abilities and knowledge. Such dependencies highlight the vital importance of developing and utilising the knowledge, achievements and abilities of the operators working with production on the shop-floor. Teamwork, including both novice and highly experienced shop-floor operators, in a production environment with a high level of automation, is essential already today and is predicted to increase, when the complexity and demands of future production systems intensify. This trend is confirmed in both the research literature and by specialists within industry.

The key to future competitiveness and effectiveness of the manufacturing industry is the shop-floor operators who handle the production systems. In addition, the future information intensive working environment, with its increasing complexity and less time available for decision-making, demands adaptive decision support and adaptive control systems that facilitate collaborative work on the shop-floor. It is therefore important to emphasise how decisions are supported in the time-limited working environment of the shop-floor, because this has a large impact on production output and quality and is vital to the success of the company. Consequently, this dissertation presents a framework for an adaptive decision support system that concentrates on shop-floor operators, in order to enhance their development and future contribution to leading edge production systems.

The overall aim of the research presented is to define a framework for an Adaptive Decision Support System, to address the scope and demands of the future shop-floor, as indicated in the research literature, and confirm its relevance, as well as further elaborate it on the basis of interviews with production managers and HR specialists.

The research presented uses the design science research process. In parallel, decision support systems and the industrial shop-floor have been studied in the research literature and the current state of industrial practice has been assessed. These areas together form the basis for the research on adaptive decision support for shop-floor operators. A framework enabling adaptive decision support and adaptive system control, based on event-driven function block technology and Augmented Reality technology, is formulated.

The gap of research on decision support for shop-floor operators, indicated in the research literature is addressed by the research performed. Adaptive and dynamic decision support and system control able to process vast amounts of information in real time demonstrates utility for shop-floor operators. The research presenting the Adaptive Decision Support System has demonstrated its utility for shop-
floor systems and production operatives in two extensive studies using demonstrators based on real-life production environments.

A methodology, the ‘User group’, has been formulated for research collaboration and bi-directional knowledge transfer between academia and the industrial partners. It provides tools that enable cooperation between the experienced research partner and the novices, despite their different levels of engagement in the same project, without dividing them into separate groups. The ‘user group’ case study presented describes how both the inexperienced and the research mature companies gain new knowledge and engage in ongoing research. By doing so, the industrial project partners have extensively supported the research presented and will subsequently be the expected beneficiaries.
Acknowledgements

During one of the speeches at the university’s Christmas party in 2009, my colleague whispered: “You can join Philip as one of his new PhD students. I think that is a good idea.” Thank you Prof. Amos Ng for offering me such a Christmas present, opening a door to research for me. I also want to thank Prof. Philip Moore, my first supervisor, and Prof. Lihui Wang, my second supervisor, for their support and guidance during my research. My gratitude also goes to Dr. Seng Chong and the team at De Montfort University.

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My gratitude to the University of Skövde for its financial support and to the partner companies for their extensive involvement in my research.

My greatest appreciation of all goes to my wife, Maria, and our precious children, Johan and Sandra, for the encouragement and support they have given me during these years. Especially during these last months when many late nights and weekends have been spent finalising this dissertation.

Skövde 2017

Magnus Holm
Declaration

I declare that the work described within this dissertation was originally undertaken by me, (Magnus Holm), between the dates of registration for a degree of Doctor of Philosophy at De Montfort University.
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<td>Augmented Reality Expert System</td>
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<tr>
<td>CNC</td>
<td>Computer Numerical Control</td>
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<td>FBD</td>
<td>Function Block Diagram</td>
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<td>HMI</td>
<td>Human Machine Interface</td>
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<tr>
<td>I/O</td>
<td>Input / Output</td>
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<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
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<tr>
<td>IEC</td>
<td>The International Electrotechnical Commission</td>
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<td>ISO</td>
<td>International Organisation for Standardisation</td>
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<tr>
<td>MTM</td>
<td>Method Time Management</td>
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<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
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<td>SME</td>
<td>Small and Medium sized Enterprises</td>
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<td>STEP</td>
<td>The STandard for the Exchange of Product model data</td>
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<td>STEP-NC</td>
<td>STEP for Numerical Control</td>
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<td>TPS</td>
<td>Toyota Production System</td>
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<td>TQM</td>
<td>Total Quality Management</td>
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1 Introduction

This dissertation introduces a novel framework and concept design for an adaptive decision support system using function block technology. The introduced framework is supported by implementations and case studies.

The introductory Chapter describes the background and motivation of the research presented in this dissertation. It is based on challenges emerging from the research literature and industry. The research question, its aims and objectives are defined and followed by a brief review of research methodology, including a short introduction to the one chosen. The Chapter concludes with the organisation of the dissertation for guidance of its content.

1.1 Research background

The background of the conducted research is explained in four introduction Sections.

1.1.1 Challenges of the production industry: a brief overview

For the last decades, the production industry in Sweden, as well as in Europe and the whole industrialised world, has experienced a general change from protectionism favouring each country's own industry through trade restrictions, customs fees, etc., to an open international market where accuracy in price, quality and delivery always matters. Being an industrialised and export intensive nation, with an international market where competition constantly grows and evolves, demands a proactive approach to maintain a front-edge position. Most production companies face tough competition on today’s international market and pervasive challenges when preparing for future requirements and businesses. These challenges can, from a production perspective, often be defined as demands for increased flexibility, increased knowledge and an extended ability to run the production systems to achieve higher productivity (Bellgran and Säfsten, 2010, Mourtzis, 2016).

The upcoming state of the ongoing production evolution is often given the name Industry 4.0. It facilitates a vision of a modular structured Smart factory (Radziwon et al., 2014, Lee, 2015). The challenges comprise not only the production system, but also affect the whole company. Liker (2004a) emphasises the importance of the whole to reach success: “...success is ultimately based on its (the company’s) ability to cultivate leadership, teams, and culture, to devise strategy, to build supplier relationships, and to maintain a learning organisation”.

The production system is of course the back bone of a production company, if there are no products to sell there is no business. Increasing demands, both internally and externally, require the production system to frequently adapt to new conditions. Flexibility and
adaptability are, and will be, keys to future competitiveness (Boutellier et al., 2013, Adams, 2015). Groover (2014) defines seven types of flexibility to be adopted by the production system and company:

- **Machine/Workstation flexibility** - the capability to adapt to a range of production operations and parts.
- **Production flexibility** - the range of parts to be produced or assembled in the system.
- **Mix flexibility** - the ability to change the mix of products produced or assembled while maintaining the productivity.
- **Product flexibility** - how easily revised and new products can be implemented in the system.
- **Routing flexibility** - the capacity to produce products through alternative machine/workstation sequences.
- **Volume flexibility** - the ability to produce different quantities of products in an economically sound way.
- **Expansion flexibility** - how easily the system can adapt to increased production volumes.

The utilisation levels of the flexibility are affected by the shop-floor operators’ skills, abilities and knowledge. Such dependencies highlight the vital importance of developing and utilising the knowledge, achievements and abilities of the operators working with production on the shop-floor. Teamwork, including both novice and highly experienced shop-floor operators, in a production environment with a high level of automation, is essential already today and is predicted even to increase when the complexity of and demands on future production systems intensifies (Teknikföretagen et al., 2011, Teknikföretagen et al., 2013).

Maintaining high productivity and high quality and, at the same time, coping with stochastic events, such as delayed jobs, machine breakdowns, shortage of fixtures, broken or missing tools and express orders, put the shop-floor operators into challenging circumstances. Such situations and events easily lead to information overload and unscheduled incidents that negatively affect the efficiency of the production. To be able to handle the future production systems, the Swedish production industry, as well as most industries in developed countries, has identified a vital need of technical ability and competence for its future teams of operators (Teknikföretagen et al., 2011, Teknikföretagen et al., 2013). Keys to its future competitiveness and effectiveness are the shop-floor operators who will handle the production systems. The future information intensive working environment with increasing complexity, where less time is available for decision-making, demands an adaptive decision
support and adaptive control systems facilitating collaborative work on the shop-floor (Fasth et al., 2010, Grane et al., 2012, Karlsson et al., 2013b, Lindberg et al., 2013, Holm et al., 2016). It is therefore important to emphasise how decisions are supported in the time limited working environment of the shop-floor, because this has a large impact on the production output and is vital to the success of the company. Consequently, shop-floor decisions and the decision support systems are interesting areas for both academia and industry. Much attention has been focusing on the level of manager and engineering decision support, but less focus has been on the shop-floor level of support (Arnott and Pervan, 2008, Arnott and Pervan, 2014, Holm et al., 2014c). Consequently, there is a need to focus research effort on an adaptive decision support system that concentrates on shop-floor operators, in order to enhance their development and future contribution to leading edge production.

1.1.2 Adaptability and event-driven function blocks: a brief overview

Adaptability is an ability to quickly and efficiently adjust to changing conditions, to counteract unpredictable events negatively affecting the performance of a production system. Adaptability needs to be a substantial ability of a production control system. The use and implementation of event-driven function blocks using online data in a distributed control system facilitate adaptive and dynamic control capabilities that enhance decision-making and enable the system the important and valuable capacity to handle uncertainty (Monostori et al., 2010, Wang et al., 2012a, Holm et al., 2014c, Wang, 2015).

The concept of event-driven function blocks, specified in the international standard IEC-61499 (IEC, 2005) enhances an approach meeting the needs of flexibility, adaptability and reconfigurability for production systems. It is an IEC standard focusing distributed processes and control systems applicable to industrial systems. The standard is not a programming methodology. It provides a set of models used to describe distributed systems using function blocks (Lewis, 2001).

A function block is an event-triggered software component comprising algorithms and an execution control chart. Internal algorithms inside the function block are executed when triggered by external events and are controlled by the internal execution control chart. The execution control chart works like a finite state machine and when algorithm execution is finished an output event is triggered. Each function block encapsulates a software solution for the task at hand, using one or several algorithms. It might be a simple task, toggling an indication lamp on or off, or a complex industrial process. Function blocks are used as enablers to encapsulate generic functionality through the internal algorithms. By combining
and connecting basic function blocks into networks, complete applications with complex functionality can be built.

Function block technology facilitates autonomous and intelligent behaviour of the system at hand, enabling adaptive decisions at run time and an ability to handle the dynamic nature of the shop-floor. The ability of the function blocks to handle changes during run time and execution enables optimal system output, which are the effects of its modular and distributed technology (Holm et al., 2013, Wang, 2015).

1.1.3 The shop-floor operator and shop-floor decision support: a brief overview

A human operator’s ability to adapt to different situations is, in general, good (Payne et al., 1993). However, in a dynamic shop-floor environment with changing demands and stochastic events, it is not possible for an operator to make the correct decisions and prioritisations in every situation, since it is impossible to either have all the relevant production information in real-time or to have the ability to evaluate or process it. No operator can receive and process all available information on the shop-floor online, as a rational decision maker (Lee, 1971). Since shop-floor operators are vital to a production system, the decisions and actions taken by them will directly affect its productivity.

Unlike shop-floor operators in the early part of the 20th century, shop-floor operators of today generally have a more diverse spectrum of responsibilities and a widening range of tasks. The change in responsibilities and scope of tasks of shop-floor operators has occurred in parallel to a fading difference between blue and white collar responsibilities. Duties of past-time engineers are often done by the shop-floor operators of today (Dencker et al., 2009). Changing conditions within the production industry and altering management strategies have of course affected the working environment of the shop-floor operator and will keep on doing so. Shop-floor operators with a proactive approach and behaviour counteract possible uncertainty, which leads to flexibility gains and also a reduction of the total lead time at assembly lines (Dencker et al., 2009). The ability to interpret information, adapt and act on it, is a main requirement for the operator of the future (Fasth et al., 2010). In order to maintain the high level of productivity that is necessary for success on the competitive international market, the future shop-floor will demand that team players have extensive technical abilities and comprehensive interpersonal skills.

Shop-floor operators need system support that enhances communication, control, collaborative work and constant learning. Intuitive systems with in-situ information have the ability to increase flexibility and enhance proactive decisions on the shop-floor (Grane et al.,
Due to its adaptability and online response, the demands of future decision support systems can eventually be met by function block technology (Holm et al., 2013, Holm et al., 2014c).

### 1.1.4 Knowledge transfer: a brief overview

Exploring and generating new knowledge are the essence of research and together with knowledge transfer to other researchers and to society they represent the main driving forces of an academic body. Knowledge obtained by research forms a foundation for future innovation. Innovations through research are key mechanisms for companies striving to reach or keep a leading position in their markets (European Commision, 2007). The University of Cambridge (2009) defines knowledge transfer as “... a very broad range of activities to support mutually beneficial collaborations between universities, businesses and the public sector”.

From a researcher’s perspective, knowledge transfer often involves publishing in academic journals, presenting at conferences and establishing collaborative research with other universities and project partners. In addition, it is also important to engage new companies to participate in research, so that knowledge gained is spread to, understood and implemented by many.

### 1.2 Motivation

When the research project Wise-ShopFloor began in 2011, the following questions were put by one industrial project partner:

In the engineering department we know how to run the production system and what decisions have to be made and when, thanks to simulation models and multi-objective optimisations made. But how can we transfer this knowledge to the operators on the shop-floor? In what way is it possible to support shop-floor operators in making decisions for optimal productivity when the production system calls for action at several locations?

The point made by the industrial partner, regarding the lack of shop-floor decision support, was supported by the research literature and strengthened by the predicted increasing demands of shop-floor work.

Much research has been conducted with a focus on decision support systems, supported by several journals, but the major approach has been from an Information Systems’ perspective and primarily focused at a management level (Arnott and Pervan, 2008, Arnott and Pervan, 2014). Few researchers have published work from the industrial shop-floor operators’
perspective of decision support and their need of online adaptive support. Online abilities of event-driven function block technology facilitate adaptive and dynamic capabilities enabling the handling of uncertainty. This technology meets the demands of adaptive decision support and online system control facilitating collaborative work on the shop-floor.

This led to a merging of research on shop-floor decision support with the already initiated research on event-driven function blocks. The identified problem driving this research is the lack of decision support for shop-floor operators. Furthermore, in order for decision support to be effectively used on the shop-floor by the operators, event-driven function block technology for adaptability, online data, a responsive approach and control are to be explored and developed (Wang, 2008, Wang et al., 2010, Wang et al., 2011a, Holm et al., 2014c).

In parallel to developing a framework for an Adaptive Decision Support System, there has been ongoing work, facilitating knowledge transfer, engaging industrial research partners with a range of previous research knowledge. These partners have been involved in the presented research and development and will subsequently be the expected beneficiaries.

1.3 Aim and objectives
The overall aim of this research is to define a framework for an Adaptive Decision Support System for shop-floor operators and to explore its vital modules, associated techniques, algorithms and usability. Based on the research background and the overall aim, the goal of the research can be further refined into the following objectives:

1. Through an appraisal of research literature and the current state of industrial practice, investigate event-driven function block technology and shop-floor decision support as a basis of adaptive decision support for shop-floor operators.

2. Through interviews with production managers and shop-floor operators in combination with a literature review, establish the requirements of the future shop-floor and its operators, as well as identify the properties needed for shop-floor decision support to enhance production output.

3. Design, test, implement and evaluate a framework, using event-driven function block technology, for an adaptive decision support system for shop-floor operators.

4. Develop, test and implement a methodology for knowledge transfer between academia and industry, facilitating the implementation of research results for industrial partners with less previous research experience.
Objective 4 as presented can at first reading seem to be “outside of scope” and difficult to directly relate to the overall aim of the research study and the associated objectives 1, 2 and 3. However, it is the authors strong belief and conviction that the close cooperation with industrial partners, enabled and strengthened through the method formulated for bidirectional knowledge exchange, namely, the “User group” that facilitates effective knowledge transfer (the ‘User Group’ methodology is presented more fully in Chapter 8), has been an essential component of the research programme presented. The “User group”, companies’ participation has been the foundation for the industrial connections, originated the basis for research questions and facilitated the development of realistic demonstrators and test cases. The companies participating in the research programme, who participated in the “User group”, are the recipients of the knowledge gained, thereby closing the research cycle, from research question through to research outcome. The close relationship to industrial partners, throughout the execution of the research programme, corresponds closely to the research methods applied, namely a design science approach, which emphasises the importance of utility and communication of the knowledge gained (Drechsler et al., 2016).

1.4 Research methodology
Conducting research is an iterative process demanding an understanding of many aspects: research domains, identifying and formulating research questions, applying appropriate research methods, drawing conclusions on the results achieved and transferring knowledge. Research in general has a common aim. It seeks knowledge in the form of answers, relationships, explanations, confirmations, etc., as defined by Blake (1978): Research is a “…systematic, intensive study directed towards fuller scientific knowledge of the subject studied”, however, research is not uniform. Different research domains use different methodologies and approaches, trying to answer diverse questions, and have various philosophical definitions of knowledge, truth and reality. One branch of philosophy, Epistemology, is concerned with the theory of knowledge (Audi, 2010). It studies the nature of knowledge and its relationship to concepts such as truth, beliefs and justification. Another branch of philosophy is Ontology, which focuses on what can be known and how it can be known (Floridi, 2008). Different philosophical beliefs view knowledge, truth and reality differently (Roth and Mehta, 2002).

Epistemology can further be refined into several philosophical orientations. According to a Positivist approach, the truth or cause can be found, tested and verified by scientific standards. The closely related Post-positivism emphasises that knowledge is built by careful
measurements and observations of the reality existing “out there”, but absolute truth cannot be found. An Interpretivist though, rather than approaching an objective truth, would seek a subjective understanding, assuming that the truth is shaped by the viewers’ perception and understanding. A Constructivistic approach is related to the Interpretivistic, through focusing more on the ongoing processes of interaction between the individuals. A third orientation is represented by the Pragmatists who state that instead of focusing on the methods to use the researcher should emphasise the problem or question at hand and use any available approaches to understand the problem. These philosophical orientations’ different beliefs and approaches do not necessarily oppose each other. They approach the same data, but from different viewpoints, and their results can ultimately complement each other (Roth and Mehta, 2002, Creswell, 2013, Gray, 2013).

A researcher needs to decide how to approach the topic to be studied, choosing research design along with appropriate research methods. These decisions are influenced by the researcher’s philosophical beliefs and assumptions. There are three main research designs or procedures: 1) Qualitative, 2) Quantitative and 3) Mixed methods. These three are not as unrelated as they may first appear to be. Qualitative and Quantitative approaches can be seen as the two parts of a scale and the positions of different research designs on the scale are either somewhat more qualitative than quantitative or vice versa. Research using Mixed methods appears somewhere in the middle of the scale, combining features from both parts. A general description of a qualitative design can be framed in words and open-ended questions, rather than numbers and close-ended questions for a quantitative design. However, a more complete gradation of differences between the two is based on the researcher’s philosophical beliefs, applied research strategies and research methods used. From a general point of view, Positivism and Post-positivism use quantitative methods while Interpretivism and Constructivism use qualitative methods. For a long time, choosing either a quantitative or qualitative research approach was a basic choice for researchers; however, pragmatic, multi-method approaches, combining quantitative and qualitative methods, have evolved (Nunamaker Jr and Chen, 1990, Hevner et al., 2004, Hevner and Chatterjee, 2010, Gray, 2013, Creswell, 2013).
The research presented in this dissertation concerns ICT-devices, applications and tools to be used by human operators in a dynamic environment, the shop-floor. It concerns qualitative processes, as well as quantitative methods, approaching mixed methods. The technology and the users cannot be separated when researching and developing such systems, they are inseparable. Such arguments can be derived from Pragmatism, that a justified theory – truth, and effective artefacts – utility, can be seen as the two sides of a coin (Hevner et al., 2004, Goldkuhl, 2011). Hevner et al. (2004) state that “scientific research should be evaluated in the light of its practical implications” and that “design science address research through the building and evaluation of artefacts designed to meet the identified business need” which assures its relevance. They also state that “the goal of design science is utility”. It is also emphasised that knowledge gained should be communicated, so-called research resonance (Drechsler et al., 2016). The design science research processes have been used for the research presented in this dissertation and are described in Figure 1.

![Figure 1. The design science research process.](image-url)  
Originally from Takeda et al. (1990), and further developed by Peffers et al. (2007) and Vaishnavi and Kuechler (2015).
The output from the first step, *Identify problem*, is a proposal derived from both academia, i.e., literature reviews, and from consulting industry, to gain an initial understanding of the problem. From the proposal, the *Suggestion* or tentative design is generated. The Suggestion is intimately connected with the proposal formulating a tentative design. The tentative design is then implemented during the *Development* stage with an artefact as an output. The artefact is further evaluated using mix methods. If any problems are identified during the process, the constraints are fed back informing the identification of the problem in an iterative cycle. The final step, *Conclusion*, is reached if the evaluation phase scores the developed artefact as satisfactory, or at least “good enough”. At the final step, it is important to not only conclude and write a report, but also to document the knowledge gained and to transfer it to both fellow researchers and external stakeholders such as industry (Takeda et al., 1990, Peffers et al., 2007, Vaishnavi and Kuechler, 2015). It is unlikely that all five steps of the process are given equal time and consideration, it would depend on the research question or problem at hand (Johannesson and Perjons, 2014).

Artefacts in design science are broadly defined by Hevner et al. (2004) as:

- Constructs (vocabulary and symbols)
- Models (representations and abstractions)
- Methods (algorithms and practices)
- Instantiations (implemented prototype systems)

The artefacts used during the research presented in this dissertation are mainly instantiations. The mapping of the research process to the Chapters of the dissertation is shown in Figure 2.
When conducting the research presented in the dissertation, demonstrators were used extensively. The research objectives target real-life production systems, however, it has not been possible to test the prototypes devised in real production situations, due to potential production disturbances. Therefore, demonstrators were used extensively during the research and development. A demonstrator emulates the production process and enables the researcher to construct scenarios and perform evaluations via test cases, without disturbing the real production environment. The research methods in Table 1 have been considered during the research and development. The reason for choosing and using the methods applied are justified in the relevant Chapters.
<table>
<thead>
<tr>
<th>Research method</th>
<th>Description</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>To, under controlled conditions, manipulate an independent variable (IV) and measure its effects on a dependent variable (DV).</td>
<td>Can find cause and effect relationships between the IV and the DV.</td>
<td>A limited ability to generalise findings to real world conditions.</td>
</tr>
<tr>
<td>Focus groups</td>
<td>Interviewing a group of people about the issue being examined.</td>
<td>Captures scope, motivations and details, and possibility to fine-tune questions.</td>
<td>The members of the group might influence and limit each other. Fewer details compared to one-to-one interviews.</td>
</tr>
<tr>
<td>Interviews</td>
<td>The interviewer asks questions and talks to the interviewee about the issue being examined.</td>
<td>Captures scope, motivations and details, and possibility to fine-tune questions during interview. Truthful answers. One respondent is unlikely to influence another.</td>
<td>The interviewer can introduce bias. Only include a limited number of individuals.</td>
</tr>
<tr>
<td>Mathematical modelling</td>
<td>The process or question at hand is described as a mathematical algorithm, tested and evaluated.</td>
<td>Provides precis answers to questions.</td>
<td>Difficult to apply to real-world processes and human behaviour.</td>
</tr>
<tr>
<td>Questionnaires</td>
<td>Obtain large samples of answers, abilities, opinions, etc., from a selected number of people.</td>
<td>Respondents have relevant knowledge/background. Quick response. Can handle many respondents. Easy to handle scoring.</td>
<td>Distorted results due to response errors. Not possible to fine-tune questions.</td>
</tr>
<tr>
<td>Surveys</td>
<td>Obtain large samples of answers, abilities, opinions, etc., at a specific time and place.</td>
<td>Quick response. Can handle many respondents. Easy to handle scoring.</td>
<td>Distorted results due to sampling and response errors. Not possible to fine-tune questions.</td>
</tr>
<tr>
<td>Test case</td>
<td>An enquiry investigating a situation, phenomena, connection, etc., in a real life context.</td>
<td>Provides detailed descriptive data. Can use models of real life scenarios to avoid interfering with real life processes.</td>
<td>Cannot completely describe reality leading to possible summarisation and bias.</td>
</tr>
</tbody>
</table>
When evaluating design science research, fundamental questions such as the following must be answered: What utility does the new artefact provide?; What demonstrates such utility? Guidelines for evaluating design science research (Hevner et al., 2004, Hevner and Chatterjee, 2010) are used in discussing and evaluating the results of the research and are presented in Chapter 9.

Design science is one of the main methodologies used in decision support system research. Instantiations is the most common artefact of published, decision support system research applying design science methodology. It constitutes almost two-thirds of all the artefacts (Arnott and Pervan, 2012).

1.5 Thesis organisation
The thesis is organised according to the Sections described below.

1.5.1 Chapter 2 – Event-driven function blocks
This Chapter describes event-driven function block technology, the international standard IEC 61499, and how it can enhance an adaptive production process. A case study investigating a three-layer system of event-driven function block based control concludes the chapter.

Part of the work in Chapter 2 has previously been published in:


1.5.2 Chapter 3 – The future shop-floor: Its operators and decision support
This Chapter describes the evolution of the shop-floor operator, according to the research literature, and also utilises interviews with production managers and HR-specialists. In addition, the Chapter presents the response of future Swedish shop-floor operators, today’s high-school students, to the description of their possible future work as shop-floor operators. This provides a foundation and establishes prerequisites for developing a framework for a future shop-floor decision support system.

Part of the work in Chapter 3 has previously been published in:


1.5.3 Chapter 4 – Shop-floor decision support systems
This Chapter appraises research literature of shop-floor decision support systems and explores technologies to be merged into such system to enhance shop-floor decisions in an information intensive environment.

Part of the work in Chapter 4 has previously been published in:


1.5.4 Chapter 5 – A framework enabling adaptive decision support and adaptive system control

This Chapter discusses the architecture of the proposed framework, its main components including possibilities and limitations.

Part of the work in Chapter 5 has previously been published in:


1.5.5 Chapter 6 – Dynamic shop floor instructions using Augmented Reality

This Chapter presents test cases and evaluations of the Adaptive Decision Support Systems module Operators device. The module integrates the technologies of Augmented Reality and Expert Systems, forming a user interface that enables dynamic instructions facilitating shop-floor decisions.

Part of the work in Chapter 6 has been submitted to:


1.5.6 Chapter 7 – Dynamic production planning using online path optimisation for guided vehicles

This Chapter continues the evaluation of the Adaptive decision Support System with a test case focusing proof of concept and utility. The test case embraces the whole presented Adaptive Decision Support System using a demonstrator mimicking a production system.
1.5.7 Chapter 8 – Method of knowledge transfer

This Chapter presents a method, ‘user group’, facilitating research collaboration that includes both less experienced and well-established project partners. The method focuses the transfer of knowledge and technology in collaborative research programmes. The ‘user group’, and the companies engaged, have had a key position in developing and communicating the research presented in this dissertation.

The work in Chapter 8 has been published in:

Holm et al. ((in Press)) A methodology facilitating knowledge transfer to both research experienced companies and to novice SMEs. Int. J. Enterprise Network Management.

1.5.8 Chapter 9 – Discussions, conclusions and future work

This Chapter discusses and evaluates the results evolving from the applied design science research process of the dissertation. In addition, the overall conclusions of the dissertation are presented together with ideas on future work.
2 Event driven function blocks

The global economy of today constantly demands adaption to changes in the market and exposes production systems to an increasing degree of uncertainty. This leads to variations in production, new products, new variants, changing batch sizes etc., which the controllers (PLC, robots, CNC etc.) in a production system must be able to cope with. Production systems and their controllers must have a high degree of adaptability and flexibility to meet the changing demands of the global market (Groover, 2014).

This Chapter appraises research literature and the current state of industrial practice, in order to establish an understanding of event-driven function block technology, as defined in the international standard IEC 61499, and how it can enhance adaptive production.

2.1 Introduction to IEC 61131

Traditionally, Programmable Logic Controllers (PLCs) have been the “brains” of production systems, since they have held the general intelligence controlling both low level devices and entire production cells. The setup of the control systems has been centralised using a polling structure. The international standard IEC 61131, which has defined and specified requirements for programmable controllers, has nine parts (IEC61131-1 → IEC 61131-9). The most used one is IEC61131-3 (IEC, 2003) which defines basic programming elements, syntactic and semantic rules for the five PLC programming languages, the three graphical: Ladder Diagram, Functional Block Diagram and Sequential Functional Chart, along with the two textual: Instruction List and Structured Text. The initial version of IEC 61131 was published in 1993 and the third edition of IEC61131-3 was published in 2012.

The evolution of the computer has, of course, also affected the evolution of the PLC. When IEC 61131 was introduced in 1993, the sensors, actuators, conveyers etc., wired to the PLC, usually had none or, in rare cases, very limited computational power of their own. Computing power has, during the years, diminished in size and gained capabilities that find their way into the devices of production systems, both at a low and high level. Today, more and more computing power enabling intelligent behaviour is encapsulated in different devices, such as sensors and actuators. The concept of IEC 61131 is time-triggered and data-driven. It does not support either a distributed control system or an event-driven concept. An application based on IEC 61131 has a centralised setup and cannot be distributed over multiple resources utilising their computing power (IEC, 2003, Holm et al., 2012a).
One latent problem with complex Function Block Diagram (FBD) programmes is the execution order. The network of function blocks in FBD is linked together by simply connecting the inputs and outputs of each function block. A FBD-program is normally executed from left to right, which complicates the determination of the execution order in a complex function block network with feedback signals since the FBD lacks a clear definition of execution order (Lewis, 2001).

An example is given in Figure 3: The output OUT_1_3 (which is connected to the input IN_2_1) is dependent on the input IN_1_3 through the internal algorithm of the FBD-function block FB-1. The input IN_1_3 is connected to output OUT_2_3 which, through the internal algorithm in FBD-function block FB-2, is dependent on the input IN2_1. The execution order of feed-back loops as shown in Figure 3 is not covered by IEC 61131. As a result are the execution and resulting output of the FBD-diagram in Figure 3 not clear.

Additional mechanisms to counteract problems with the execution order are provided by several IEC 61131-3 programming software, although such supplementary mechanisms are not included within the scope of IEC 61131-3. As a consequence, the execution of FBD is defined inconsistently, which limits portability between different control systems (Lewis, 2001).

2.2 Introduction to IEC 61499
The international standard IEC 61499 (IEC, 2005), initially published in 2005, is derived from IEC 61131 and the programming language FBD. In contrast to IEC 61131, IEC61499 defines models for an event-driven real-time execution environment. The primary purpose of IEC61499 is not to be a programming language, but instead it establishes architectures and provides sets of models for distributed systems using event-driven function blocks. The IEC 61499 standard provides generic models for distributed systems. The generic models
describe the distributed control system, including processes and communication networks, for embedded devices, resources and applications. An approach for distributed control systems that enable interoperability, re-configurability and portability is facilitated through event-driven function blocks.

The IEC 61499 standard introduced the concept of event-driven function blocks. In addition, it uses the widely spread computational power of the spectrum of devices in a production system, forming distributed control systems to address demands of adaptability, re-configurability and flexibility. It also enhances event-driven environments, limiting uncertainty in terms of execution sequence, compared to the PLC programming language FBD (Lewis, 2001, Zoitl, 2009). Distributed industrial process measurement and control (e.g. PLC, robotics and CNC) are the main application areas of IEC 61499, but it is also relevant and can be applied to other industrial systems as well as high-level process planning. A device or controller in a distributed control system where event-driven function blocks have been applied can become more autonomous, facilitating decision-making at runtime. An event-driven function blocks-based control system can, for example, handle execution control, process monitoring and the scheduling of dynamic resources (Lewis, 2001).

Programming using function blocks was not introduced when the IEC 61499 standard was published. The concept of function blocks was already well established (through IEC 61131), offering robust and reusable components for the programmers working with industrial processes. The encapsulated algorithms inside the function block can include a simple task, e.g., controlling an actuator or a complex multi-facetted function. With function blocks, the programmer does not need the full knowledge of the embedded algorithms. It is enough to have an overall knowledge of the functionality offered by the function block at hand, when designing and developing a new system. Event-driven function blocks ensure a well-structured and easy-to-control execution, compared to the FBD-language from IEC 61131-3 (Lewis, 2001).

When designing an autonomous and distributed system, event-driven function blocks can be used together with intelligent control components. Early research (Wang et al., 2001) describes how the “next-generation” of production systems will require agility, flexibility and fault-tolerance and how these demands can be met by a real-time control architecture for distributed control offered by the emerging event-driven function blocks’ concept. Further examples of how IEC 61499 has been studied and discussed in the research literature are: the development of an architecture for function block-oriented engineering support systems (Thramboulidis and Tranoris, 2001), a reconfigurable model for functions blocks and its
implementation using real-time Java (Brennan et al., 2002) and an automatic verification of industrial control systems based on function block technology (Völker and Krämer, 2002).

There are some IEC 61499 software. Freeware platforms for development and testing according to IEC 61499 are FBDK (Holobloc) and the FBench project (FBench). FBDK has been used by many researchers and the software is still further developed but the FBench project has been terminated. In comparison a more user friendly freeware is the 4DIAC/FORTE which provides an open source infrastructure based on the IEC 61499 standard (4DIAC/FORTE). 4DIAC is used in both commercial applications and research. There are today two major commercial software based on IEC 61499. A software compliant with both IEC 61131 and IEC 61499 is ISaGRAF 5 (ICS Triplex) and a software solely focusing IEC 61499 - nxtSTUDIO (nxtControl). Both include a run-time environments, visualisation and simulation capabilities.

Literature reviews show that several approaches using function blocks have been proposed. Furthermore, IEC 61499 has made an important contribution to the current practice in software engineering concerning production system control. However, even though the standard was published some years ago, commercial software being available, it will still take a long time before it will be as widely spread and adopted by industry as IEC 61131 (Strömman et al., 2005, Thramboulidis, 2007, Thramboulidis, 2009).

As previously discussed, IEC 61499 facilitates a well-defined execution control, compared to the programming language FBD in IEC 61131. The fact that IEC 61499 does not define any formal semantics has led to an emerging diversity of interpretations of the standard, when implemented in different applications. As a consequence, the execution behaviour of different IEC 61499-systems varies negatively, affecting the transferability of applications between different platforms. These challenges are discussed by several who propose altering semantic models and approaches (Dubinin and Vyatkin, 2006, Vyatkin et al., 2007, Čengić and Åkesson, 2010, Lindgren et al., 2015, Pang et al., 2015).

The new abilities presented by IEC 61499 and the relationship to IEC 61131 opened an interest in whether and how traditional IEC 61131 programmes can be updated and converted in accordance with IEC61499: Rules and an implementation method for converting IEC 61131 programmes into IEC 61499 compliant function blocks (Gerber et al., 2008, Wenger et al., 2009), as well as a guide to how to migrate centralised PLC-control and function blocks from IEC 61131-3 to a distributed environment based on IEC 61499 covering limitations and cautions during the migration process (Dai and Vyatkin, 2009, Dai and Vyatkin, 2010). More recently, IEC 61499 has been used in an approach that addresses software design for a cyber-
physical automation system, in the case of the relocation of the software to a different hardware (Vyatkin et al., 2015), and how IEC 61499 can be used to fill the gap of the proper intuitive visual representation of a reconfigurable service-oriented architecture for industrial automation (Dai et al., 2014). Subsequently, in this dissertation when referring to function blocks, it means as defined in IEC 61499.

2.3 The IEC 61499 Architecture
The close relationship to IEC 61131 is often misleading, in terms of IEC 61499 being described as a programming methodology or programming tool. A more adequate label is an architecture and model describing the behaviour of event-driven function blocks in distributed systems (Lewis, 2001, Zoitl, 2009, Vyatkin, 2011, Holm et al., 2012a, Holm et al., 2012b). A distributed control system utilises smart devices and sensors, allowing intelligence to be distributed throughout the system, which leads to it being difficult to define where the main intelligence of the system resides (Lewis, 2001). To model the behaviour of the function blocks and the network is the main focus of IEC 61499.

IEC 61499 defines five models that support a system architecture for distributed industrial processes. Through these models, the developers are able to use a graphical approach when developing distributed control applications. The five models are:

- The system model
- The device model
- The resource model
- The application model and
- The function block model
2.3.1 The system model

The top level defined in IEC 61499 is the system model. The system model includes all the devices (controllers, sensors etc.) and applications of the controlled process that interact and communicate with each other in the system outlining the affiliation between them. The more processing capacity possessed by the devices in the system, the more it can become a truly distributed one. When the controlling software is distributed in several devices, none of them can be recognised as the main controller. A system model can hold one or several applications and an application can exist in a single device or be distributed over several devices (Figure 4). A distributed application holds a network of function blocks and when compiled and downloaded onto a system, parts of the function block network will be located in different devices that include provided communication services to ensure data and event connections throughout the application.

2.3.2 The device model

The second level of the defined models is the device model. A device is commonly a physical unit, such as a sensor, PLC, actuator etc., and each device accommodates one or more resources. The applications loaded onto the devices can be spread along several of its resources or onto just one resource. The device has a process interface with inputs and outputs (I/Os) interfacing the physical signals from the controlled process. The device model also defines a communication interface that exchanges data with other internal resources or other external devices through the communication network (Figure 5).
2.3.3 The resource model

A resource is part of a device and each device can have one or more resources. Each resource can host a whole or part of an application or sub-application. The resource model defines services such as communication and process interfaces. These services along with a scheduling function support the execution of the function block network within the resource. The communication interface of each resource facilitates the exchange of data with function blocks in other resources and internally within the same device. The communication interface of the resource maps the data exchange and event flows passing between the function blocks, both within the resource and also to and from remote resources. The resource’s process interface handles all requests concerning reading and writing the devices I/Os to be executed by the process interface.

Figure 5. A device model of IEC 61499
(Device #3 from Figure 4).

Figure 6. A resource model of IEC 61499.
Inside a resource, the local application or a part of a distributed application consists of interconnected function blocks which are linked together into a network by data and event flows (Figure 6). The scheduling function within the resource controls the event flow of the network and the execution of the internal algorithms of each function block, to ensure they are executed in the right order. When communicating with another resource, sending or receiving events or data, special function blocks called service interface function blocks are used. Several types of service interface function blocks are defined in IEC 61499. An important characteristic of the resource model is the so-called “independent operations”. It means that each resource, independently from other resources, can be reconfigured and reinitiated during runtime, without affecting other resources or devices in the network. Worth noticing, however, is that a distributed system requires co-ordinated control of when and where applications and networks are initiated and downloaded and that such control is not fully facilitated by IEC 61499. Although not fully defined by the standard, researchers discuss how true real-time reconfiguration of function block networks can be defined (Sünder et al., 2007, Zoitl, 2009, Dai et al., 2015).

2.3.4 The application model
The definition of an application in IEC 61499 is a network of interconnected function blocks linked together by event and data flows. An application is either downloaded onto a single resource or split onto several resources and multiple devices. In practice, an application can be seen as the function block network needed to control a specific system, e.g., a machine, an automatic assembly cell or a production line. An application can be disaggregated into sub-applications, each of them holding a defined functionality of the application.

2.3.5 The function block model
The function block model and its description of the embedded algorithms and the data structure of the function blocks are the core of the IEC 61499 architecture. The main features of a function block (Figure 7) can be summarised as (Lewis, 2001, Holm et al., 2012a):

- The function blocks have a type name and a unique instance name. These should always be shown when graphically represented.
- Each function block has a set of event inputs, receiving events from preceding function blocks, and one or more event outputs, passing on events to succeeding function blocks.
Each function block has a set of data inputs, receiving values from function blocks, and a set of data outputs, passing data values produced within the function block to other function blocks in the network.

Each function block has a set of internal variables retaining data until the internal algorithms are invoked the next time.

The behaviour of the function blocks is defined by its internal algorithms and its finite state information (execution control chart). Various strategies can, through the execution control chart, be modeled when designing the internal algorithm to be executed as a reaction to incoming events and current internal states.

Figure 7. A function block model of IEC 61499.
The Execution Control Chart specifies how the algorithms are activated upon the arrival of incoming events, in terms of a finite state machine. When executed, the algorithms produce data output values and an output event depending on the data input values and the internal variables. The processes inside the function block are supported by the hosting resource’s capabilities, such as scheduling, communication and process mapping.

The execution of a function block follows a sequence as described below (Figure 7):

1. The data inputs are updated by outputs from preceding function blocks or I/O-signals from the process.
2. An event arrives from a preceding function block or an I/O-signal from the process.
3. The Execution Control Chart is triggered and changes state, notifying the resource’s scheduler to schedule the algorithm for execution.
4. The algorithm indicated by the Execution Control Chart is executed.
5. The algorithm is executed and the data outputs are updated accordingly.
6. After the execution of the algorithm has ended, the resource scheduler is notified.
7. The scheduler notifies the Execution Control Chart accordingly.
8. An output event to succeeding function blocks is fired by the Execution Control Chart.

The Execution Control Chart is a finite state machine controlling the execution of the internal algorithms of the function block. The Execution Control Chart (Figure 8) of the basic function block in Figure 9 has four states: START, INIT, RUN and UPDATE. When an event arrives at one of the event inputs, the Execution Control Chart reacts and eventually sets a new state, triggering its algorithm and firing the associated output event. The following happens when an event arrives at EI_2:

- The state of the Execution Control Chart is changed from START to RUN.
- The algorithm ALG_2 is executed, updating the data outputs and internal variables.
- The event output EO_2 is fired.
- The state of the Execution Control Chart returns to START.

When an event arrives at EI_1, there are two options for the Execution Control Chart. If the data input DI_1 = 0, then the Execution Control Chart state is set to INIT, but if DI_1 = 1, then the Execution Control Chart state is set to UPDATE. After executing the related algorithms and firing event outputs the Execution Control Chart state returns to START.
Three types of function blocks are defined in the IEC 61499 standard. A basic function block and a composite function block are depicted in Figure 9.

1. **Basic function block** – For low level control. A basic function block can only be executed in a single resource.

2. **Composite function block** – For a higher level of functionality. Inside a composite function block, several basic function blocks or lower level composite function blocks are combined into a function block network. A composite function block cannot be distributed over several resources or devices. A composite function block does not have an Execution Control Chart or internal variables of its own.

3. **Sub-application** – A special form of a composite function block that can be distributed. A sub-application is a decomposition of a larger sub-application or an application. A sub-application cannot be executed on its own.
Function Blocks Used for Execution Control of Production Equipment

Research focusing on IEC 61499 and the use and implementation of function blocks for control applications and production systems has been conducted since the late 1990s. A majority of published research using function blocks is focused on low level control and basic machining operations. Such an approach is not able to handle issues of uncertainty, regarding, e.g., configuration, layout and process planning in high level production systems, nor is it able to establish adaptive process planning or control systems that can execute complex machining or robotic operations. An issue hampering the use of function blocks for adaptive control of production equipment is the inability to interface standard machine controllers using function block-based control. It drives a continued use of machine-specific programming languages, e.g., G- and M-code for CNC machines and vendor-specific robot languages. The scope and abilities of both machine controllers and vendor-specific programming code have expanded much during the past decades. Therefore, portability, the ability to use identical programmes for altering CNC machines and robots, is still limited. This situation counteracts alteration possibilities, including function block-based control, of controlling production equipment, as such restrains new developments (Wang et al., 2012a, Holm et al., 2013).

However, some research focusing on adaptability, interoperability, portability and configurability for production equipment has been conducted. The standard for the exchange of information in a modular system is the Composite Function Block.
of product model data (STEP) (ISO, 1994) has been used together with the closely related data model STEP-NC (STEP for numerical control) (ISO, 2007) and with IEC 61499 to develop a STEP-NC architecture enabling open CNC controllers (Minhat et al., 2009a, Minhat et al., 2009b). The STEP-NC model provides feature-based data on the machining operation to be executed. Unlike G-code describing “how-to-do”, the models of STEP-NC are similar to function blocks that have the ability to describe “what-to-do” at task level using features and “working steps”. The absence of a CNC-controller that is able to directly execute STEP-NC models is targeted in Wang et al. (2007) which presents a system using function blocks able to accept STEP-NC data that is translated into the G-code of the specific CNC-controller. A design approach that facilitates and realises the integration of a CNC controller in a distributed production environment using function block technology is proposed in Huang (2010). The ability of function blocks to dynamically execute its embedded algorithms enables an adaptive, generic and portable alternative, compared to executing static data such as G-code. Controllers that are able to execute function block-based programmes can, when events occur that cause uncertainty in a production system, make dynamic decisions at run-time to implement the new conditions. Such capability enables the dynamic scheduling of resources, adaptive execution control as well as process monitoring that facilitates high level control, and adaptive and distributed process planning of production equipment (Wang et al., 2009).

It is the case that production equipment other than CNC-controllers has been adopted using function blocks to enable a distributed production environment. Another kind of machine that uses specific controllers such as CNC-machines do is industrial robots. Research has shown that robot control is possible by using function block technology. A function block-based application that controls a three-axis robot arm and a robotic assembly planning and control system with enhanced adaptability enabled by function blocks are presented in Doukas et al. (2006) and Wang et al. (2012b). A literature review (Vyatkin, 2011) focusing on IEC 61499 enabling distributed and intelligent automation concludes that the promising achievements facilitate control systems that can be automatically generated directly from the design documentation using integrated design methodologies. The review also concludes that system integrators, with experience of IEC 61499 implementations, have efficiently proven its design benefits, compared to other technologies used for automation control.
2.5 **Feature-based function blocks**

An adaptive production system is able to tune its behaviour according to internal changes within the system or to external changes in the surrounding environment. Combining function blocks with assembly and manufacturing features that facilitate high level operations and processes through identification, classification and mapping of the process at hand has been done for some time (Kyprianou, 1980, Shah and Rogers, 1988, Van Holland and Bronsvoort, 2000, Wang et al., 2003). Later research approaches present robot systems that combine assembly features and function blocks which are able to respond to and handle changes during run-time, in order to increase adaptability in planning and control (Wang et al., 2011b, Adamson et al., 2014) and feature-based control in cloud environments (Adamson et al., 2016a, Adamson et al., 2016b). Other novel approaches integrate process planning and scheduling using machining features controlling a CNCs (Wang et al., 2010, Wang et al., 2012a).

![Figure 10. Examples of machining features.](image)

*Figure used with permission from L. Wang.*
The capability to embed a set of algorithms and the event-driven environment to generate adaptive outputs enables functionalities to complete specific operations in dynamic environments. When an incoming event triggers a function block, linked operations are produced through corresponding control commands set by real-time data. Consequently, it is the actual conditions of the production system that causes the function blocks to dynamically control each individual operation performed by the production equipment.

When manufacturing a product, a combination of basic machining operations is sequentially executed. Each of these basic operations can be identified as a machining feature. The same approach can be used for an assembly task. It can be divided into a series of basic assembly operations, so-called assembly features. Examples of machining features and assembly features are depicted in Figure 10 and Figure 11.
Feature-based function blocks, like any function blocks, although with different inputs applied, may generate identical results. This key feature enables, for example, the cutting parameters to be modified during execution, without any need to re-programme or reconfigure. By changing the internal state of the function block, a machining feature function block downloaded onto two different CNC-machines will be able to produce identical results (e.g. a 4-Side pocket), even though the configurations, capabilities and setup of the machine’s cutting tools may differ. A change of the internal state enables the same machining feature function block to be used for roughing, semi-finishing or finishing operations and for machining different materials. A graphical description of the Machining feature function block 4-side pocket, its inputs and outputs together with its Execution Control Chart, is given in Figure 12.

The machining feature function block 4-side pocket (Figure 12) has three event inputs and four Execution Control Chart states START, INIT, RUN and UPDATE, each of them corresponding to the four states of the function block and the three internal algorithms ALG_INI, ALG_RUN and ALG_UPDATE. The function block has yet another three inputs, data inputs. Data on the cutting tool to be used is held by the input Tool_ID, while the following data input Oper holds information about the kind of operation to be performed, roughing, semi-finishing or finishing. The third data input Pos holds information about the actual feature (position, depth etc.). The data output FB_Exe is updated during the execution of the machining operation, providing data on the estimated remaining machining time to succeeding function blocks.
2.6 Evaluation of IEC 61499
To further investigate and evaluate IEC 61499, its flexibility and ability to enhance adaptive systems, a test case was undertaken using a production cell with an IEC 61499 based control system. As the research literature indicates, translation to machine specific control code is usually necessary. The production cell used for the test case included a CNC-machine and gantry robot directly controlled by function blocks, without translation to machine specific control code in between.

2.6.1 Scope of the test case
When setting the scope of the test case, to evaluate the ability of IEC 61499 to enhance adaptive systems, four main areas were focused on. The four areas were Machining, Robot tasks, Communication and Control code for CNC and robot facilitating an evaluation touching the first four types of flexibility indicated in Section 1.1.1:

- **Machine/Workstation flexibility** - the capability to adapt to a range of production operations and parts.
- **Production flexibility** - the range of parts to be produced or assembled on the system.
- **Mix flexibility** - an ability to change the mix of products produced or assembled while maintaining the productivity.
- **Product flexibility** - how easily revised and new products can be implemented in the system.

The latter three types of flexibility indicated in Section 1.1.1 Routing, Volume and Expansion are beyond the scope of the test case.

2.6.2 Set-up of the test case
The production cell was not a copy of a live production cell, but designed to contain a relevant and broad scope of both production processes and communication standards for the implemented control system to handle. The production cell included both machining and assembly operations and a variety of product variants and possible system set-ups. The test case also included three different communication protocols, screen, keyboard, mouse and I/Os enabling a broad scope of functionalities for the function block based control system to handle. The machining was done by a three-axis table top CNC-machine and the assembly and transportation operations were assigned to a three-axis gantry robot. The CNC-machine and also the gantry robot were directly controlled by the function blocks network, without any vendor specific controller in between. The production cell also had two pneumatic
cylinders, fixtures and magazines for parts. A sketch of the set-up of the production cell is depicted in Figure 13.

Using the screen, keyboard and mouse, the operator inputs an order, type of product and quantity, to be produced. All the products use the same raw material, cuboids (10*6*2 cm) of foam material. The products to be produced were:

- Cuboids with a 4-side pocket with/without another blue/white coloured cuboid assembled onto the 4-side pocket.
- Cuboids with a chosen number of drilled holes.
- Cuboids with the letters HIS (abbreviation for University of Skövde in Swedish) milled onto the surface.

Raw material is transported by the robot from the magazine (using a vacuum tool) to the CNC-machine and machined accordingly while clamped by the pneumatic cylinders. When finished, the robot transports the machined part either to the assembly station where an assembly operation is performed prior to moving it to the magazine for finished parts or moving it directly to the magazine for finished parts. The production is continued until the whole order is complete.

Figure 13. Sketch of the production cell used for the test case.
2.6.3 A three layer structure

The control system of the production cell uses three functional layers (Figure 14). The top layer, called the Interface layer, includes two interfaces: 1) the operator interface where the operator inputs and receives information before and during production and 2) the programming interface used by the engineers when designing the control system. The engineering interface uses a separate PC and the operator interface uses a screen, keyboard and mouse directly connected to a controller in the Process layer. The engineering interface uses Ethernet communication.

Figure 14. The three layer system used in the test case.
The second layer, the Process layer, holds and executes the function block network. The three machining feature function blocks, 4-side pocket, Blind Slot and Blind Hole (Figure 10), were implemented for the machining operations and the assembly feature function block Inserting (Figure 11) for the assembly was done by the gantry robot. Function blocks for Ethernet and USB communication connected the Process layer to the Interface level, while function blocks for RS232 and for the I/O-modules (-10 - +10VDC and 0-1000 Ohms) connected the Process layer to the Operation level. In addition, other function blocks, e.g., handling transportation of parts, complete the function block network.

The third layer is the Operation layer. From the Process layer, output commands are sent to the Operation layer: Communication with the CNC-machine uses RS 232. The function blocks output hexadecimal code directly controlling each separate axis, without any machine specific controller in between. For communicating with the gantry robot, I/O-signals are used. Each separate axis of the gantry robot is controlled through a PI-controller. The motor of each axis is steered by a signal -10 VDC to +10VDC and the actual position of each axis is fed back using a built-in potentiometer. At system startup, the configuration of the fixtures, magazines, etc., were updated by the operator through the interface. Entries from the operator concerning new orders were handled by the system during run-time.

The controller was a CX1010 with associated I/O modules from Beckhoff. The CNC-machine used was a KOSY3 and the gantry robot was designed in the University’s lab. The software nxtSTUDIO was used for the engineering interface.

2.7 Conclusions and key results
An adaptive production system must have a control system enabling a high degree of flexibility. The approach using a function block-based control system, as defined in the IEC 61499 standard, has in the implemented test case demonstrated an ability to handle a variety of altering production conditions during run-time. The approach has shown the capability to, without reprogramming, adapt to a range of production operations (Machine flexibility) and it has shown that an alternative mix of products (Mix flexibility) can be handled without negatively affecting the production. The control system fully facilitates altering parts to be machined and assembled (Production flexibility) within the physical limits of the set-up. It has also proven its capability in terms of revision and implementing new products into the control system facilitating Product flexibility.

The test case used a three layer structure where high-level information, such as the production plan, is separated from low-level machine instructions. It facilitates the exchange
of production equipment and other devices as well as extensions of system functionality. The function block approach facilitates adaptability, flexibility and portability. Previous research has not considered function block control which directly controls both a CNC-machine and a gantry robot. The presented approach controls the CNC-machine and the gantry robot directly through the function blocks, instead of including vendor specific controllers. The need to translate function block algorithms to vendor specific control code is eliminated. Function blocks can eventually be used, realising an adaptive control approach in distributed manufacturing environments, facilitating cloud manufacturing.

Although the literature review and the presented test case mainly focus on production equipment and production systems, a function block approach can eventually be extended beyond the presented scope to facilitate adaptability, flexibility, portability and real-time abilities in other shop-floor systems, such as a shop-floor decision support system.

The appraisal of the research literature and the current state of reported industrial practice concerning function block technology, together with the test case studied, indicates the following key results:

- Function block technology, as defined in IEC 61499, facilitates adaptability and real-time abilities. The research literature indicates that the need of translators when using vendor specific controllers can be eliminated. The test case has shown that function blocks have the capability to directly control production equipment, without the need to translate into vendor specific control code.

- Function block technology can eventually be used not only in low-level control but also for high-level shop-floor control facilitating shop-floor adaptability beyond the production system itself.

The next Chapter in the dissertation examines the demands to be faced by future shop-floor operators, and the need of shop-floor decision support, which eventually can be met by function block technology.
3 The future shop-floor: Its operators and decision support systems

The evolution of production industries, both in Sweden and internationally, reveals continuous progress and development throughout the years. This evolution not only includes production methodologies and the production equipment, it also includes the working environment of the shop-floor operators. The demands faced by the shop-floor operators have developed from strictly controlled, simple and monotonic tasks to self-controlled team work requiring a holistic approach that aims at continuous improvements and achieving a high degree of flexibility, adaptability and initiative.

This Chapter describes the evolution of the shop-floor operator, according to the research literature and interviews with production managers and HR specialists. In addition, the Chapter presents the response of future Swedish shop-floor operators, today’s high-school students, to a description of their possible future work as shop-floor operators. This provides a foundation and establishes prerequisites when developing a framework based on function block technology, for a future shop-floor decision support system. The Swedish production industry competes, to a large extent, on and responds to the international market (Statistics Sweden, 2016). The findings made in this Chapter are thus also interesting for other industries and countries acting on the international market (Lindberg et al., 2013).

3.1 Research methods

In addition to reviewing the published research literature, two related studies were undertaken investigating the future shop-floor. The first study involved interviews with production managers and HR specialists from industry, to obtain their perspective on the future shop-floor operator. The second study involved questionnaires with high-school students about their response to the future shop-floor operator proposed by production managers and HR specialists. The considered research methods and studies are shown in Table 1 (page 12).

The three methods, Focus groups, Interviews and Questionnaires, could been used for the first study with the production managers and HR specialists. The goal was to capture each individual manager’s understanding and predictions for the future shop-floor. The predefined questions of a questionnaire are not able to fine tune and capture the circumstances and situation of each individual and company, which is why this method was not considered further. Both Focus groups and Interviews can handle the fine tuning of
questions and adapt to particular circumstances. However, it was not possible to gather all
eight managers and specialists for a focus group and, therefore, the method of use selected
was Interviews. The interviews with the managers and specialists were made individually at
each company during the spring of 2014. The questions used are listed in Appendix 1. In the
presentation of the results from the interviews in this Chapter, the names of the participants
and the companies are anonymous, to avoid any possible identification of the sources.
Students attending technical high schools, with relevant backgrounds and a predicted future
within industry, were targeted as participants in the second study. Recurrent visits at our
University by several technical high school classes provided a representative group, including
more than 200 students who could participate in the second study. It was not possible to
implement Interviews and Focus groups, due to the number of participants and the available
time. Questionnaires were chosen rather than surveys, in order to gain better control of the
process in general and especially regarding the information given to the participants. The
second study was conducted during 2014 and 2015. The questionnaire used is listed in
Appendix 2.

3.2 Introduction
In recent times, Sweden has had a positive national trade surplus (Statistics Sweden, 2016).
The competition in the international marketplace is constantly increasing and, as an export-
dependent country, it is vital that the nation’s manufacturing industries are competitive and
adaptive, in order for them to maintain a leading position. The challenges faced by
production companies not only include variables of productivity, but also an increased level
of knowledge among staff that enables them to fully utilise the production systems. Future
production challenges are anticipated to emphasise the importance of developing the
knowledge, abilities and scope of the employees, not only in the engineering departments,
but also on the shop-floor. Good collaboration within shop-floor teams that have both novice
and highly experienced operators is vital, when complexity and the demands of adaptability
in future production systems increase and time-to-market decreases. An increasing pace
together with more advanced machines and complex production systems lead to a more
information intensive working environment that demands technical support systems to help
the shop-floor operators handle, prioritise and act on available and incoming information, in
order to maintain a high production output.
The production industry in Sweden has identified the need for extended technical knowledge and competence in handling future production systems, in order to maintain a high level of competitiveness and productivity (Teknikföretagen et al., 2011, Teknikföretagen et al., 2013). Among the key employees are the ones closest to the production systems, the shop-floor operators. To facilitate and enhance a collaborative approach on the shop-floor, supportive tools focusing on the operators are needed (Fasth et al., 2010, Grane et al., 2012, Karlsson et al., 2013b, Lindberg et al., 2013, Holm et al., 2016).

3.3 Evolution of the industrial shop-floor operator

Yesterday’s shop-floor operators were stationed at one machine or focused on one specific task. In contrast, today’s shop-floor operators face an increasing range of tasks, demands and responsibilities. Parallel to this transformation, the difference between blue collar and white collar responsibilities and scope has faded. Many of the engineering duties formerly carried out by white collar workers are today within the responsibilities of the shop-floor teams (Dencker et al., 2009).

The development of the shop-floor is, of course, a mirror of the changing conditions faced by the production industry in general. Shifting management strategies have obviously affected all employees in one way or another. The concept of Scientific Management presented at the beginning of the last century focused on efficiency. The shop-floor operator was almost considered as a machine along with other machines on the shop-floor. According to Scientific Management, the shop-floor operator was in need of firm supervision and a rigid structure, in order to reach high productivity. The areas of explicit knowledge, decisions and conclusions belonged to the white collar workers who were not expected to emerge from their offices onto the shop-floor (Björkman, 2002, Taylor, 2004, Börnfelt, 2006).

In 1948, the concept Method Time Management (MTM) emerged and during the following years it was introduced to industry. Through analyses of manual tasks, focusing on and evaluating possible improvements, MTM enabled improved ways of working. The MTM-concept has had a substantial impact on the development of the manufacturing industries’ productivity and competitiveness, also, of course, on the working environment of the shop-floor operators. In the 1980’s, the Toyota Production System (TPS), a production and management concept, began its triumphal march over the world, also strongly influencing Swedish industry. Along with yet another management philosophy, Total Quality Management (TQM), the focus was set on the expectations and requests of the customer, as well as the production variables, quality and flexibility. These somewhat new shop-floor foci resulted in an increased motivation to work with continuous improvements and the
elimination of waste, not only for the engineers but also including the shop-floor operators. A high level of commitment and a broad range of adaptability are keys to the successful implementation of any management and/or production philosophy, not least on the shop-floor. The production philosophies emerging from TPS, TQM and Lean have strongly influenced most of the world’s production companies, and still do so today (Maynard et al., 1948, Payne et al., 1993, Hellsten and Klefsjö, 2000, Nilsson, 2000, Laring et al., 2002, Liker, 2004b, Börnfelt, 2006, Johansson and Abrahamsson, 2009, Johansson et al., 2013, Lindberg et al., 2013).

Having a pro-active approach on the shop-floor is an important strategy that facilitates greater flexibility and a possible reduction of the total lead time at assembly stations. Such approaches can counteract possible uncertainty caused by stochastic events (errors, breakdowns, etc.) during production (Dencker et al., 2009, Fasth et al., 2010). Definitions, requirements, responsibilities and knowledge of the “Operator of the future” have been discussed in some workshops with Swedish production and process companies (Berlin et al., 2012, Grane et al., 2012), where one of the main topics was the shop-floor operators’ ability to interpret and act according to shop-floor information. One of the strengths of a human operator is the ability to adapt to different situations, make a decision and act upon it. However, in a dynamically changing workshop environment with stochastic events that negatively affect the production system, shop-floor operators neither possess all the available information nor do they have the capability to process or evaluate it in real time. To make good decisions, the operators need a system that supports decision-making, communication and collaborative work, as well as facilitates a learning process enhancing a proactive shop-floor (Payne et al., 1993, Grane et al., 2012, Harlin et al., 2012, Holm et al., 2014c). Views of and demands on the shop-floor operators of today, provided during the interviews and from the research literature, are described in Figure 15.
As indicated in the research literature, the evolution of industry has not had the shop-floor operators in focus. Research has concentrated on management, methodologies and the production systems. Though the role and importance of the shop-floor operators are eventually going to change.

3.4 Managers’ views of the future Swedish shop-floor operator
To further investigate the scope and demands of the future shop-floor, interviews were conducted with eight production managers and HR specialists at six Swedish production companies. These six manufacturers range from a local company with 60 employees to an international production company whose local factory site has more than 1000 employees. These companies, process and cut metal and wood, in sectors such as automotive, industrial automation and supply of the construction industry. Their shop-floor operators are engaged in machining as well as assembly operations.

The managers, who have been engaged in research collaboration with the University of Skövde for several years, have given their views of the present and the future Swedish shop-floor operators and shop-floor working environments. The conclusions of the production managers and HR specialists have been presented to the future and up-coming shop-floor operators, namely, today’s high school students. Their response embraces both deviations and consensus. The citations subsequently used in this Section are from the interviews.
During the interviews with the production managers and HR specialists, a model describing four quality areas when developing industrial work was used as a basis for the interviews (Harlin et al., 2012). The four areas are:

- Individual – team
- Skills
- Improvement and development work
- Management and communication.

When developing the shop-floor, the focus should not only be on the individual operator, it should also include the whole team. The shop-floor team of the future will have both a broader scope and a wider range of responsibilities in a working environment with a higher degree of complexity, compared to today. One of the challenges will be the ability to interpret and interact in an information intensive shop-floor environment (Harlin et al., 2012).

A team-based approach on the shop-floor and operators within the teams that rotate workplaces are used by all companies engaged in the interviews. The vital importance of social interaction and discussion on the shop-floor was emphasised by all interviewees and they all agreed that a team-based working environment in the future will be the leading approach. However, a probable extended scope requires shop-floor operators with an ability to handle an additional number of complex tasks, in order to maintain high productivity as well as a high level of quality. A trend that was identified in some of the companies was factories within the factory (Nilsson, 2000). The team (or teams) responsible for each of these in-house factories had all the responsibility to optimise the production. The teams’ responsibilities not only included normal production tasks, such as machining and assembly operations, but also included, e.g., preventive maintenance, continuous improvements, production analyses and failure handling. Nonetheless, the members of the teams will, of course, change over time. Assuring the total competence of the teams was emphasised, to ensure the ability to maintain high productivity and quality.

“It is popular to give the operators and the team more responsibilities. This is both positive and negative. The organisation must have a maturity to handle this, to have a positive output. Man is lazy; it is the way it is. You cannot just give full responsibility to the team and expect that every problem will be solved.”
The predicted increasing scope of responsibility on the shop-floor indicates possible variables limiting the capability of the teams. The shop-floor operators’ own interest and experience is regarded by the interviewees as the most important variable facilitating the level of individual responsibility and eventually the teams’. Today, most of the interviewees’ companies demand a degree from a technical high school, when employing a shop-floor operator, but knowledge in automation, NC and material science is also sought-after. Although the most important individual variable is personality, all of the interviewees agreed that technical knowledge and competence cannot compensate for lack of momentum or individual responsibility.

All of the interviewees agreed, as stated in Harlin et al. (2012), that each individual’s understanding of tasks and acceptance of applied working standards are key variables for making continuous improvements and developing the process along with an engaged individual’s own knowledge and ideas. Other vital issues raised during the interviews were the importance of having short decision processes, to ensure that the engagement on the shop-floor is not lost, and the importance of understanding the level of quality required by the customer.

“We engage the operators in all improvement and development projects. It is obvious why. They are the ones who will work with the machine/process.”

Looking back, one can clearly see that the level and complexity of automation and the number of embedded systems have increased and, looking ahead, the interviewees predict that it will continue to evolve. Beyond technical excellence, which is predicted to become even more important than today, the subsequent attributes are considered by the interviewees as being vital for future shop-floor operators, in addition to the previously mentioned: a thorough technical education, having multi-language skills, being a creative team player, logical and mathematical thinking, dexterity, flexibility, awareness, innovation, momentum and accuracy.

Technical progress enables large volumes of production data and information to be displayed to the shop-floor operator in real-time. However, the information systems of today still look the same as yesterday’s systems and are usually not able to sort, prioritise and handle the large volume of information in a smart way. The teenagers of today, who will be the future shop-floor operators, often use smartphones and other powerful ICT-devices as an indispensable part of life, but using these devices on the shop-floor is often a delicate matter today. Smartphones are seen by some of the interviewees as possible tools on the future shop-floor and all of them foresee that the importance of decision support tools will increase.
The intense and demanding shop-floor environment that requires an even broader range of knowledge and technical expertise, together with increasing quantities of information and more speed, predicts a need of shop-floor decision support. In striving to make the shop-floor an even more attractive work-place, it is important to merge different demands. Can IT-devices, such as smartphones, etc., be used as shop-floor tools for a decision support system, e.g., and at the same time enhance the shop-floor’s attractiveness?

“Young people do not perceive industry as an attractive place to work. We are still seen as boring. How do we want it to be in the future? I think it would be really good if we could create a working environment that looks more like a video game!”

Probable technologies that could be integrated on the future shop-floor are Augmented Reality, as an every-day tool for displaying information, along with Cobots – robots cooperating with human shop-floor operators without fences between them (Djuric et al., 2016). When discussing Augmented Reality applications, the interviewees drew a timeline of six to eight years until practical shop-floor implementation was expected to become a reality. It is expected that an increased level of technology on the shop-floor is essential for making the shop-floor an appealing workplace for young people in the future. The scope of enhanced demands on future shop-floor operators provided during the interviews is depicted in Figure 16. The demands depicted in Figure 16 are not completely new (e.g. not present on today’s shopfloor) but are predicted having enhanced importance by the interviewees.

![Figure 16. Enhanced demands to meet for the future shop-floor operators.](image-url)
3.5 Responses to the managers’ views of the future shop-floor operators

The number of demands and skills that employers require of future shop-floor operators, as predicted by the production managers and HR specialists, will drastically increase, compared to the situation faced by today’s shop-floor operators (Figure 15). A majority of the defined abilities demanded by the managers and specialists can be considered as non-technical or personal characteristics (modelled to the left, above and to the right in Figure 16). Only a limited number are referred to as the individuals’ technical knowledge and abilities, along with requested level of education (modelled in the lower part of Figure 16). The managers’ and specialists’ expectations of the abilities and knowledge of their future employees were presented to their probable future employees and colleagues: 237 Swedish high-school students, 17-18 years old, attending 2nd or 3rd year of three-year technical programs. The high school students came from eight classes at four different high schools from Skövde and nearby cities (high school in Sweden is the educational level before University). The classes visited the University of Skövde on an annual research event focusing technical high-school students.

During a seminar the high-school students were given information about ongoing research focusing the future shop-floor and the predictions made about the future shop-floor during the interviews with production and HR-managers. They were then asked to respond to a questionnaire about their contacts with production industries, their view of shop-floor work and their response to the managers’ predictions.

Of all the high-school students, almost 70% had attended field trips to production companies and approximately 45% had worked at a production company themselves. Only 6% stated they had no previous contact with any production company (Figure 17). The answers to the questionnaire from the high-school students without previous contact with the production industry did not diverge from the answers by the students with personal experience of the production industry and are consequently not presented separately. The high-school students answering the questionnaire are further on referred to as the respondents.
The 237 respondents were given 30 words/short statements and asked to select the 3-5 they thought most applied to their view of the work of a shop-floor operator at a Swedish production company today. The selected top three were development, teamwork and accuracy, followed by other positive opinions, such as good salary and good working environment. Their view of shop-floor work is predominantly positive. An alignment of the respondents’ answers and the given words/statements is shown in Figure 18.

Figure 17. The 237 respondents’ previous contacts with the production industry (more than one input per respondent were allowed).

Figure 18. The 237 respondents’ views of the work of a shop-floor operator (3-5 inputs per respondent).
So what are the respondents’ interpretations of the managers’ demands of the future shop-floor operators, as presented in the interviews? Six of the predicted future demands depicted in Figure 16 were presented to the respondents:

- To be a team player with interpersonal skills
- Innovative, creative and get things done
- Holistic understanding of the production system
- Flexible and multi-skilled
- IT-knowledge
- Work proactively and an ability to interpret processes and relationships

When analysing the interviews made these were the demands having a somewhat fuzzy definition made by the interviewees. To further analyse the understanding of the demands each respondent was given a pair of the demands and asked to provide their own interpretations, given the context that they were shop-floor operators working at a production line with both manual and automatic assembly stations. Their answers for each statement were categorised into groups (see Sections 3.5.1 - 3.5.6).

3.5.1 To be a team player with interpersonal skills

Already today teamwork is a reality on most shop-floors. The managers predict this will continue and that more responsibilities will be demanded from the shop-floor teams in the future. A uniform view emerges from the respondents’ answers to the question “What does it mean to be a team player with interpersonal skills?” Of a total of 68 answers as many as 66 considered it to be an ability to cooperate, interact and support each other.

3.5.2 Innovative, creative and “get things done”

The importance of having a well-functioning knowledge triangle (education, research and innovation – further discussed in Chapter 8), and an ability to keep and further develop a leading position, is indicated by Swedish industry (Teknikföretagen et al., 2011, Teknikföretagen et al., 2013). All of the interviewees agreed that the workers entering the shop-floor as operators in the future must have at least a degree from a technical high school to be able to interact with the intense technical environment and be part of further development. The shop-floor operators are expected use and further develop innovations emerging from research. How did the respondents answer the question “What does it mean to be innovative, creative and get things done”?

The answers can be divided into three groups. Two of the groups were of equal size embracing 80% of the 81 answers. One of the major groups interpreted the question as “new
ways of working, new solutions and a positive attitude”, while the other group understood it as “broad knowledge, development of both company and individual”. The remaining 20% of the answers ranged from “I do not know” to “Continuous improvements” to “More automation” and irrelevant answers.

3.5.3 Holistic understanding of the production system

The complexity of the shop-floor is expected to increase, according to the managers, along with increasing production demands resulting in multifaceted scenarios requiring abilities to interpret situations and processes. This demands a holistic view of the shop-floor and its processes. The respondents’ answers to the question “What does it mean to have a holistic understanding of the production system?” can be divided into three levels of expected detailed knowledge or understanding (Figure 19). The answers referring to it as “Understanding the process” accounted for 38% while 29% stated that it is understood as having “A detailed and deeper knowledge”. The answers from 11% were categorised as “To know every detail”. However, as many as 22% of the 79 answers could not be categorised into any of these three groups, with answers like “I do not know” or irrelevant responses such as “Working with robots.”

![Figure 19. Interpretation of "Holistic view".](image)
3.5.5 Flexible and multi-skilled

As discussed in the research literature, flexibility is already today important, when evaluating the competitiveness of the production industry. The interviewees predict that its importance will further increase in the future. The ability to handle events that occur and the ever-changing demands affecting production systems require shop-floor flexibility and the skills to handle complex machines and processes. The answers to the question “What does it mean to be flexible and multi-skilled?” can be divided into three groups or levels of ability (Figure 20). In total, 70 students answered this question and 60% considered it to be to know a lot and an ability to work with a lot of things. The next group, 24%, broadened the scope and their answers can be regarded as an extended proficiency and ability to solve problems. Two students (3%) took it even further. They stated that flexible and multi-skilled could be seen as abilities beyond expectations and scope. Those not knowing or giving an irrelevant answer comprised 13% of the respondents.

![Figure 20. Interpretation of “Flexible and multi-skilled”](image)

3.5.6 IT-knowledge

Young people of today that acknowledge ICT as an inseparable part of life will eventually presume it to be a part of their working hours in the future. During the interviews, the managers and specialists predicted that IT-knowledge will be vital for future shop-floor operators and that emerging technologies, like Augmented Reality, will be used on the shop-floor of the future. But what is knowledge of IT to the respondents? The 71 answers to the question “What does it mean to have IT-knowledge?” emerged into three levels of IT-abilities (Figure 21). A basic level of IT-knowledge was referred to by 46% of the respondents as having a “General knowledge of computers and a basic ability to use them”. Another 21% of the answers extended the IT-knowledge to cover “Knowledge about and ability to use the IT-
systems in use in production”. The third level of IT-knowledge covering 10% of the answers claimed “Knowledge about and ability to program computers and robots in use in production”. However, as many as 23% answered “I do not know” or gave irrelevant responses to the question.

One answer from a high-school student, who interpreted the meaning of having IT-knowledge, highlighted a gap in the expectation between everyday life and industry:

“IT-knowledge is as important during your work as in everyday life, though industry is possibly a little bit behind”.

For industry, it is important not to appear to be overtaken by the IT-evolution. It is important that the impression is the opposite: That industry offers an environment with front-edge technology attracting the possible future employees.

![Figure 21. Interpretation of “IT-knowledge”](image)
3.5.7 Work proactively and an ability to interpret processes and relationships
Recurring events that negatively affect the production output demand a shop-floor with proactive ways of working and a broad understanding of the production processes, to prevent losses. A proactive approach, which is seen as a common attribute among experienced shop-floor operators, facilitates competitiveness, flexibility and extended functionality of the production systems (Dencker et al., 2009). The answers to the last of the six questions “What does it mean to work proactively and have an ability to interpret processes and relationships?” are depicted in Figure 22 (in total, 70 answers). Of the answers 31% could be referred to as “Understand how it works and see connections” and 21% as “Good at solving problems and see connections”. To “Have a broad knowledge and know what to do” concluded the answers from 19% and 3% considered it as “Working towards the future”. This was the question with the largest group of answers, 26%, that referred to the group of “I do not know” and irrelevant responses. No clear common understanding emerged from the answers. This was the question where the respondents’ answers clearly comprised the largest and, in some cases, incompatible scope.

![Figure 22. Interpretation of “Proactive work” and of “Processes and relations”.](image)

3.6 The respondents understanding and expectations of the future shop-floor
During the interviews, a versatile view of the future shop-floor operator including ample demands, especially concerning the personal abilities, was given by the managers and specialists. For some of these views and demands, the respondents gave uniform interpretations, but for most of the views and demands the respondents’ interpretations encompass a widely defined scope that includes a large number of irrelevant answers, indicating that there was no common understanding of the questions posed in the
questionnaire. The managers and specialists interviewed predicted that the future employment processes for finding and keeping shop-floor staff will be demanding and challenging. This indicates the importance of continuous interaction between school and industry to counteract negative and inaccurate images which will negatively affect the students’ future approach towards employment in industry.

The respondents were asked to formulate what they thought to be the most important issues if they were to work as a shop-floor operator in five years from now. Their top three priorities were “A good working environment” followed by “Work mates” and in third place “A good salary” (Figure 23). When their views of shop-floor work (Figure 18), together with the expectations of their future workplace (Figure 23), were analysed a uniform opinion emerged. Their top three priorities of workplace conditions can all be found within their top five statements of shop-floor work.

Figure 23. The prioritised conditions for a future working environment according to the 237 respondents.
3.7 Conclusions and key results
The scope of the shop-floor operator has, during the last century, evolved from “low knowledge level and single tasks” to “high knowledge level and extensive tasks”. Both the research literature and the interviewees provide consistent predictions of a future with even more intensive and demanding shop-floor environments. Such future conditions will need shop-floor operators who are team players with extensive technical abilities and comprehensive interpersonal skills, in order to maintain the high level of productivity that is necessary to succeed on the competitive international market. Since they are vital aspects of the production system, the decisions and actions taken by shop-floor operators directly and strongly affect the productivity. As the volume of real-time production data and information on the shop-floor rapidly increases and, at the same time, available time for the consideration of options decreases, the need of shop-floor decision support able to adapt to rapidly changing production situations becomes obvious.

During the interviews, the limitations of the current shop-floor information systems emerged. To a large extent, the interfaces of the shop-floor information systems look as they did 20-30 years ago, while the rapid development of ICT in general in society has only marginally reached the shop-floor. The use of the computationally powerful smartphones and tablets is usually restricted on today’s shop-floors and only used for dedicated production applications in a limited number of companies. Such ICT-devices that are considered as vital parts of many teenagers’ lives have the potential to form the basis of a future shop-floor decision support system able to handle and process a vast amount of data and also incorporate emerging technologies such as Augmented Reality.

The demands of the future shop-floor, as described by the interviewees, emphasise the broad scope of abilities and knowledge to be used by the future shop-floor operators. It underlines the need of up-to-date shop-floor support systems but also the necessity that the future shop-floor is developed management and shop-floor operators together, avoiding a dissonance understanding of its presumptions. The demands of future decision support systems can eventually be met by function block technology, due to its adaptability and real-time response (Holm et al., 2013, Holm et al., 2014c).

The future shop-floor will face tough competition in attracting the highly competent staff required. Although, when analysing the questionnaire, it can be concluded that the starting point for shop-floor recruiting is not that dark. As future shop-floor operators, the respondents’ view of shop-floor work coincides to a high degree with their own priorities of their future working environment. A future shop-floor decision support system is not only
able to facilitate technical and productivity needs. A well-designed decision support system that supports shop-floor decisions and work could also enhance the attractiveness of working on the shop-floor, by incorporating every-day ICT-devices, such as smartphones and tablets, and in that way support future recruiting.

The interviewees confirm the research literature, but also extend and confirm the demands that will be faced by future shop-floor operators. However, for many of the investigated requirements, the respondents’ interpretations of the future shop-floor demands are irregular. The respondents present uniform interpretations of the two demands “be a team player” and “be innovative, creative and get things done”, but the interpretations of the other four demands are less uniform. This indicates that companies must clarify, probably not only to their future staff but also internally, how the demands should be understood, interpreted and implemented.

Findings from the literature review that was conducted, confirmed and extended during the interviews with managers and specialists and the response from the questionnaire indicate the following key results:

- Shop-floor decision support systems that are adaptable to changing production situations and are able to handle vast information in realtime are anticipated to be used on the future shop-floor to enhance production output.

- Extensive demands for both technical and interpersonal skills will be faced by future shop-floor operators.

- Future shop-floor staff expects ICT-devices and technologies, such as smart phones, tablets and Augmented Reality, to be integrated and used to a larger extent compared to today’s shop-floor.

It is predicted that the future shop-floor will be a demanding environment for its future operators, but what these demands constitute is not clear, not to the future shop-floor operators nor internally at the companies. A proposed shop-floor decision support system can use function block technology as the basis for a framework that meets the future demands of adaptability and online response. The basis for such a framework is discussed in the following Chapter.
4 Shop-floor decision support

This Chapter appraises research literature of shop-floor decision support systems and technologies that may be merged into such system to enhance shop-floor decisions in an information intensive environment. As previously indicated, the future shop-floor needs adaptive decision support for the shop-floor operators, in order to facilitate a high level of productivity and quality. Such a system will facilitate decision-making within the limited time available on the shop-floor. Previous research of decision support has mainly focused on managerial decision-making and limited research has been spent on the decisions of the shop-floor. Future shop-floor requirements, as indicated in previous Chapters, limited available time and the lack of transparent consequences for available options challenge shop-floor operators who face extended demands when they consider appropriate actions, both during ordinary production and when unexpected or unscheduled events negatively affect production.

4.1 Research literature on shop-floor decision support systems

The human operator is, in general, flexible and can adapt to different situations (Payne et al., 1993). However, during production in an information intensive environment, facing dynamically changing demands and stochastic events that negatively affect production, the shop-floor operator is not able to either process or evaluate all existing information needed to make informed decisions and prioritisations at all times. It is not possible for any shop-floor operator to hold and process all production information in real-time and be a rational decision-maker (completely informed, infinitely sensitive, rational and know exactly what to do) (Lee, 1971), but a well-designed decision support system can help.
The concept of industrial decision support systems is not an immature academic topic. It has been a concept for more than 45 years (Gorry and Morton, 1971). Much research has been conducted on decision support systems and in two comprehensive publications (Arnott and Pervan, 2005, Arnott and Pervan, 2008) seven major sub-fields of decision support systems have been defined from the research literature reviewed. The sub-fields are:

- **Personal Decision Support Systems** – A small system usually developed for one or a limited number of users.
- **Group Support Systems** – Decision support technologies used in combination with communication to facilitate team work.
- **Negotiation Support Systems** – A decision support system focusing on negotiation of opposing teams.
- **Intelligent Decision Support Systems** – Systems using Artificial Intelligence technologies for decision support.
- **Knowledge Management-Based Decision Support Systems** – Systems facilitating memory and knowledge storage, retrieval, transfer and access to support decision-making.
- **Data Warehousing** – A large-scale data infrastructure facilitating decision support.
- **Enterprise Reporting and Analysis Systems** – Decision support system for enterprises at executives’ level.

An indirect indication of the lack of research focusing on decision support systems that aim to support the needs of shop-floor operators is their definition of decision support systems from the reviewed research literature:

“the area of Information Systems discipline that is focused on supporting and improving managerial decision-making” (Arnott and Pervan, 2008).

A managerial decision option usually has a time frame of at least some hours up to several months into the future. The shop-floor operator cannot spend that amount of time processing available options when events occur and actions need to be implemented. A shop-floor decision usually has to be made within some seconds (further on referred to as real-time). In a later publication (Arnott and Pervan, 2014), the same authors (Arnott and Pervan, 2005, Arnott and Pervan, 2008) expect that industrial interest and funding should increase to ensure the relevance of decision support research. However, at the same time, it is also expected that decision support research will increase in relevance for managers and, to an even larger extent, address strategic decisions. Such expectations substantiated by previous
definitions of decision support systems and the research literature show an overwhelming focus on managerial decision-making, almost omitting the emerging need of shop-floor decision support.

Some research focusing on the shop-floor operator of shop-floor decision support including case studies has been performed. A shop floor decision support system at an engine manufacturing unit is presented in Gertosio and Dussauchoy (2003). The decision support system facilitates the shop-floor operators at the final testing stations where the engines arrive from three assembly lines. The developed decision support system uses an event-driven and object-oriented real-time environment. It communicates with each shop-floor operator, presenting a list of possible actions that the operator can execute, in order to increase effectiveness. The paper describes the interface and the architecture of the decision support system presented.

A decision support system in a tube mill facilitating the operator to manually change the settings of the welding process to return it to stable conditions when problems occur is presented in Terblanche Swanepoel (2004). The decision support system monitors the welding process online and acknowledges the shop-floor operators when process data exceeds the control limits indicating available actions to be executed by the operator. The implementation of the decision support system, including an upgrade of weld box components, has indicated an average 47% improvement of the production volume.

Another decision support system recommending actions to be taken by the operators is presented in Elghoniemy et al. (2006). The decision support system uses online production data and Artificial Intelligent technologies (heuristics, genetic algorithms and fuzzy logic) for multi-objective optimisation to generate recommendations to the operators who are able to evaluate the effects of the recommended actions before choosing which one to implement. Later developments on the decision support system at the mill included an agent ontology and implementation of a prototype system into two production lines (Elghoneimy and Gruver, 2012). The continued research demonstrates both architecture and inter-agent communication within the decision support system. Furthermore, it enables the shop-floor operators to make consistent and standardised decisions. The decision support system also facilitates the learning process when training new operators, as well as knowledge acquisition and knowledge transfer when experienced operators update the recommendations in the support system. However, no improvements in productivity or quality are accounted for. The presented results are limited to evaluating different Artificial Intelligent technologies driving the decision support system.
The acquisition of knowledge from experienced shop-floor operators, as support for future decisions, is also used by a decision support system at an electronic assembly line (Gebus and Leiviskä, 2009). The proposed decision support system aims to improve product quality by facilitating the shop-floor operators’ understanding of the parameters influencing it. The shop-floor operators input comments and information on occurring events (alarms, machine stops etc.) into the decision support system. When an event occurs, the user is presented with static comments and pictures previously collected. The presented results are limited to a high usage rate, no productivity figures or numbers are included.

Technologies, such as real-time discrete event simulation and genetic algorithms, are also used by other researchers, when developing a decision support system facilitating real-time decision-making at an aluminium plant (de Ugarte et al., 2009). The decision support system proposes job priority solutions to the operators who choose which one to implement. Tests at the aluminium factory indicate that the approach is able to reduce the make span by 12%.

The decision support systems (Gertosio and Dussauchoy, 2003, Terblanche Swanepoel, 2004, Elghoniemy et al., 2006, Gebus and Leiviskä, 2009, de Ugarte et al., 2009, Elghoneimy and Gruver, 2012) all use ordinary stationary computers for user interaction. The shop-floor decision support system OPTIMIST (Frantzén et al., 2011), however, uses individual portable Personal Digital Assistants (PDA) with a built-in scanner as user interfaces (Figure 24 Left).
The OPTIMIST system uses simulation-based optimisation technology to find and display real-time and near-optimum scheduling solutions to the shop-floor operators who will choose which of the listed jobs to engage (Figure 24 Right). The OPTIMIST system was developed for a machining department at an automotive company. The results of the experiments indicated a possible decrease of the make span of up to 10% and an elimination of late deliveries.

A system facilitating shop-floor work and decisions also using PDAs is presented in Thorvald et al. (2014). It focuses the information context during assembly for the shop-floor operators and discusses in what way the performance of shop-floor operators is affected by the way that the needed assembly information is presented. During the test case, 20 parts were assembled onto a model of a truck chassis and the productivity and quality of the performed work of two groups were compared. One group used a PDA (iPod Touch) and the other group used an ordinary computer as information source for the assembly instructions. The PDAs were strapped to the operators’ arm, while the computer screen was statically positioned. Both of them displayed static instructions during the manual assembly process (Figure 25). The results of the experiments show that the group that used PDA providing portable assembly information had less though not significantly lower assembly time, but produced significantly better quality compared to the group that used a stationary computer as information carrier.
An architecture for a decision support system using RFID and cloud technologies for production monitoring and scheduling of a distributed clothing production environment is reported in Guo et al. (2015). An RFID-based system captures real-time production data from where it is sent to a cloud layer and processed, generating Pareto-optimal scheduling solutions displayed on tablets, smart phones or ordinary screens to the managers controlling the flow on the shop-floor. The system was validated during full-capacity production and indicated a 25% increase in production efficiency, a 12% reduction in production waste and an 8% reduction in labour and system costs. There are more similar examples of intelligent decision support systems used for improving the production process at the shop-floor. However, the decision support is not given to the shop-floor operators directly, it is given to engineers and managers that impact the controls of the production process (Confalonieri et al., 2015, Erozan et al., 2015, Sadeghian and Sadeghian, 2015, Shin et al., 2015).

As indicated in the research literature, Artificial Intelligence and other IT-technologies have, during recent years, been integrated into decision support systems enabling, e.g., online multi-objective optimisation and the handling of dynamic and real-time production data. Such a system facilitates decision-making in complex production environments and enables a transformation from static information to an adaptive system displaying dynamic information to the shop-floor. As indicated, portable information carriers do facilitate shop-floor operators to a higher degree compared to using statically positioned ones (Frantzén et al., 2011, Thorvald et al., 2014, Guo et al., 2015). Adaptive decision support for shop-floor operators will facilitate a continuous increase of productivity.

4.2 Adaptable user interface
As discussed in the previous Chapter, function block technology facilitates system adaptability, but the hardware used for the user interface also influences the system’s level of adaptability. Most ICT-devices today, such as smart phones or tablets, have an integrated camera functionality enabling an integration of system information with real-time and real-world images. It is also possible, in real-time, to adapt the information displayed to the product/process at hand. As indicated during the interviews, Augmented Reality is predicted to become a future shop-floor technology. By using Augmented Reality and Artificial Intelligence technologies, it is possible to overlay virtual information onto the real world and process vast amounts of information.

Shop-floor teams comprise both novice and highly experienced operators, each with individual levels of knowledge, abilities and experience, which indicates the need of system adaptability. Different information should be given depending on, e.g., the user’s level of
knowledge, but also on the status of the production, e.g., whether a new product variant or an express order is under production (Shipp et al., 2012).

The shop-floor operators’ ability to understand and execute instructions can be enhanced by facilitating access to shop-floor information that cannot be obtained through ordinary human senses. Augmented Reality uses digital information which is overlaid onto the real world, thus enhancing shop-floor operators’ perception of reality and thereby facilitating the production systems’ productivity and efficiency (Syberfeldt et al., 2014, Syberfeldt et al., 2016b).

Augmented reality has proven to be a promising technology for displaying shop-floor information (Hou et al., 2013, Makris et al., 2013, Syberfeldt et al., 2014, Wang et al., 2016). Although currently topical, Augmented Reality is not something new. The expression was used in the early 1990’s and referred to a heads-up, see-through display and a system sensing the position of the user’s head:

“This technology is used to ‘augment’ the visual field of the user with information necessary in the performance of the current task, and therefore we refer to the technology as ‘augmented reality’ (AR)”. (Caudell and Mizell, 1992)

A later and more formal definition of an Augmented Reality system and its features is covered by Van Krevelen and Poelman (2010) based on Azuma et al. (2001):

a) The ability to combine real and virtual objects in a real environment,
b) the ability to register (align) real and virtual objects with each other, and
c) the ability to run interactively, in three dimensions, and in real time.

The scope of Augmented Reality does not exclude any of the human senses, but the dominant sense used for Augmented Reality applications is sight. Therefore, subsequent references to Augmented Reality in this dissertation mean visual Augmented Reality. When using sight as the main sense for an Augmented Reality application it leads to an intimate interaction with cameras and some kind of information visualisation hardware, such as “usual screens”, “see-through-screens” or goggles, etc. However, the hardware used also affects the Augmented Reality application. The capacity of the hardware (resolution, contrast, time lag etc.) does have considerable impact on the usability of the Augmented Reality applications. These applications use some kind of anchor of the physical world (picture, QR code etc.) to position and orientate virtual objects correctly, in relation to the real world. The most common way of implementing anchors is through target images caught by a camera.

Areas such as tourism, gaming and sports are today the main sectors which use applications of Augmented Reality. A majority of existing Augmented Reality applications display static
and predetermined information. Research has been conducted on merging Augmented Reality technology and industrial applications (Zauner et al., 2003, Nilsson and Johansson, 2007, Sääski et al., 2008, Henderson and Feiner, 2011), but few have reached practical industrial usage, due to the complex and highly challenging nature of the shop-floor (Tiefenbacher et al., 2014). General studies using Augmented Reality technology for education and training and research concerning Augmented Reality technology and assembly applications have been conducted for a long time (Lee, 2012, Radkowski et al., 2015). An Augmented Reality application used for diagnostics and maintenance is presented in Wójcicki (2014) and an Augmented Reality system for virtual training of parts assembly is presented in Hořejší (2015). Both of these indicate promising results but also clearly illustrate that more research and development are needed, before a final industrial version is possible.

If the purpose is simply to guide the user through a number of steps, static information could be sufficient. However, such an approach is inflexible and does not adapt to different environmental conditions. A dynamic production system demands that dynamic and adaptive information can be displayed to the user. Assembly instructions visualised through Augmented Reality technology using variants of visual features (arrows, text, animations etc.) enable dynamic information content to be shown to the user.

4.3 Collecting and reusing shop-floor knowledge
Shop-floor operators using a decision support system are not uniform. The decision support system and its user interface must be able to adapt to workplace conditions and the individual user's level of knowledge. The shop-floor decision support system should also be able to collect and reuse users' knowledge. When knowledge gained by one individual is not accessible to others, development and progress are hampered. Access to an expert's knowledge will facilitate the execution of a task, mostly for a novice, of course, but also for an experienced user. Expert Systems, as a part of Artificial Intelligence technology, is principally a rule-based programme that can emulate a human expert's knowledge and experience and configure the information so that it can be understood and handled by a computer. Through an Expert System, it is possible to learn how to perform a task on the basis of an expert's knowledge, without the physical presence of the expert (Liao, 2005, Tasso and Guida, 2014). Possible inputs to an Expert System are, of course, the experts themselves, but also other data sources, such as written instructions, journals and articles. A recent definition of Expert System is:
“An expert system can be defined as a set of programs that use the human expertise as knowledge which is stored in an encoded form and may manipulate it to solve problems in a specialized domain. An expert system’s knowledge must be coded and stored in the form which the system can use in its reasoning processes performed by the inference engine.” (Patel et al., 2012)

A basic designation of an Expert System is to use the collected and digitalised knowledge to solve multifaceted problems through reasoning. The knowledge can be represented by “if–then” rules. An Expert System can handle intricate decision-making logic merged into Expert System rules which have been derived from large datasets that cannot possibly be handled by any human. The following basic example uses three input variables/conditions to generate disassembly instructions on a screen for an operator (Table 2). The three variables are:

- The time elapsed during current task
- The competence level of the active operator (beginner, skilled, expert)
- Level of disassembly (top cover on/off)

The main motivation for an Expert System is that human experts are a scarce and expensive resource. In addition, the individual human expert can only appear in one place at a time. By using an Expert System, it is possible to have unlimited access to the expert’s knowledge and utilise it in multiple places and for a diversity of problems at the same time. The expert then has the time to focus on specific problems, thus obtaining more and deeper knowledge. Expert systems have been used for various industrial cases. An Expert System designed and developed to help in the process planning of a CNC turning centre is presented in Prasad and Chakraborty (2015). It facilitates and automates the process of evaluating and choosing among a large number of alternatives with conflicting criteria. Expert system technology is also used for fault diagnosis, as well as the analysis and improvement of different industry sectors (Olugu and Wong, 2012, Huang et al., 2013, Laureano-Cruces et al., 2015).

Table 2. The three first rules of the Expert System example above.

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<th>Condition</th>
<th>Condition</th>
<th>Condition</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seconds</td>
<td>Competence</td>
<td>Top Cover</td>
<td>Render</td>
</tr>
<tr>
<td>&lt; 15</td>
<td>is beginner</td>
<td>is on</td>
<td>Basic text instruction</td>
</tr>
<tr>
<td>&lt;= 30</td>
<td>is beginner</td>
<td>is on</td>
<td>Detailed text instruction</td>
</tr>
<tr>
<td>&gt; 30</td>
<td>is beginner</td>
<td>is on</td>
<td>Detailed text instruction + Simple animation</td>
</tr>
</tbody>
</table>
Previous research has touched on the idea of using Expert System technology to generate dynamic information for Augmented Reality applications, but to my knowledge Expert Systems have not previously been used to make dynamic information available to individual users of an Augmented Reality application. One early study discussing a teaching application using Expert System generated instructions is Hajovy and Christensen (1990). The developed system individually customises the teaching instructions instead of using static text. Strategies on how adaptability can be implemented in an Expert System through feedback from the users were explored in Pan (2000). The developed strategies of an adaptive Expert System created and adjusted its rules in real-time. However, neither Hajovy and Christensen (1990) nor Pan (2000) merged any Augmented Reality technology with an Expert System. A study discussing expert knowledge, though not an Expert System, in relation to Augmented Reality technology is Wiedenmaier et al. (2003). It compares the time needed to complete an industrial assembly task when the shop-floor operator uses either paper instructions, guidance from an expert or an Augmented Reality application. The Augmented Reality application in the study only provided static information. It could be concluded that the longest time required to complete the assembly task was when the operator used the paper instructions. Less time was required when the Augmented Reality application with static information was used. The shortest time period was when the operator was guided by an expert present at the site. An aircraft maintenance system using a mobile device with an implemented Expert System and a user interface based on Augmented Reality technology is presented in Golański et al. (2014). The system uses mobile devices with built-in cameras, such as a tablet or a smart phone. When an image is viewed through the camera, the Expert System displays Augmented Reality information on the screen. Tests indicate substantial possibilities, but also a problem, since one of the user’s hands is occupied with the device.
4.4 Conclusions and key results
Decision support systems are not an emerging topic in production industry research. Several decision support systems are operating at various organisational levels, but as indicated in the research literature, the major approach has been from an Information System point of view. On the occasions that researchers have approached production systems, the focus has mainly been on the shop-floor managers, few of the reported decision support systems aim at the needs of the shop-floor operators.

The situation on the shop-floor limits the time available for decision-making. The shop-floor operator needs adaptive and dynamic decision support to facilitate productivity. By using the built-in cameras, smartphones and tablets can implement Augmented Reality technology which combined with Expert Systems enables the users to access expert knowledge independent of time and place. When Augmented Reality is used together with Expert Systems, it enables dynamic and adaptive information to be shown to the individual shop-floor operator, thus facilitating, e.g., the quality of output, as well as time to learn and finish a task.

An appraisal of the research literature and the reported industrial implementations of decision support systems, Augmented Reality, and Expert Systems indicates the following key results:

- The research literature indicates a lack of research and development, facilitating an adaptive and dynamic shop-floor decision support system.
- The research literature indicates that the user interface of a shop-floor decision support system should be portable, being close to the operator.
- Merging expert knowledge with Augmented Reality technology enhances the shop-floor operators’ decision process, facilitating, e.g., increased quality and a decrease of learning time and cycle time. However, Augmented Reality needs further research before implementation in industry applications.

The dynamic shop-floor with stochastic events negatively affecting the production system indicates a need of dynamic and adaptive decision support in real-time for shop-floor operators. This can potentially be addressed using technologies such as: Function blocks, Augmented Reality and Expert Systems. These technologies can together form a framework facilitating shop-floor decisions. Such a framework is discussed in the following Chapter.
5 A framework enabling adaptive decision support and adaptive system control

The literature review demonstrates that a dynamic and adaptive decision support is needed on the shop-floor, which in turn requires adaptive control of the processes at hand. This Chapter introduces a framework that uses technologies, such as Function blocks, Augmented Reality and Expert Systems, forming the Adaptive Decision Support System for shop-floor operators.

This Chapter further discusses the conceptual design of the framework, its main components, as well as the possibilities and limitations of such an approach. In the subsequent two Chapters, the framework is further developed and evaluated through test cases. Chapter 6 presents test cases that evaluate adaptive instructions to shop-floor operators, using Augmented Reality. In Chapter 7, a consideration of the whole framework is undertaken in the presentation of a test case with adaptive operator instructions and adaptive system control including online path optimisation for guided vehicles.

5.1 Introduction

During the interviews with the managers and evidenced in the research literature, the demands on future shop-floor operators are expected to expand, both in scope and complexity. The future shop-floor will have even more intensive information and data flows to process than today, therefore, possible responses and actions from the shop-floor operators need to be considered, decided and acted upon within a short period of time. It is anticipated that shop-floor decision support systems able to adapt to the dynamic environment on the shop-floor will be needed. A recurrent theme during discussions with industrial partners was:

In the engineering department we know how to run the production system and what decisions need to be made and when, thanks to simulation models and multi-objective optimisations made. But how can we transfer this knowledge to the operators on the shop-floor? In what way is it possible to support shop-floor operators in making decisions for optimal productivity when the production system calls for action at several locations?

A typical situation illustrating this is shown in Figure 26.
When implementing a decision support system, an organisation can benefit in several areas, depending on the focus of the system. Five common focuses of decision support systems are listed by Power (2002). No decision support system in the research literature, to the author’s knowledge, claims to perform in all the five listed categories:

- Improve productivity
- Improve decision quality
- Support interpersonal communication
- Improve skills in decision-making
- Increase organisational control

The proposed framework focuses on the first two categories but is designed to also support the other three. The framework enables increased productivity and decision quality by facilitating shop-floor decisions based on adaptive and online technologies, such as function blocks, Expert Systems and Augmented Reality. By implementing portable ICT devices, the proposed framework facilitates interpersonal shop-floor communication which, together with online production status and online planning, facilitates an increase in organisational control. As indicated in the research literature, a combination of Augmented Reality and Expert System technologies, especially for inexperienced users, is able to facilitate the learning process and improve the individual’s knowledge and decision-making.
The gap indicated in the research literature and confirmed by industry practitioners provides the foundation of a research programme for the purpose of realising a conceptual design for a function block-based decision support system for shop-floor operators, including adaptive system control.

5.2 Conceptual design of the Adaptive Decision Support System
The Adaptive Decision Support System provides the right operator with the right information at the right time in a dynamic production environment. The research literature and interviews with managers have indicated that a decision support system should do more than just visualise static information on forthcoming events. Adaptability is a key feature, for example, a decision support system must be able to adapt to actual situations on the shop floor, as exemplified by the following: Which operators are available? What events require action? Is production behind or ahead of schedule?

If interaction with the shop-floor operator is considered as one end of the Adaptive Decision Support System, the other end would be the interaction with the machines and equipment forming the physical production line. The Adaptive Decision Support System also includes functionalities controlling the production line, Adaptive system control.

The conceptual design of the framework has four generic modules, three of which implement distributed function block technology, namely: Adaptive system control, Adaptive decision logic and the Operator device (Figure 27). The fourth module, Dynamic position data, is only briefly covered in this dissertation, since its development has not been managed by the author of this dissertation and it has not been developed using function block technology. The conceptual design implements the three level system previously described in Chapter 2. The three level system is further described in Figure 28 and Sections 5.3 - 5.5.
5.2.1 Dynamic position data

The interviewees (Chapter 3), supported by the research literature, predict that extensive demands will be faced by future shop-floor operators. These demands include flexibility, extended skills and the ability to operate over a large area handling a variety of operations and machines. Furthermore, the locations of shop-floor operators, truck deliveries of supplies and parts, as well as other joint resources in the production premises, are important variables when handling information and assigning tasks. This requires that the positions of shop-floor operators are tracked online, creating requirements for a positioning system.

Figure 27. Conceptual design of the proposed framework.
While there are commercial indoor positioning systems available on the market, none of them tackle the challenges of the shop-floor (Syberfeldt et al., 2016a).

The module Dynamic position data uses the Operator device. A smart phone application has been developed using four parallel measurements:

- Bluetooth 4.0 RSSI (Received Signal Strength Intensity)
- WiFi RSSI
- Inertial measurement unit
-Geomagnetic field

The readings from the operator’s device are continuously sent by UDP/IP to a computer. It processes the readings using metamodels to compute the positions. Initial tests, both in office environments and on shop-floors during production, show that the module Dynamic position data is able to position the Operator’s device within one meter (Syberfeldt et al., 2016a).

5.2.2 Production management system

Generally, a Production management system handles high level production data, such as production plans, internal logistics, inventory, order tracking and customer data, e.g., data from the production plan, which holds information on the kinds of products to manufacture and when, is transferred to the production system. A Production management system is commonly also able to handle alarm distribution, availability calculations, system monitoring, etc. Examples of production management systems can be found in Meridou et al. (2015) and Rajendrakumar et al. (2015). The functionality, setup and capabilities of the Production Management System is well outside the scope of this dissertation and therefore not further discussed.

5.3 Adaptive system control

System control is the origin of the two standards, IEC 61131 and IEC 61499. The function block technology addresses demands of adaptability and flexibility, not met through IEC 61131, enabling a distributed control system that facilitates interoperability, reconfigurability and portability (Lewis, 2001). The scope of the module Adaptive system control can be regarded as the domain originally covered by the IEC 61499 standard, an industrial process measurement and control system.
The module Adaptive system control is the part of the proposed Adaptive Decision Support System that interacts closely with the physical production line. It constitutes the Operation layer of the three layer structure (Figure 28) and shares the function block network, data and information with the other modules of the Adaptive Decision Support System. The function block network is distributed to controllers and other devices such as sensors and actuators. The Adaptive system control also communicates with and processes data from the Production management system and other shop-floor systems.

Figure 28. Conceptual design of the distributed function block network of the Adaptive Decision Support System.
Adaptive decision logic

The module Adaptive decision logic of the framework comprises the major parts of the function block network. It communicates with the module Dynamic position data and external systems. The Adaptive decision logic constitutes the Process layer of the three layer structure and binds together the operator devices in the Interface layer with the production equipment in the Process layer. High level processing, such as alarm handling, production planning and process optimisation, is done by the module Adaptive decision logic. This Section also includes a description of how alarm handling, by using decision rules, has been implemented through the module Adaptive decision logic. In addition, Chapter 7 includes a test case implementing multi-objective optimisation.

During the work developing the framework with shop-floor operators, they claimed the importance of enabling the users to influence the system (Holm et al., 2014a, Holm et al., 2014c). The shop-floor teams should be able to decide how, e.g., incoming alarms should be handled and by doing so influence the behaviour of the Adaptive Decision Support System for their own team. Possible options could depend on:

- The production status – behind or ahead of schedule
- The competence of the individual operators
- The distribution of competence levels throughout the team
- The operator nearest to the origin of an event calling for action

These possible options were interpreted into decision rules enabling the shop-floor teams to steer how incoming events, such as alarms, should be processed.

An incoming event arriving at the Adaptive decision logic is processed and available operators are obtained. According to the selected decision rule, the operator is chosen to handle the event. The chosen operator is acknowledged through the Operator device and can either accept or decline the assigned task. The reply from the chosen operator is sent back to the Adaptive decision logic and processed accordingly. An example of the process flow for an incoming event is depicted in Figure 29. The example includes the two decision rules “Competence matrix” and “Chosen Operator”. Decision rules other than the two included in this example have been discussed, but these two emerged as the most requested ones.
5.4.1 Decision rule – Competence matrix

This Subsection explains the functionality of the decision rule Competence matrix used to process incoming events such as an alarm (Figure 29). A competence matrix, placed in the module Adaptive decision logic, holds information about the level of competence of all the shop-floor operators for each operation (Op10, Op20 etc.). The more training and experience each operator has, regarding every operation (production options, ability to handle alarms, maintenance etc.), the higher the number in the matrix. The competence matrix in Table 3 is an example of how it is organised at Volvo Cars Engine in Skövde.

Table 3. Example of a competence matrix. 1- Low competence; 3 – High competence.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator #1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Operator #2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Operator #3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Operator #4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Operator #5</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Data from the competence matrix, together with the actual production status, is used when executing the decision rule Competence matrix. The output from the decision rule, what operator to assign, depends on the information in the competence matrix and whether production is behind, on, or ahead of the production plan.

An example of settings for the decision rule Competence matrix is given in Figure 30 (left). The team leader, who is responsible for the settings, chooses the production line and the team ①. In addition, the team leader sets the production status ② regarding when different levels of competences should be considered ③. Since more than one operator is likely to have the competence level required, an additional rule is enabled, in this example a rule called the Nearest operator ④. The rule Nearest Operator uses information from the module Dynamic position data to find the operator nearest to the origin of the event at hand.

The output from the decision rule Competence matrix, with settings as the example in Figure 30, when an event occurs and production is on schedule, will be the nearest operator with a competence level of 2 or 3 regarding the operation generating the event. If the chosen operator declines the task, the second nearest operator is assigned.

---

Figure 30. Examples of settings for decisions rules "Competence matrix" and "Chosen operator".

<table>
<thead>
<tr>
<th>Line B – Team B3</th>
<th>Competence matrix</th>
<th></th>
<th>Chosen operator</th>
<th>Team number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use operator with at least level</td>
<td>+3</td>
<td></td>
<td>Göran Ekbladh</td>
<td>Line A – Team A1</td>
</tr>
<tr>
<td>When ahead of plan with xx units/hour</td>
<td>+2 / -1</td>
<td>2</td>
<td>Adam Eriksson</td>
<td></td>
</tr>
<tr>
<td>When according to plan</td>
<td>&gt;-2</td>
<td>3</td>
<td>Tuuva Liilja</td>
<td></td>
</tr>
<tr>
<td>Additional rule</td>
<td>Nearest operator</td>
<td>Nearest operator</td>
<td>Operation Op10-Op30</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Operation Op40-Op70</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Operation Op80-Op90</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Operation Op110-Op140</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Operation Op100</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Additional rule</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nearest operator</td>
<td></td>
</tr>
</tbody>
</table>

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5.4.2 Decision rule – Chosen Operator

The decision rule Chosen operator is more straightforward and simpler, compared to the rule Competence matrix. After setting the production line and the team, the operators are assigned to predefined working areas (Figure 30, right). An incoming event is processed by the Adaptive decision logic and the operator assigned to the working area generating the event is delegated to handle the task.

The output from the decision rule Chosen operator, with settings as the example in Figure 30, when an event occurs at operation 90, will be Nellie Gahari. Also, the decision rule Chosen operator can use an additional rule (set by the team leader). If the additional rule Nearest operator is enabled and the chosen operator declines the task, the second nearest operator is assigned.

5.4.3 Evaluation of decision rules

At the Volvo Car Engine plant in Skövde, a Voice message system is presently used in some sections of the production line. When an event (an alarm) occurs, the shop-floor operators within the actual working area are acknowledged by a voice message. The voice message is transferred through “walkie-talkies”, which are used as operator devices. The Voice message system uses one way communication. A pre-recorded voice message is transmitted to the devices used by the shop-floor operators. However, the Voice message system does not receive any acknowledgment from the shop-floor operators whether and when any operator accepts the task.

To evaluate the Adaptive decision logic and the decision rule Competence matrix, they were compared to the Voice message system installed at site. A model was built since it was impractical to gain access to the real production line. Simulations were made implementing both the Voice message system and the Adaptive decision logic applying the decision rule Competence matrix measuring the throughput of the modelled production line.

The simulations indicated that the Adaptive decision logic implementing the decision rule Competence matrix performed significantly better than the Voice message system. The throughput using the Adaptive decision logic was 5-9% higher compared to the Voice message system. The evaluation of the Adaptive decision logic using the decision rule “Competence matrix” is presented by the author in Holm et al. (2014a) and in Holm et al. (2014c). The Adaptive decision logic implementing multi-objective optimisation is further discussed and evaluated in a test case presented in Chapter 7.
5.5 Operator device

The operator device processes and handles information to/from the Adaptive decision logic and displays instructions and information to the shop-floor operator. Such devices need both computing power and some kind of display. The proposed framework uses Augmented Reality merged with the Expert Systems technology enabling adaptive information to support shop-floor decisions. This part of the framework is referred to as ARES (Augmented Reality Expert System). The ARES is part of the Operator device (Figure 27).

5.5.1 The ARES

The research literature indicates that a system which individually and dynamically customises the content of information presented will have a higher impact compared to a static system, thereby increasing the efficiency of the shop-floor operator. However, to tailor dynamic instructions to individual users is not easy. Determining what task-specific information to give to each individual user, in what form, at which moment in time, as well as what information not to show, must be done online. The individual user’s prior experience and current skill level drive the level of details of the given instructions required by the user, in order to learn and, with adequate quality, complete the task at hand in the shortest possible time (Kirschner et al., 2006).

The ARES provides the user with individualised and enhanced information for each specific task. Such support enhances the shop-floor operators’ ability to learn and master tasks, compared to an approach that uses predetermined and static information (Wiedenmaier et al., 2003). In addition, using graphical information reduces the users’ mental workload, compared to text-based information (Speier and Morris, 2003).

The Expert System of ARES determines the content of the information displayed (what to show and when to show it), while the Augmented Reality part controls the user interface and displays the information. The overall design including the exchange of information within the ARES is shown in Figure 31.
The Augmented Reality of the ARES system is developed using the software Unity 3D and the software developing kit, Vuforia, has been used for the realisation of the Augmented Reality functionality. Vuforia can implement vision technology for the recognition and image tracking of targets and 3D-objects in real time. It uses the camera of the mobile device for feature recognition and orientates virtual objects in relation to objects in the real world. The viewer can, no matter the device’s position, see the virtual objects aligned with the real world on screen.

The rendering of the Augmented Reality features is determined by the Expert System rules in real time. The implemented Expert System rules in the ARES are written using the OpenRules format (Appendix 3). The Expert System rules are dynamically analysed in real time, which updates the information content of the Augmented Reality system. The knowledge in the Expert System is derived from a human expert who uses an ordinary spreadsheet programme to define the Expert System rules (Appendix 3). Through this approach, Expert System rules can be created, changed and extended without reprogramming.

5.5.2 Dynamic instructions enabled by ARES

When implementing ARES, a device with a camera and some kind of display is used. Through the camera, the anchor for the augmented reality functionality is found. The graphical Augmented Reality objects are then shown on the display, positioned according to the anchor. A set of rules implemented in the ARES application steers what kind of information and how it is presented. An example of such rules are given in Table 2 (in Chapter 4). Basic examples of ARES implemented in a tablet are shown in Figure 32.
The basic example (using a tablet) in Figure 32 shows parts of the instructions for performing maintenance on a battery placed in the grey box. The Expert rules steering the application are set according to the elapsed time. The initial instructions given are general high-level instructions (top left). If the instructions are not performed within the set time, additional, more detailed instructions are given (top right). If still more detailed instructions are required (elapsed time), graphical Augmented Reality objects (green arrows and image of screwdriver) are visualised on the screen. The ARES and adaptive shop-floor instructions are further discussed and evaluated in Chapter 6.

5.6 Conclusions and key results
It is predicted that the future shop-floor’s working environment will be intensive and pressurised. An increasing number of intelligent devices will produce large amounts of data, and operators will need decision support to process and handle the available data into manageable information and instructions, within a limited amount of time. The framework proposed focuses on the needs of the shop floor operator and is able to be customised at a team level and, in some cases, at an individual level.
The module Adaptive Decision Logic implements a rule base, facilitating decision-making on the shop floor. The decision rules not only enable the users to steer how incoming events are processed in the Adaptive Decision Support System. They also eventually increase the operators’ acceptance of the system, thus meeting their requirements to not only be steered by the system but also to be able to steer the system themselves.

The appraisal of the framework proposed indicates the following results:

- The framework enables dynamic and adaptive decision support for operators in an intensive shop-floor environment that industry requires.
- The framework enables increased productivity and decision quality, by facilitating shop-floor decisions on the basis of adaptive and online technologies. Interpersonal shop-floor communication is facilitated by implementing portable ICT devices which, together with real-time production status and online planning, facilitate an increase in organisational control. The framework facilitates the learning process and improves the individual’s knowledge and decision-making.

The framework proposed, implementing ARES, is further discussed and evaluated in Chapter 6. A test case embracing the whole framework, with adaptive operator instructions and adaptive system control including online path optimisation for guided vehicles, is presented and evaluated in Chapter 7.
6 Dynamic shop-floor instructions using Augmented Reality

This Chapter evaluates the Operator device of the Adaptive Decision Support System implementing the ARES presented in Chapter 5.

6.1 Motivation
The work presented in this Chapter originated at an existing quality control station at one of the production lines of the Volvo GTO Powertrain site in Skövde, Sweden. At this quality control station, the shop-floor operators regularly perform a sequence of measurements to verify the quality of the preceding machining tasks. The station uses a spreadsheet-based system for instructions during the measuring sequence. Volvo GTO Powertrain had indicated that the shop-floor operators approached the quality station and its tasks differently, depending on their level of experience. Due to this variance, two shop-floor operators were asked to participate in an experiment. One of the operators is regarded as an expert, with many years’ experience and the other is a relative novice, with little experience. Both of them performed the same quality control sequence at the station. Afterwards, both operators were interviewed regarding the approaches they adopted.

It became obvious that the novice and the expert approached the same quality control sequence quite differently. The novice worked his way through the spreadsheet-based control instructions step-by-step, performing the exact sequence as intended by the author of the instructions. The novice often went back to read the instructions again and to check the correct reference data, what tool to use, etc. The expert, however, knew the instructions from memory and only looked at them if and when any problems occurred. The sequence given in the instructions was not followed by the expert, rather, the measurements were performed in another sequence and no measurement was omitted. When the participants’ colleagues were asked about these two different approaches, they confirmed them and stated that the approaches were representative of the two groups of shop-floor operators, namely, novices and experts.

This led to the following question: Could some other system or arrangement be used for the delivery of instructions, in order to enhance primarily quality, but also productivity? The module Operator device of the Adaptive Decision Support System was consequently tested and evaluated according to the question.
6.2 Research method
The research programme proposed needed a method of assessing the capability of Augmented Reality including possible ICT-devices to support the delivery of dynamic decision-making in a shop-floor environment.

The Chapter comprises three studies that were undertaken:

1. Test and evaluation of smart glasses for ARES
2. Test and evaluation of the current system of providing measurement instructions in the production system
3. Test and evaluation of the Operator device of the Adaptive Decision Support System implementing ARES, in comparison with the results from the existing system (test 2 outlined above).

The production line at Volvo GTO Powertrain is run over two shifts daily, which strictly limits access to the real quality control station for the purpose of conducting tests directly at this station. The best option was to build a demonstrator emulating the actual quality control station and establish scenarios that could be investigated via test cases. Details of the demonstrator are given later in this Chapter.

Of the research methods considered, experiments were rejected due to the ambition to simulate a real-world environment. Mathematical modelling was also rejected for the same reasons. The usability, productivity and quality achievable were all investigated and evaluated. To measure usability, the SUS questionnaire (see Section 6.3) was used, rather than Focus groups. The SUS questionnaire is a well-established method and much less time is needed, compared to Focus groups. To measure productivity (time to finish the task) and quality (number of errors made), the Observations method was chosen. Interviews were also used to investigate the work undertaken at the real quality control station at Volvo GTO Powertrain.
Since the users of the Adaptive Decision Support System are anticipated to be representative of future shop-floor operators, students from a technical high school were chosen to participate in test case II and test case III. Forty three students from three classes (17 and 18 years old) participated in test case II and test case III. Each participant performed the study individually and received the same information prior to the start of the study. In presenting the results from the interviews and observations in this Chapter, anonymity was used to avoid any possible tracing of the sources of the results. If some of the participants of these studies also participated in the studies presented in Chapter 2, it is unknown. The three studies are further on in this Chapter referred to as test case I, test case II and test case III.

6.3 **Measuring usability**

A key factor for success of any system is the level of acceptance and perceived effectiveness (Ben-Zvi, 2012) from the ones using the system, in this case the shop-floor operators. However, high usability does not compensate for low productivity or low quality output. All three test cases measure the usability. Usability tests are often accomplished by selected users (as representative as possible of the planned users of the system). In measuring usability and analysing the results, it is important to remember that measuring is done relative to the chosen group of users within the specified scope of tasks. Another combination of users and tasks could evaluate the same system and come to a different outcome (Bangor et al., 2008, Bangor et al., 2009, Kortum and Bangor, 2013).

A definition of usability divided into five basic dimensions is presented in Nielsen (1994):

- **Learnability** – The user should be able to learn the system easily and begin to work it quickly;
- **Efficiency** – Once the system has been learned, the user should be able to reach a high level of productivity;
- **Memorability** – Also a casual user who has learned the system should easily remember how to use it without needing to go through the learning process again;
- **Errors** – The error rate of the system should be low and recovery after mistakes made by the user should be easily completed. In addition, errors with catastrophic consequences must not be possible;
- **Satisfaction** – Using the system should be pleasant and liked by the users.
The first and possibly the most fundamental dimension of usability is learnability, since any system initially requires that users learn how to use the system (Grossman et al., 2009). A well-established, inexpensive, but yet effective tool for assessing usability is the System Usability Scale (SUS) (Brooke, 1996). It has been used to assess a broad variety of services and products for a long time. The SUS method uses a questionnaire with ten questions (Appendix 4). The odd-numbered questions express positive experiences and the even-numbered express negative experiences. The questions are answered using a five point scale ranging from 1 (Strongly disagree) to 5 (Strongly agree). The resulting SUS score, ranging from zero (worst) to one hundred (best), is calculated according to a specific formula (Brooke, 1996). Despite the similarity, the values of the SUS scale are not percentages. The SUS scale can be divided into two rough categories: below 70 and above 70. Several thousand evaluations using SUS for a broad variety of products and systems have shown that a product or system with a SUS score below 70 usually has reasons for concern regarding its usability (Brooke, 1996, Bangor et al., 2008, Bangor et al., 2009, Kortum and Bangor, 2013). Conclusions from these studies show that usability results from SUS are reliable. The SUS results are not biased by gender, and there is only a minor correlation between age and the SUS score (the SUS score slightly decreases with increasing age). The SUS questionnaire used was translated into Swedish.

6.4 Test case 1 – ICT-device for the Operator device
The first test case evaluated the available hardware to be implemented as the Operator device of the Adaptive Decision Support System.

6.4.1 ICT-devices to be tested
The shop-floor operator using the Operator device of the Adaptive Decision Support System will wear or carry the Operator device during work, limiting its size and weight. The Operator device implementing ARES must have some sort of display presenting information to the shop-floor operator. Based on these conditions, the following requirements were set for choosing, testing and evaluating hardware for the Operator device:

Requirement #1 - Ability to display information to the operator on the shop-floor.
Requirement #2 - Size and weight appropriate to wear or carry during a full working day (preferably a mobile solution not occupying the hands of the user).
Requirement #3 - Implementation of ARES.
Table 4. Available categories of ICT-devices and requirements for test case I.

<table>
<thead>
<tr>
<th>Category of ICT-device</th>
<th>Requirement #1</th>
<th>Requirement #2</th>
<th>Requirement #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Usual” computer</td>
<td>Yes</td>
<td>No, too heavy and too large</td>
<td>----</td>
</tr>
<tr>
<td>screen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile PC</td>
<td>Yes</td>
<td>No, too heavy and too large</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tablet</td>
<td>Yes</td>
<td>Yes, eventually too large</td>
<td>To be tested</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smart glasses</td>
<td>Yes</td>
<td>Yes</td>
<td>To be tested</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smart phones</td>
<td>Yes</td>
<td>Yes</td>
<td>To be tested</td>
</tr>
</tbody>
</table>

The available ICT-devices (Table 4) meeting requirements 1 and 2 are the three categories: smart glasses, tablets and smartphones. Tablets and smartphones can be considered as one category with regard to implementation of ARES, both have a screen and a camera, only the size is different. The category of available ICT-devices best meeting the requirements is the smart glasses, since they do not occupy the hands of the user.

Four glasses have been evaluated as possible Operator devices for the Adaptive Decision Support System. These four (Figure 33 and Table 5) are:

1) Google glasses from Google. They have a small screen to the upper right.
2) Mod Live. A small display developed for sports practitioners like cyclists and skiers.
3) C Wear from Penny. The displayed information is directly reflected into the iris of the right eye.
4) BT-200 from Epson. By projecting the information through prisms in the thick glass the information is projected to both eyes.
Figure 33. Glasses evaluated for the Operator device.
(Upper left – Google glasses; Upper right – Mod Live, to be mounted in ski googles, etc.;
Down left – Penny; Down right – Epson Moverio BT-200)

The information displayed by both Google glasses and Mod Live is not in the direct line of sight of the user, thus users must drop their gaze to absorb the displayed information (Figure 33). Further drawbacks are that the development of Google glasses has been terminated by Google and that the display of the Mod Live can only handle simple and limited text besides information such as bars and diagrams. Mod Live cannot implement any camera functionality. As such, further evaluations of these two glasses were not considered.
Table 5. Technical data for smart glasses.

<table>
<thead>
<tr>
<th>Model</th>
<th>Weight</th>
<th>Resolution of screen</th>
<th>Virtual image size</th>
<th>Camera in glasses</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epson Moverio</td>
<td>96 grams</td>
<td>960*540</td>
<td>40 inches 2.5</td>
<td>Yes</td>
<td>Needs additional device (looks like a smart phone). In line of sight.</td>
</tr>
<tr>
<td>Google glass</td>
<td>~70 grams (depending on model)</td>
<td>640*360</td>
<td>25 inches 2.5</td>
<td>Yes</td>
<td>Not in line of sight. Not sold any more</td>
</tr>
<tr>
<td>Mod Live</td>
<td>65 grams</td>
<td>428*240</td>
<td>11 inches 1.5</td>
<td>No</td>
<td>Needs to be mounted on ski glasses or similar. Not in line of sight.</td>
</tr>
<tr>
<td>Penny</td>
<td>~100 grams (depending on model)</td>
<td>875*500</td>
<td>70 inches 2.1</td>
<td>No, option</td>
<td>Needs additional device. In line of sight.</td>
</tr>
</tbody>
</table>

Both the glasses from Penny and those from Epson display information in the direct line of sight and the area available for displaying information covers a considerable amount of the whole field of view (Table 5). The two glasses use an external device that both powers the glasses and handles computing requirements. The Epson glasses have an in-built camera, but its field of view is so narrow that it cannot be used for image tracking in an industrial setting. The Penny glasses do not have a built-in camera, but can use an external one connected to the additional device. The glasses from Epson and Penny were used in test case I. Due to the limited camera functionality only static instructions were used in test case I.
6.4.2 Demonstrator used for test case I

The demonstrator used in the first test case was an engine block from Volvo GTO Powertrain that had been put on a manual lifting table (Figure 34). The participants in test case I performed a sequence of measurements in the marked area (Figure 34).

The total measurement sequence consisted of nine pictures and a total of twelve measurements to be taken. Examples of the instructions are shown in Figure 35. The background of the pictures is dark, since the black colour becomes transparent in the glasses. The participants themselves paced through the pictures by pressing a button on an external device.

![Figure 34. Demonstrator used in test case I.](image-url)
6.4.3 Results from test case I

The participants performed test case I using either the glasses from Penny, 21 participants, or from Epson, 22 participants. Each was given the same information about the test case prior to starting. During the taking of the measurements, the test leader observed the performance of the participants, counting any errors made. After finishing the measurement sequence, the participants answered the SUS questionnaire.

The SUS score for both glasses ranges from very low to very high SUS values. The glasses from Penny received an average SUS score of 66 and those from Epson had an average SUS score of 71. A boxplot of the SUS scores is shown in Figure 36. The average SUS score for Epson is on the edge of being considered adequate, while the average SUS score for the Penny glasses is low; however, the individual participants assess the glasses very differently.
The test leader observed the participants during the test case. If they made any incorrect measurements or missed a measurement, it was considered an error. The total number of errors for each participant was added together and the results are shown in Figure 37. Only half of the participants, valid for both Penny and Epson, managed to execute all the measurements without any errors. The obtained usability levels and the number of errors made indicate a need of improvements.

Furthermore, none of the four glasses are able to implement dynamic Augmented Reality information in the main, due to limited camera capability. Thus, the conclusion is that the glasses present a promising technology but are not currently suitable for industrial applications. Therefore, as devices for the operators, the best option to pursue with current technology is tablets or smart phones.

Figure 36. SUS score for the glasses from Penny and Epson.

An “x” indicates a single data point.
Tablets and smart phones have proven to have enough computing power and include an embedded camera that can enable Augmented Reality applications. It is, however, recognised that tablets have associated drawbacks, such as size and weight (compared to glasses), and that the users often need to drop their gaze when looking at the screen (Syberfeldt et al., 2016c). Smart phones have the same drawbacks as tablets and, although they are smaller and lighter than tablets, they also have smaller screens. Due to the size of the screens, the implementation of ARES for an Adaptive Decision Support System is further considered using tablets.
6.5 Introduction to test cases II and III
Test cases II and III investigate instructions presented to pseudo shop-floor operators using the Operator device of the Adaptive Decision Support System, where the instructions given are modified in response to contextual information. The test cases cover five aspects which, when summated, distinguish them from other reported studies using Augmented Reality:

- **Focus on both usability and performance**
  Enhanced effectiveness (i.e. quantitative results) is the focus of a majority of existing studies on Augmented Reality. These studies do not take usability into account (Dünser et al., 2008). This dissertation’s study, however, investigates the usability and also takes into account the achieved level of productivity and quality.

- **Focus on users with little or less experience**
  All the participants in this study have less than one month experience of shop-floor work. This is motivated by the fact that operators with little experience are the ones who benefit the most when using Augmented Reality, from a training perspective.

- **Focus on future shop-floor operators**
  The participants in this study are high school students who are presumed to be potential future shop-floor operators. They have a general high acceptance of integrating ICT in every-day life, including their future working hours.

- **Focus on test cases that can readily be reproduced for future benchmarking purposes**
  The demonstrator used in the test cases can easily be replicated and used for future benchmarking, or evaluations.

- **Focus on inexpensive, off-the-shelf consumer hardware**
  The presented ARES uses inexpensive consumer products that can be bought in any electronic store at a low price.

6.5.1 Pre-test of demonstrator for test cases II and III
A pre-test of the demonstrator set-up was carried out to ensure that the working procedures could be performed in a similar way to those at the Volvo GTO Powertrain quality control station. A demonstrator, together with the tools needed, computer, etc., synthesising the actual quality control station, was built in order to perform the pre-test and test cases II and III without disturbing the in-plant production. An engine block from the real production line was placed on a lifting table and a sequence of measurements (approx. 15% of the whole quality control sequence) was chosen. The measuring sequence of 14 different measurement
tasks was used, both for the pre-test and for test cases II and III. The measurement instructions used for the pre-test and test case II are shown in Figure 38. The steps A1-A3 and B1-B2 include one measurement task each, while the steps A4-A6 include three different measurement tasks each (Table 6).

Table 6. Sequence of measurements

<table>
<thead>
<tr>
<th>Step</th>
<th>Measurement</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Diameter 21 mm</td>
<td>Gauge</td>
</tr>
<tr>
<td>A2</td>
<td>Diameter 21 mm</td>
<td>Gauge</td>
</tr>
<tr>
<td>A3</td>
<td>Diameter 21 mm</td>
<td>Gauge</td>
</tr>
<tr>
<td>A4</td>
<td>Diameter 147 mm</td>
<td>Calliper</td>
</tr>
<tr>
<td>A5</td>
<td>Diameter 139 mm</td>
<td>Calliper</td>
</tr>
<tr>
<td>A6</td>
<td>Depth 10.5 mm</td>
<td>Calliper</td>
</tr>
<tr>
<td>B1</td>
<td>M8 threads</td>
<td>Gauge</td>
</tr>
<tr>
<td>B2</td>
<td>M8 threads</td>
<td>Gauge</td>
</tr>
</tbody>
</table>

Figure 38. Measurement instructions (in Swedish) used in the pre-test and test case II.

The thick red line indicates the end of the measurement sequence during the tests.
The tools used for the measurement sequence were a calliper and two gauges. Some wrenches were also available in the toolset. The set-up of the demonstrator (text instructions, configuration of tools, computer screen, etc.) was as similar as possible to the site situation (Figure 39). A copy of the original spreadsheet instructions (Figure 38), together with information on the locations of measurement tasks (Figure 40), was used during the pre-test.

Figure 39. Set-up for pre-test
(positions of computer, tools, etc., as on site)

Figure 40. Locations of the measurement tasks.
Eight university students, engaged for the pre-test, were given information about the measurement tasks to be performed, prior to the start of the pre-test. During the pre-test, the participants were observed by the test leader. Upon completion, they scored the usability of the instructions (the spreadsheet in Figure 38) through SUS.

The pre-test strongly indicated two areas in need of improvement: poor usability and high error rates. These two issues were primarily due to the long distance between the position of the tools and screen (displaying the instructions) and the position of the engine. The participants often had to move between the screen and the engine, due to problems with remembering the exact instructions, which negatively affected the ergonomics and the quality of the performed work. The same behaviour was indicated by the novice operator at the original quality control station. Three changes that would possibly improve the usability of the demonstrator emerged. The SUS-score of the pre-test is analysed further in Section 6.7.

6.5.2 Demonstrator used during test cases II and III
The three improvements to the demonstrator, identified during the pre-test, were implemented to eliminate the problems associated with the distance between the information carrier and the actual working position, which had negatively affected the performance during the pre-test (Thorvald et al., 2014). These improvements could also easily be implemented into the real quality control station at Volvo.

- The toolset was mounted onto an adjustable arm at the work station, so that the participants did not have to move between the computer screen and the measuring position.
- The “usual” screen was replaced by a touch screen (which makes scrolling easier compared to the original set-up with mouse and keyboard) mounted onto an adjustable arm. The screen was placed so that the operator could readily glance at the screen when working.
- Instructions clarifying measuring tasks A4-A6 were included (Figure 41).

The set-ups for each of the two test cases are further discussed in Section 6.6.
6.6 Test cases II and III

This Section describes test cases II and III. Two different information systems were used for the test cases. Test case II used the spreadsheet system from Volvo GTO Powertrain and test case III used a tablet as the Operator device implementing ARES. Test case II had 21 participants and test case III had 22 participants.

6.6.1 Set-up of test case II

Test case II used the existing instructions at the quality control station and served as a comparison to the Operator device implementing ARES in test case III. The reason for implementing the three improvements for test case II and thus distinguishing it from the set-up used at Volvo was that the original position of the screen and tools notably negatively impacted the variables to be measured, usability, productivity and quality, without it being part of the instructions. The resulting set-up for test case II after implementing the improvements is shown in Figure 42.

Figure 41. Additional instructions for tasks A4-A6 used in test case II (In Swedish).

Figure 42. Set-up of test case II.
6.6.2 Set-up of test case III

The purpose of test case III was to evaluate the Operator device implementing ARES. The measurement sequence, position of the screen and the toolset used in test case III were identical to test case II. A tablet placed in front of the demonstrator was used to execute ARES in test case III (Figure 43). The screen of the tablet holding the ARES instructions (replacing the spreadsheet instructions) was duplicated onto the bigger screen so that the position of the instructions in both test cases II and III were the same.

Three screenshots exemplifying the ARES information presented to the participants during test case III are shown in Figures 44A-C. The ARES only gives information on the present measurement task to avoid information overload and to determine that the measurements are performed in the preferred sequence. Upon finishing one task, the participant presses a button on the lower-left corner of the tablet (KLAR - Figures 44) to continue to the next measurement task. The picture mounted in front of the engine block during test case III (Figure 43) acts as the anchor used for the Augmented Reality functionality.

Figure 43. Set-up of test case III.
The screenshots (Figures 44A-C) give instructions for the measurement of the diameter of a hole for the cylinder. The green sphere indicates the position of the measurement task and, after the set time, additional basic text information is given (Figures 44B). If the user needs further time, a more detailed picture explaining the measurement together with a photo of the tool to use is rendered (Figures 44C).

The level of information content displayed to the user is controlled by an Expert system as part of ARES. The Expert system uses two input variables, elapsed time and measuring step to be performed. The Expert system rules for task A5 that generates the instructions in Figures 44A-C are shown in Table 7.

Figures 44A-C. Examples of increasing level and richness of instructions in ARES for measurement task A5.1 in test case III.
Table 7. Expert system rules of ARES for measuring task 5.1 in test case III.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Element</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seconds</td>
<td>Render</td>
<td></td>
</tr>
<tr>
<td>&lt; 5</td>
<td>A5.1</td>
<td>Basic AR-position information</td>
</tr>
<tr>
<td>&lt;= 10</td>
<td>A5.1</td>
<td>Basic AR-position information + basic text instruction</td>
</tr>
<tr>
<td>&gt; 10</td>
<td>A5.1</td>
<td>Basic AR-position information + basic text instruction + detailed picture + picture of tool</td>
</tr>
</tbody>
</table>

6.7 Results from test case II and test case III

Both the spreadsheet system and ARES prototype used during the two test cases are evaluated in this section, using the SUS score for usability and the observed execution time and number of errors incurred (incorrect or unperformed measurements) for productivity and quality respectively. The usability (the SUS-score) of the pre-test is also presented.

A boxplot of the SUS scores obtained for the pre-test, and test cases II and III are shown in Figure 45. Individual scores outside the lower extremes, so-called single data points, are indicated with “x”. The average SUS score for the pre-test only reached 55, indicating a need for improvements (scores below 70 indicated low usability). As discussed previously, three improvements were made to the demonstrator to avoid unnecessary bias during the subsequent test cases. Test case II obtained distinctly higher SUS values compared to the pre-test, confirming that the modifications made enhanced the usability. The Operator device of the Adaptive Decision Support System implementing ARES evaluated in test case III received an average SUS value of 78, compared to test case II which reached an average SUS value of 71. An observation made during the test cases was that the participants in test case II often scrolled back and forth in the document ensuring the correct information, while the participants in test case III just glanced at the screen shortly before addressing each new task.
When analysing the quality (Figure 46) of the work performed and the execution time (Table 8), the differences in output of test case II and test case III become clear. For test case II, 52% of the participants completed the measuring sequence without performing any error, 10% had one error, and while as many as 38% had two or more errors. In test case III, 68% of the participants completed the measuring sequence without performing any error and the rest, 32%, accounted for one error only. None of the participants in test case III made more than one error.
When analysing the execution times (Table 8), another advantage of the Operator device of the Adaptive Decision Support System implementing ARES was demonstrated. Even though more errors were counted during test case II (often completing fewer measurements), it took the participants longer to finalise the measuring sequence compared to test case III, where a lower number of errors occurred. The mean time (in minutes) for all the 21 participants performing test case II was 4:33, while the mean time for all the 22 participants using the ARES system was 3:47.

Only two participants in test case II had one error and one of them took a very long time to finalise the measuring sequence, which explains the high mean time. The most common error was to omit one or more measurements of the sequence, thus needing less time in total.

See Appendix 5 for all data on SUS values and Appendix 6 for productivity and quality data for test case II and test case III.

Table 8. Mean time (in minutes) for finishing the measurement sequence in test cases II and III depending on number of errors incurred.

<table>
<thead>
<tr>
<th></th>
<th>No error</th>
<th>One error</th>
<th>Two or more errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test case II</td>
<td>04:29</td>
<td>05:47</td>
<td>04:24</td>
</tr>
<tr>
<td>Test case III - ARES</td>
<td>03:49</td>
<td>03:43</td>
<td>--</td>
</tr>
</tbody>
</table>
6.8 Conclusions and key results
The Chapter has presented three test cases evaluating the Operator device of the Adaptive Decision Support System implementing ARES. The research literature identifies that the novice shop-floor operators are the group in most need of decision support during work and also during training, when they face new challenges. These findings were confirmed by operators working at the quality control station at Volvo GTO Powertrain in the analysis of the two differing approaches, applied by the novices and the experts. The novices spent a lot of time reading and scrolling the computer screen for the information needed, whilst the experienced operators knew the measuring sequence from memory, which indicates that the group in need of support, generally speaking, is the novices not the experts.

The Operator device of the Adaptive Decision Support System implementing ARES enables adaptive instructions to be delivered to individual shop-floor operators. It facilitates the individual’s learning process through its ability to dynamically adapt to the user’s level of knowledge and experience. The Operator device of the Adaptive Decision Support System implementing ARES facilitates both training options and decision support during production. It can be implemented for practical everyday use, not only for novice shop-floor operators, but also for experienced users, due to its ability to dynamically display instructions, regardless of whether they are newly introduced or changed instructions, or whether they are well-known but comprise essential information that must not be overlooked.

In order for the proposed Adaptive Decision Support System to be acceptable to users, the level of usability of the operator’s device is critical. If the users, the shop-floor operators, do not experience high usability, it will most likely not be used. Glasses which allow users to experience Augmented Reality employ a promising technology that avoids the main drawbacks of other devices. They do not occupy the users’ hands and can function in the line of sight. However, initial tests indicate that the technology is not ready for real industrial settings, due to limited camera capabilities and a wide diversity of estimated levels of usability.

The main hardware in the Operator device of the Adaptive Decision Support System implementing ARES is a tablet, which is a relatively inexpensive and standardised off-the-shelf product that enables multiple users, without overextending the budget. Using a tablet for an Augmented Reality application has advantages; most people are familiar with tablets nowadays, facilitating a high degree of acceptance and affinity. The tablet also has both a camera and a screen, thus enabling a fully functioning Augmented Reality application in one single device. However, there are some disadvantages. Using a tablet for an Augmented
Reality application either occupies one hand of the operator or, if placed on a stand as in test case III, it only covers a limited working area. If applied to larger working areas, the stand has to be moved during operations. The stand might hinder the operator’s work and, when placed on a stand, the tablet may not always be in the operator’s line of sight during working operations. Also, if a hand, arm or tool gets in the way of the camera, the virtual objects disappear, since the picture used as the anchor for the Augmented Reality functionality is no longer identifiable by the camera. The virtual objects disappear when the Augmented Reality system cannot locate the anchor.

In test case III, an additional display was used to mirror the display on the tablet. This enabled the shop-floor operator to read the instructions almost in line of sight when working. If goggles with Augmented Reality functionality could be used, they would display information in line of sight and eliminate the drawback of having to place equipment on stands with limited coverage and possibly hindering access to the work area.

The ability to position shop-floor operators online within the work area, as presented in the framework for Adaptive Decision Support System (the module Dynamic position data), enables work instructions with context-driven, dynamically adjusted content for a specific shop-floor operator at a specific workstation location. The response from Volvo GTO Powertrain to the Operator device of the Adaptive Decision Support System implementing ARES and the results achieved has been positive. It is aligned with the company’s ambition to improve decision support especially for novice shop-floor operators.

The rules of the Expert system, part of ARES, need further work to determine optimal settings, but optimising these is beyond the scope of this research study.

The results from the test cases undertaken indicate the following results:

- The study has confirmed indications from the research literature that novice shop-floor operators are the ones in most need of decision support, compared to shop-floor operators with long experience.
- Glasses implementing Augmented Reality employ a promising technology, but evaluations indicate that further development is required before such glasses can be used on a daily basis on the shop-floor.
- The Operator device of the Adaptive Decision Support System implementing ARES demonstrates better usability facilitating quality and productivity compared to the current spreadsheet-based system.
The Operator device of the Adaptive Decision Support System implementing ARES has proven to be fully functional in the performed test cases. The next Chapter continues the evaluation of the Adaptive Decision Support System with a test case that focuses proof of concept and utility. The test case subsumes the whole presented Adaptive Decision Support System, using a demonstrator emulating a production system.
7 Dynamic production plans using online path optimisation for guided vehicles

Chapter 6 considers a test case for evaluating the Adaptive Decision Support System with a main focus on the ARES Operators device. ARES facilitates adaptive and dynamic instructions to shop-floor operators, using Augmented Reality. This Chapter continues the evaluation with a test case as an assessment of the concept of the Adaptive Decision Support System as a complete entity. The test case embraces the modules previously described in terms of the Adaptive system control, Adaptive decision logic and the Operator device, with a focus on the first two entities.

The test case presented here uses a demonstrator emulating a production system with four assembly stations and two storages areas, one for incoming parts and one for finished products respectively. Furthermore, the system uses two guided vehicles to distribute material and products between the stations in the production system. The test case uses products from CEJN, a company that produces quick couplings for various media. The quick couplings used in the test case are pneumatic. All three modules of the Adaptive Decision Support System embraced by the demonstrator have been implemented using function block technology.

7.1 Research method

The research programme needed an appropriate method of assessing the concept of the Adaptive Decision Support System as a complete entity. To build and use a demonstrator that emulates assembly operations in combination with a test case was determined to be the best available method identified. The Chapter comprises one study, testing and evaluating the concept of the Adaptive Decision Support System proposed. Details of the demonstrator are provided later in this Chapter.

In cooperation with CEJN, a demonstrator and a test case were developed involving an assembly process that uses robots which work collaboratively with human operators. This demonstrator, customised for the defined assembly process and chosen CEJN products, was used for the research study, but the robots were not included. The test case developed in cooperation with CEJN as a representative system was used to evaluate the concept of the Adaptive Decision Support System.
The test case uses two modes, a real mode and a virtual mode. In the real mode, the main modules of the Adaptive Decision Support System are tested and evaluated, both separately and as a whole concept. In the virtual mode, the ability of the Adaptive Decision Support System to incorporate complex algorithms, such as the NSGA-II algorithm, to find optimal production plans, is tested and evaluated.

7.2 **Introduction to dynamic production planning**

A broad spectrum of shop-floor parameters, often random and unpredictable, affects manufacturing production outcomes, emphasising the need to dynamically plan and re-plan production schedules. In contrast, static production plans can only be optimal as long as no changes occur, which is unrealistic in such environments. Therefore, to counteract the effects of stochastic events causing uncertainty, while maintaining high productivity, the control system needs an ability to determine and execute optimal production plans online (e.g., dynamically in real time). Function block technology facilitates adaptive and dynamic control capabilities that enable a control system to handle uncertainty caused by random events (Monostori et al., 2010, Wang et al., 2012b).

In the test case, two guided vehicles transport parts from the storage area to one of the assembly stations, where they are manually assembled into finished products which are thereafter transported to the storage area for finished products by the guided vehicles. Product assembly times vary and incoming orders are added to the order backlog on an irregular basis.

The shop-floor operators are the main value-adding resources of the test case and, to minimise operator inactivity, dynamic planning is applied. An online multi-objective optimisation method is implemented in the Adaptive Decision Support System to find dynamic production plans that address the following examples of questions. In what sequence should current orders be processed? Which operator should be assigned each order? Which guided vehicle should support the allocation of orders? Dynamic path planning is needed for the guided vehicles, handling two conflicting goals during the running of the test case. The two conflicting goals for the test case are to maximise the number of orders produced and, at the same time, to maximise the revenue.
7.3 Introduction to evolutionary algorithms

The shop-floor environment and the operators within it can face conflicting goals during manufacturing production. Evolutionary algorithms are often used in building systems able to find optimal solutions where conflicting goals arise, e.g., maximum throughput, minimum delivery time and minimum buffer size. Such algorithms use the same evolutionary principles as nature, including natural selection, breeding and mutations (Deb, 2015). The output, when using an evolutionary algorithm, is called a solution and a good solution is said to have a good fitness. The solution contains settings of the input variables and resulting values for the goals, in terms of optimisation. A solution with a high fitness level that outcompetes other solutions is then selected to breed the next generation of solutions.

There are many evolutionary algorithms, however, comparing and evaluating them is outside the scope of this research study. A well-known evolutionary algorithm NSGA-II (Deb et al., 2002, Deb, 2015) was chosen and implemented for the test case. The combination of the algorithm NSGA-II, enabling multi-objective optimisation, and function block technology was used to dynamically find optimal production plans for the test case identified.

The evolutionary algorithm NSGA-II (Non-dominated sorting algorithm – II) uses an elitist principle emphasizing non-dominated solutions. The flowchart of the NSGA-II algorithm is depicted in Figure 47: The population is initiated \(\odot\) and evaluated according to the objectives chosen \(\odot\) and ranked \(\odot\). A child population is created according to chosen variables (crossover and mutation) \(\odot\) and the child population is evaluated according to the objectives chosen \(\odot\). Through its elitist principle are the parent and child populations combined and ranked \(\odot\) and thereafter are the chosen number of individuals selected to the next generation \(\odot\). If the stopping criteria is met \(q\) the algorithm is terminated and the final population is presented \(\odot\). If not the iterative process continues and a new child generation is created \(\odot\).
The NSGA-II algorithm offers a powerful approach to multi-objective problems, when it is not possible to calculate all the combinatorial solutions to problems, in the time available. The population-based evolutionary algorithm is based on theories of genetics and reproduction. The output from NSGA-II is a Pareto front of the dominant solutions identified displaying the trade-off between each individual goal. The NSGA-II algorithm is executed during several generations (execution loops), the more generations the higher the probability of finding solutions with higher level of fitness, but eventually the resulting fitness level becomes independent of further iterations of generations executed. The output from each generation holds several possible solutions to the problem at hand. The execution of the NSGA-II algorithm is usually terminated when a certain number of generations have been looped or when the time limit has been reached. When using the NSGA-II for a max-max problem, i.e., maximising two conflicting goals (represented by the X and Y axis respectively), the output from one generation can look like the example in Figure 47 (to the left). Four possible solutions, each represented by a coloured dot, are illustrated. Each solution, with a value for both the X-goal and the Y-goal, represents a combination of input variable values. The blue dot represents the dominant solution found in the specific generation (not limited to one per generation). A dominant solution offers a combination of X and Y scores that outcompetes the other solutions. The dominant solution is stored by the algorithm, when executing new generations, and compared to newly found solutions. During execution, a Pareto front emerges (Figure 47 to the right). It holds several solutions (represented by the dots), each representing a dominant solution. Since the optimal solution being sought is a combination of X and Y scores, then all solutions on the Pareto front are optimal. The solution in the middle of the Pareto front (red dot) is normally selected (Das, 1999).
Approaches using multi-objective optimisation and a spectrum of methodologies aiming at path optimisation are common in the research literature. Most research efforts have a theoretical basis using variants of methods, for example, Spline representation (Ahmed and Deb, 2011), Dijkstra’s algorithm (Ferariu and Cimpanu, 2014), NSGA-II (Ahmed and Deb, 2013), Particle swarm optimization (Zhang et al., 2013) and dispatching rules (Chang et al., 2013). Studies including physical test cases often use mobile robots (Khoukhi, 2015) or Unmanned Aerial Vehicles (Besada-Portas et al., 2013). Research literature related to path optimisation for guided vehicles on the shop-floor using evolutionary algorithms is also present (Reddy and Rao, 2006, Udhayakumar and Kumanan, 2010, Umar et al., 2015). Further information on evolutionary algorithms, multi-objective optimisation and the algorithm NSGA-II can be found in Deb et al. (2002) and Deb (2015).

### 7.4 The demonstrator

The demonstrator, developed together with the industrial partner, emulating a production chain that starts with a customer placing orders and continues through to the manufacture of finished products, has been used for the test case. The products to be assembled in the demonstrator are variants of quick couplings (Figure 49). The demonstrator has six stations, each with an allocated operator, four assembly stations (Op 1-4), one storage station for parts to be assembled (to the left in Figure 50), and one storage station for finished products (to the right in Figure 50). Two guided vehicles transport parts to be assembled from storage to the operators and assembled products from the operators to the storage area for finished products. A costumer initiates orders to be assembled in the production system.
The two guided vehicles use a track with four switches. The guided vehicles can travel both forwards and backwards, but cannot occupy the same section of the track as another vehicle – one vehicle cannot overtake another. The layout of the track is represented by the thick black line in Figure 50. When a guided vehicle receives a new transportation task, it is loaded at the storage area for parts and then it delivers the parts to the relevant operator. The operator unloads the parts and loads the previously assembled products onto the vehicle. The vehicle then takes the assembled products to the storage area for finished products where it is unloaded. Thereafter, the guided vehicle is ready for a new transportation task.
The demonstrator has three sub-systems, external to the Adaptive Decision Support System. The first sub-system, Switch in track (yellow in Figure 50), controls electromagnets steering the four switches of the track for the guided vehicles. The second sub-system, Sensor in track (orange in Figure 50), collects sensory data from the tracks. The 16 sensors divide the track into 14 sections and detect which sections are occupied by a guided vehicle. The third sub-system, Guided vehicle communication (blue in Figure 50), uses IR-communication to control the guided vehicles. There are in total four transmitters positioned at the corners of the track. The three sub-systems use Arduino controllers and UDP/IP for communication with the Adaptive Decision Support System.

A network of distributed function blocks (green in Figure 50) is allocated in the tablets used by the six operators at the assembly stations, the storages areas and in the computer. A function block-based application is also used by the customer placing new orders. The function block network employs UDP/IP communication within the local network of the demonstrator. The network is hardwired and is not connected to any other networks, minimising the risk of corrupt or lost data packages.

7.5 The test case

Previous Chapters have focused primarily on the evaluation and validation of individual elements and technologies of the Adaptive Decision Support System proposed. In this test case, the focus is on proof of concept and capability of the Adaptive Decision Support System as a complete system. The test case utilises all three modules of the Adaptive Decision Support System, but the Operator device is given less attention here, since it was a focus of the test case presented in Chapter 6.
Table 9. Products available during the test case.
The assembly times are given in seconds and the value in units.

<table>
<thead>
<tr>
<th>Product</th>
<th>Assembly time</th>
<th>Value</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30</td>
<td>0.25</td>
<td>High</td>
</tr>
<tr>
<td>B</td>
<td>35</td>
<td>0.35</td>
<td>Medium</td>
</tr>
<tr>
<td>C</td>
<td>45</td>
<td>0.4</td>
<td>Medium</td>
</tr>
<tr>
<td>D</td>
<td>70</td>
<td>0.88</td>
<td>Medium</td>
</tr>
<tr>
<td>E</td>
<td>90</td>
<td>1.1</td>
<td>Low</td>
</tr>
<tr>
<td>F</td>
<td>122</td>
<td>1.4</td>
<td>Low</td>
</tr>
<tr>
<td>G</td>
<td>170</td>
<td>2</td>
<td>Low</td>
</tr>
<tr>
<td>H</td>
<td>200</td>
<td>3</td>
<td>Low</td>
</tr>
<tr>
<td>I</td>
<td>273</td>
<td>3.3</td>
<td>Low</td>
</tr>
<tr>
<td>J</td>
<td>350</td>
<td>4.5</td>
<td>Low</td>
</tr>
</tbody>
</table>

During the running of the test case, randomly generated orders were given to the assembly system. Each order is equal to a product with a value and a certain allocated amount of time for assembly. The probability that an incoming order is a high volume product compared to a low volume product is 4:1. The ratio between medium volume products and low volume products is 2:1 (Table 9). A product with a high value, a complex product, needs more time for assembly than a product with a low value, a basic product. This relationship is also the factor that generates the two conflicting goals of the test case. To maximise the number of orders produced, the focus should be on the basic products with short assembly times but also with a low value. To maximise the other goal, the revenue, the focus should be on the complex products with a high value but longer assembly times. The number of incoming orders for complex products is much smaller than the number of orders for basic products. The multi-objective optimisation algorithm, NSGA-II, is able to find solutions with a high fitness level for the conflicting goals.

The Adaptive Decision Support System, its function block network includes the implementation of the NSGA-II algorithm. In the test case presented, the NSGA-II algorithm has been programmed in C# using Visual Studio.
7.5.2 Process for finding dynamic production plans

In running the test case, the process for finding dynamic production plans is iterative. When a new order arrives from a costumer, the process is reinitiated. The multi-objective optimisation process of the test case is depicted in Figure 51. It begins when a new order from a customer is received \( \odot \) and is finalised when the Pareto optimal solution identified is executed \( \bigcirc \).

When a costumer places a new order, it is added to the list \( \odot \) and the multi-objective optimisation process is reinitiated, seeking the Pareto optimal solutions. Each solution holds a sequence of orders to process, including which operator and which guided vehicle to use. The multi-objective optimisation loop \( \odot \) generates a set of solutions and ultimately the Pareto front \( \odot \) (green dots). The solution in the middle of the Pareto front (red dot) is chosen to be implemented. The sequence of orders, assigned operators and guided vehicles, representing the chosen solution is then executed \( \bigcirc \). The guided vehicles are controlled accordingly and instructions are given to the operators and at the storage area from which parts are delivered for assembly. When a new order arrives from a costumer, the whole process is reinitiated.

![Figure 51. Finding dynamic production plans and execution of found solution.](image-url)
At the start of the test case, a “warm up period” was performed so that the order list initially contained approximately 50 unprocessed orders. A “warm up period” is used to ensure that production conditions for the demonstrator are similar to those at any start of an ordinary production day. The production system has a backlog of orders to be processed and the assembly stations have assigned tasks.

7.5.3 The function block network

Individual function blocks are combined into a distributed function block network which controls the whole process, from incoming orders to assembled products at the final storage. The function block network also comprises the multi-objective optimisation functionality.

The function block network is distributed onto the tablets used by the six operators and the customer, as well as the computer responsible for the communication system to the sub-systems (Figure 52). Additionally, the function block network also displays adaptive individual information, through function block controlled tablets, to each operator. The trio of function blocks controlling the tablets are: Order UI, Storage UI and Operator UI (green function blocks in Figure 52). The customer uses the function block Order UI to initiate new orders which are registered and kept in the function block Order List. The function blocks Storage UI and Operator UI receive information from the function block Simulator and display assembly information accordingly.

The function block network also includes the trio: Simulator, Optimiser and Order List (blue function blocks in Figure 52). The function block named Simulator holds a virtual model of the physical track including updated positions of the guided vehicles during execution. It enables the evaluation of possible solutions given by the function block Optimiser. A modified version of Dijkstra’s algorithm (Dijkstra, 1959) is used by the function block Simulator to evaluate the possible paths for the guided vehicles. Dijkstra’s algorithm seeks the fastest possible path for the guided vehicle that has an assigned operator. The function block Optimiser holds the NSGA-II algorithm. When found and chosen, the Pareto optimal solution is executed by the function block Simulator. It communicates with and controls the sub-systems: “Switch in track”, “Sensor in track” and “Guided vehicle communication”, which interface the track switches, physical sensors and communication devices of the guided vehicles respectively (Figure 50). The function block Simulator is a so-called composite function block that encapsulates a network of function blocks including a virtual model of the track, switches and the guided vehicles. The function block Order List keeps a list of unprocessed orders. It is updated with incoming orders from customers and by the function
Dynamic instructions to the operators

During production, the four operators are seated as shown in Figure 53. Tablets are used for assembly instructions which are generated dynamically for each assembly task. After a guided vehicle has arrived at the assembly station, the operator acknowledges (through the tablet) when the assembled product has been loaded, so that it can then be transported to the storage area for finished products. Simultaneously, a new assembly task is allocated to the operator and the material needed is delivered by one of the guided vehicles, thus minimising the operator’s idle time.
7.5.5 Test case design

The test case has been designed for two modes:

1. Real mode - A real-time mode, when the human operators and the guided vehicles operate the demonstrator and
2. Virtual mode - A virtual mode emulating the assembly process and the guided vehicles.

The first mode is used to test and evaluate the functionality of the main modules, both separately and as an integrated whole, the Adaptive Decision Support System. The second mode is used to test and evaluate the implemented multi-objective optimisation functionality that finds optimal production plans. Both modes use a virtual customer that generates incoming orders.

- The virtual mode emulates the distribution of the assembly times.
- The virtual mode emulates the time it takes for the guided vehicles to move within the demonstrator.
- No operator instructions are generated in the virtual mode.
- No guided vehicles run in the virtual mode.

The real mode has been used to run the test case and validate the concept and full functionality of the Adaptive Decision Support System, including the multi-objective optimisation. The module Adaptive system control communicates with the external shop-floor systems and controls the physical systems, guided vehicles and switches on the track. The module Adaptive system control also collects sensor information from the track position.
of the guided vehicles. The module Adaptive decision logic implements the multi-objective optimisation algorithm NSGA-II and the module Operator device displays dynamic assembly instructions to the operators.

The virtual mode has been used to test and evaluate the multi-objective optimisation functionality. All three modules of the Adaptive Decision Support System were run as in real mode, but external interfaces and communications were emulated. The ability of the NSGA-II algorithm to find Pareto optimal solutions was tested by comparing it with a random search algorithm. It used the same input variables as the NSGA-II. The same computing time for the two algorithms, using the same virtual model of the test case, was evaluated and the solutions identified were compared.

7.6 Results

The test case used the two modes to test and evaluate the concept of the Adaptive Decision Support System as a complete entity. The test case embraced its main modules, Adaptive system control, Adaptive decision logic and the Operator device, with a focus on the first two entities.

The test case ran, in real mode, the whole demonstrator as set-up together with the industrial partner. The whole Adaptive Decision Support System, with all of its three main modules implemented using function block technology, has been tested. The three main modules, Adaptive system control, Adaptive decision logic and Operators device, were implemented using the three-level structure. The Adaptive Decision Support System, during real-mode operation, has demonstrated its ability to:

1. control and interact with the physical production system (guided vehicles and the track),
2. implement complex algorithms that can find multi-objective optimised production plans and
3. handle adaptive assembly instructions for multiple users.

The Adaptive Decision Support System has been implemented as a fully functional, distributed function block network. The demonstrator has used a stable local network to enable the distributed function block network to use UDP/IP communication. Despite its lack of handshake dialogue between devices, it did not suffer from lost or corrupt communication packages (events in the function block network).
The ability of the function block-based Adaptive Decision Support System to encapsulate algorithms enabling complex functionality has been tested and evaluated using the virtual mode of the test case. The module Adaptive decision logic has proven its capability to incorporate and handle complex algorithms, such as the NSGA-II, in an online shop-floor environment. To evaluate the performance of the NSGA-II algorithm in the function block-based Adaptive Decision Support System, the Pareto front, found by the NSGA-II algorithm, has been compared to the solutions found by a random search algorithm (Figure 54). Each blue dot in the graph represents one solution found by the NSGA-II, indicating its individual value of revenue and the number of processed orders. The final Pareto optimal front is shown as a red line. The area covered by the set of solutions found by the random search is bordered by the grey dashed line in Figure 54. It demonstrates that the Pareto front, generated by the Adaptive Decision Support System implementing the NSGA-II algorithm, outcompetes the solutions found by the random search, enabling higher productivity.

Figure 54. Set of solutions with final Pareto front compared to random search.
During the multi-objective optimisation loop (in Figure 51), the Pareto front evolves, striving to reach as high as possible to the upper-right corner of the graph. The evolution of the Pareto front, represented by the Pareto fronts in four different generations of the multi-objective optimisation loop, is illustrated in Figure 55. It reveals the minor increase in total fitness for the 50th generation, compared to the 25th. It indicates that the probability of finding solutions with better fitness executing beyond 50 generations is limited.

During the test case, the Adaptive Decision Support System has supported multiple users with dynamic assembly instructions. Adaptive instructions were given to the individual operators, depending on the assembly task at hand. The Adaptive Decision Support System has handled and communicated with three external systems during the test case. As with any system, its ability to interact with the surrounding environment is an essential feature. During the test case, the capacity of the Adaptive Decision Support System to interact with both human operators and other computer systems has been tested. The test case has demonstrated the full functionality of the Adaptive Decision Support System, its three main modules, confirming that the underlying precepts and concepts are sound.
7.7 Conclusions and key results
The test case, using the demonstrator designed together with the industrial partner, has demonstrated that the underlying precepts and concepts of the Adaptive Decision Support System implemented using function block technology are sound. It has been shown that the Adaptive Decision Support System is able to subsume a wide range of control of external systems, and support complex and demanding functionality, such as multi-objective optimisation, for finding and executing dynamic production plans and generating dynamic shop-floor operator instructions. Due to the generic nature and the modularity of both the function block technology and the Adaptive Decision Support System, it is believed this approach can be adapted to other industrial scenarios. The ability of the function block-based approach to generate solutions online means that the needs and demands of a dynamic shop-floor can be responded to, thus improving the efficiency of production.

The novelty features of the proposed system can be summarised in the following terms:

1. The unique combination of a distributed function block network and the evolutionary algorithm NSGA-II, and
2. The Adaptive Decision Support System’s ability to generate dynamic production plans targeting shop-floor demands.

The results from the test case undertaken indicate the following results:

- The approach merges function blocks with the evolutionary algorithm NSGA-II to enable online multi-objective optimisation facilitating improved productivity.
- The Adaptive Decision Support System has demonstrated the full functionality of its three main modules, confirming that the underlying precepts and concepts are sound.

The methodology used for knowledge transfer during the research programme is presented in Chapter 8. Chapter 9 discusses the outcomes from the research programme, in reference to the checklist for design science research (Hevner et al., 2004, Hevner and Chatterjee, 2010, Drechsler et al., 2016).
8  Method of knowledge transfer

Design science methodology emphasises the importance of transferring knowledge gained during research. This Chapter presents a method which facilitates research collaboration that includes both less experienced and well-established project partners. The method focuses on the transfer of knowledge and technology in collaborative research programmes.

The method has been initiated and developed by the author of this dissertation who has also engaged more than ten companies, both regional, national and international, to participate in our research projects and in the ‘user group’ presented. The author has, together with colleagues, implemented the method as presented in the Chapter. The ‘user group’ method and the companies engaged have had a key position in the development and communication of the research presented in this dissertation.

8.1  Motivation

Exploring and generating new knowledge are the essence of research and together with knowledge transfer to students, project partners and to society they represent the main driving forces of an academic body. Knowledge obtained by research forms a foundation for future innovation for both students and companies. Innovations through research are key mechanisms for manufacturing companies striving to reach or keep a leading position in their markets. The European Union sees the integration of education together with research and innovation as a key to future international competitiveness for the manufacturing industry (European Union, 2015a). In addition, the European Union emphasises research, innovation and education as the three central drivers of our knowledge-based society and stresses the importance of developing strong links between them. These three drivers are together referred to as the Knowledge Triangle (European Commission, 2010) (Figure 56). It is essential that the knowledge gained through research projects does not remain solely with the researchers but also reaches and is understood and possibly implemented by appropriate commercial project partners. The transfer of project results is an important part of research programmes and vital to building towards the knowledge-based society.
8.2 Introduction
As pointed out by Hevner et al. (2004) and Hevner and Chatterjee (2010), the communication of research is an inseparable component of design science research. Throughout the research study, the author has had close cooperation with several companies of different sizes and business areas, all with a common interest in together capturing more knowledge from research within and related to a production context. During the past few years, a method called ‘user groups’ has been devised and implemented for the purpose of enhancing knowledge and technology transfer with commercial partners. It is regarded as part of an ongoing research process and not something that must only be done at the end of a project to satisfy industrial partners and funding agencies.

The ‘user groups’ method was initially devised and used together with eight collaborative companies engaged in four different research projects. Two of the larger companies were engaged in more than one of the research projects and the six Small and Medium sized Enterprises (SME, a company with up to 250 employees, European Union (2015b)) were engaged in one project each. The method is not limited for use in a specific field of research but needs a sympathetic and inclusive approach from the research team. All research partners associated with a research programme are invited to engage in ongoing ‘user groups’ when participating in a research project. The most important input to the method from both the researchers and the participating companies is an interest and willingness to share and gain knowledge, both inside, outside and beyond the scope of the specific project.

Outcomes from research projects should not only be of interest to academics at universities. The research can and should impact society. This can be achieved through the engagement of project partners, typically companies which can implement and conduct research projects. Many public research funding agencies demand the involvement of non-academic project partners and also highly value the transfer of technology and knowledge, especially into SMEs.
Setting up a research consortium is often a complex task which involves building partnerships with a range of partners including SMEs. Establishing collaboration with the project participants, both on an individual basis and at a company level, is an important starting point and crucial for project implementation and delivery. Determining the scope and objectives of a project with the project partners can lead to them asking some questions such as the following. “What can we gain from the project?” and “How do we participate and engage during the project?” The individuals in a national or global company involved during the establishment of a project usually encounter similar kinds of questions concerning planning and development that stretch several years into the future. They are familiar with handling the uncertainty that is inevitably part of longer term projects. However, the situation can be quite different for an SME, whose planning horizons are often relatively short term. Furthermore, SMEs usually have less experience becoming engaged with academic organisations and research projects. In addition, an SME has fewer resources which can be specifically used for the planning and development of projects. Accordingly, one main challenge in research proposals is how to engage both larger companies and SMEs in a research agenda that both meets their expectations and aims and, at the same time, performs cutting edge research. In addition, the transfer of technology and knowledge to individuals who cover a spectrum ranging from no prior experience in research cooperation to well-established and experienced is usually a key feature of the project agenda.

8.3 Transfer of knowledge and technology during a research project
There are several definitions of knowledge transfer and technology transfer, some mentioned by Wang (2006), while a synthesis of definitions has been concluded by Hyppölä and Skournetou (2013): Knowledge and technology transfer “is often understood as explicit (e.g. intellectual property, IP, policies and patents) and tacit (e.g. experience and know-how) sharing of knowledge and technologies ..... between organizations”. Knowledge transfer is defined here as the process of disseminating both technological and theoretical understanding as well as enhancing both industrial and academic knowledge through research conducted for/by project partners collaborating within a research project. This definition also includes the method introduced here and used for the process of knowledge transfer and the exchange of knowledge as described in the following Sections.
In the transfer process, receivers of the knowledge in the companies are not just the engineers. The increasing complexity of the production systems demands that shop-floor operators have enhanced technical skills and knowledge (Teknikföretagen, 2013, Karlsson et al., 2013a, Holm et al., 2014b). The future “knowledge worker” and the education needed to reach that level of understanding is discussed by Mavrikios et al. (2013). They introduce a cognitive framework for industrial training and learning with four main steps that the “knowledge worker” needs to complete: Attitude (feel), Knowledge (think), Skills (do) and Competence (master). In combination with a technological framework based on an extended Teaching Factory method, they introduce a cognitive approach that enables industrial learning, as a key to bridging the gap between research and industrial innovation to support the growth and competitiveness of the company.

As with any research project, planning and management are essential for achieving a successful outcome. The same also applies to industrial-academic joint research projects. Managing a research project is not only about setting up the research consortium, it of course also involves implementation and delivery stages, including knowledge transfer during the project period. Initial planning and a detailed description of the research goals reduce the risk of misunderstandings between the project partners later during the project. The importance of initial planning as well as both formal and informal interactions among project members are emphasised by Cummings and Teng (2003) and Morandi (2013). Thune and Gulbrandsen (2014) examine the initial conditions and management of university-industry partnerships in the study of the relationship development within six different research projects. They conclude that there is no definite link between initial conditions and how collaborative research projects evolve in the longer term. However, initial mutual interests and strong interdependencies between the project partners help enforce the relationships within the project group. Nevertheless, the formation of the group and good initial conditions are alone not enough for positive long-term group development. As in any human relationship, the partners have to work continuously on the relationship. The importance of inter-relational trust for successful knowledge transfer cannot be overstated. Inter-relational trust and engagement can enable joint meetings, hosted by partner companies, for observation and discussion of project case studies, implemented at the host’s company, emphasising the exchange of ideas and knowledge, as well as overcoming impediments such as differences in status, aim and culture, thus providing value to all participants. Partners that trust each other are also willing to facilitate both the project and each other in reaching and exceeding project goals (Santoro and Gopalakrishnan, 2000, Bellefeuille and Rice, 2002,
Santoro and Bierly, 2006, Braun and Hadwiger, 2011, Hirose, 2012, Breznitz and Feldman, 2012, Plewa et al., 2013, Battistella et al., 2015). A solution to maintaining a long-term relationship within the project is to design support programmes that enhance project partner efforts and interactions, which are considered beneficial to the learning process and needed for technology and knowledge transfer (Cummings and Teng, 2003, Muthusamy and White, 2005, Thune and Gulbrandsen, 2014).

The barriers to knowledge transfer within a research project are almost identical, whether the transfer processes are between industry-industry or academia-industry. An obstacle to knowledge transfer can often be identified as one of these four barriers: the barrier of “not knowing”, “not wanting”, “not capable” or the barrier of “not allowed” (Albers et al., 2014).

When facing a barrier, motivations are important counter measures. The following four categories of rationale for engaging in academia – industry research cooperation are given by Broström (2012):

- Cooperation for product and process development
- Access to academic networks
- Human capital management
- Direct business opportunities

Broström (2012) indicates that some companies see academic cooperation more as a way to generate knowledge and abilities for future innovations, rather than a way of achieving direct research outputs (normally seen as innovations). Depending on the knowledge to be transferred, the importance of facilitators differs. For tacit knowledge (e.g. experience and know-how), trust is an important facilitator, together with social connectedness, technological capability and technological relatedness. When transferring explicit knowledge (e.g. intellectual property, IP, policies and patents), the same facilitators matter, of course, but the organisation’s IP-policies also play an important role in the interaction (Santoro and Bierly, 2006). To reach an effective stage of transfer, especially concerning SMEs, some typical challenges have to be addressed (Table 10).
Table 10. Challenges during the knowledge transfer process according to Braun and Hadwiger (2011).

<table>
<thead>
<tr>
<th>Challenges for the donor partner</th>
<th>Challenges for the receiving partner</th>
</tr>
</thead>
<tbody>
<tr>
<td>An assumed benefit of exclusive possession of knowledge</td>
<td>Trust deficiency</td>
</tr>
<tr>
<td>Lack of ability in transferring knowledge to a non-specialist</td>
<td>Absence of structures for knowledge processing</td>
</tr>
<tr>
<td>Not enough direct contact with the receiving industrial partners</td>
<td>A knowledge gap in how knowledge is transferred</td>
</tr>
<tr>
<td>Barriers of culture and language</td>
<td>Barriers of culture and language</td>
</tr>
</tbody>
</table>

With an aim to enhance the technology transfer performance, some recommendations are given to the researchers: Create strategic partnerships using research networks; establish consortia and exploit intermediary institutions, as well as assure that project members in both academia and industry have hierarchical power within each organisation, enabling decision-making and integration of the research outputs (Heinzl et al., 2013, Morandi, 2013).

To reach and exceed an aim of successful knowledge transfer, which is the responsibility of all entities in the research process, the information to be transferred has to be processed and presented so that it is easily understandable by the receiving individuals. The receivers’ level of understanding of the transfer process is an important variable. As important, however, is also a common and consistent understanding of the scope and timing of a research project, together with the challenge of including the “right” people (e.g. decision makers) in both the companies and the academic body (Bellefeuille and Rice, 2002, Braun and Hadwiger, 2011, Czarnitzki et al., 2012).

### 8.4 Engaging companies in research and knowledge exchange

A knowledge society needs education and research in order to create innovations. In addition, an ability and maturity to implement and master research output and innovations are vital for maintaining competitiveness. The method introduced, namely, ‘user groups’, facilitates cooperating companies to learn, apply, implement, share and master knowledge gained through research, in order to strengthen their competitiveness (Figure 57). It is not a one-way method, it is bi-directional. It also eases feedback from the reception and
implementation of research output back to the researchers, reducing the risk of misunderstanding and divergent aims and, thus, strengthening research and facilitating new innovation.

8.4.1 Building the knowledge society

The number of companies engaged in research and with the ability to use and implement research results needs to increase. If only “old” partners are invited to engage in new research projects, the growth of the knowledge society will be limited. Academic institutions have a responsibility to engage with companies that have little previous experience of research participation in building the knowledge society. The method introduced, ‘user groups’, enables researchers to include both mature and immature partners in the same project, facilitating all of them to reach new levels of knowledge and, at the same time, give continuous feedback to the researchers during the project.

An initial question asked by the researcher when meeting a company representative during the setup of a research project has often been: Will you work towards improving your productivity during the coming years? If the answer is no then there are perhaps insufficient foundations for future cooperation and the management of the company in question does not recognise the demands of the market. Our experience, however, is that the answer to this question is always yes. This positive response has been and will be a good foundation for further dialogue regarding research cooperation.

Long-term associations with some companies are common in many research groups and these project partners usually have no problem understanding the aims and objectives of related and subsequent research projects. The results of previous research are understood and sometimes already implemented in daily work. However, new research partners do not,
of course, have the long-term experience of the established partners. This affects both their participation during the research project and their ability to absorb knowledge gained through the project and implement it.

Major Swedish research funding agencies, such as the Knowledge Foundation and Vinnova, as well as the European Union Research and Innovation agencies, emphasise the importance of industry-related research and the participation of SMEs. Larger companies acting in the international arena usually have their own research departments with experienced researchers, while SMEs often have limited research resources or experience. Nevertheless, the size of the company does not, in itself, determine the probability of successful knowledge transfer (Santoro and Gopalakrishnan, 2000, Saunila and Ukko, 2014). However, when further on describing the method introduced, a research-inexperienced company is symbolised by “SME”, while a research-mature company is symbolised by “Large company”. Different data is, of course, a challenge when leading a research project and it becomes even more challenging when facing knowledge transfer. Each company’s ability to understand and implement research outputs is often determined by its prior experience and level of maturity.

![Diagram](image)

Figure 58. "One-way" knowledge transfer
8.4.2 “One-way” knowledge transfer

An obvious foundation for a research project is, of course, the researcher’s own particular research interest. When this interest is aligned with an industrial need or productivity improvement demand, then a research question (Figure 58), as well as a basis for an industry-related research project, is initiated. The research question and the problems it addresses are relevant for all the project partners. However, previous experiences show that the active project is often carried out as described in Figure 58. Each company participant contributes with test cases conducted in the company’s own production facilities. In addition, each test case is exclusive to the specific company and each company’s interest is focused on its own challenges, with no real interaction between the project partners taking place besides seeing each other at project meetings. The process of knowledge transfer is focused on the specific results of each test case and is, in essence, a one-way transfer between the researchers and the specific company. Besides joint project meetings, there is little interaction between the individual representatives from the separate companies within the project.

8.5 A method for multi-directional knowledge exchange

In order to bridge the gap between the mature and immature project partners on the basis of both research experience and ability to accept and implement new ideas, as well as to achieve a multi-directional knowledge exchange, the method called ‘user groups’ is introduced. It is a method where cutting edge research and its innovative outputs together with knowledge transfer can be understood, adopted and implemented, both by the research experienced “Large company” and the research immature SME, thus meeting each project partner at its own level. The method facilitates multi-directional knowledge exchange between companies and also from the companies to the researchers. The setup and initiation of the project’s research questions and test cases applying the method are similar to those previously described in Figure 58.

The ‘user group’ has two major aims:

1. To transfer knowledge, methodology and innovations from both prior and ongoing research projects to the partners in the ‘user group’, through training, seminars, customised courses, field trips and presenting good examples of applied research results. Also, for the companies to disseminate knowledge to the researchers about the process of introducing research into real production and the issues that occur, thus building the companies’ competitiveness and strengthening the researcher.
2. To build long-term relations, both between academia – industry and industry –
industry, achieving inter-relational trust and understanding, facilitating cooperation,
knowledge exchange and future research in building our knowledge society.

The initiation of a research project using the ‘user groups’ method is enabled when a research interest meets industrial needs (i) (Figure 59). The participating companies then contribute to the project by conducting real-world test cases at their facilities (ii).

Besides the usual project meetings (2-3 annual meetings), the ‘user group’ meets 4-6 times per year. The researchers present both previously proven methods and innovations, together with new knowledge, to the participants of the ‘user group’ (iii) who apply this knowledge, according to each company’s ability and aim, in their own production facilities (iv). Through the ‘user group’, the researchers have a direct link to the participants applying and using the research output. This enables knowledge exchange and a fast feed-back loop that facilitates discussions on the usability of the research output, the degree of satisfaction and the level of project accomplishment (v). Since the larger company has prior research experience, it can directly understand, apply and implement the project outcome (vi) while the research inexperienced SME has not yet reached that level of maturity. When a project is nearing completion and a successful research project has been established, the initiating process (i) is facilitated and the previously research inexperienced partner companies are ready to shoulder a greater responsibility.

Figure 59. The ‘user group’ method.
In parallel to the ‘user group’ meetings, university courses covering the aspects of the ongoing research projects are arranged for the staff working with the project partners. These courses have covered topics such as: Lean Philosophy, Simulation and modelling, Methods engineering, Industrial robotics, Maintenance and Production systems development. Through the courses, the partner companies are able to train their employees, both in theories and in practising the knowledge gained, at their own workplaces. These courses enable the project partners to train their staff at both basic and intermediate levels and they facilitate the adoption of research output at both engineering and shop-floor levels.

8.6 Case study of implemented ‘user group’

The ongoing ‘user group’ covers decision support for managerial, engineering and shop-floor levels supplemented with human/machine interaction. The case study describes ongoing work where the ‘user groups’ are implemented, focusing decision support that uses simulation-based optimisation, data mining and techniques for extracting knowledge. All of the companies engaged during the research for the presented Adaptive Decision Support System also participated in this ‘user group’.

8.6.1 Activities within a user group

A central and important aspect for the realisation of research outcomes is to establish an arena for collaboration and knowledge exchange between academia and research partners, as well as between the research partners themselves. In order to facilitate this knowledge exchange between the project partners, workshops are initiated with the aim of creating a fellowship between the project partners so that they can learn from each other’s experience and share and exchange knowledge. The activities of the ‘user group’ during a twelve month period are illustrated in Figure 60.

![Figure 60. ‘User group’ activities during a 12 month period.](image-url)
Project meetings are arranged, within each research project, once or twice a year. These meetings focus the project-specific issues and, if two projects have closely related issues that need handling (for example, shared demonstrators), joint project meetings are arranged ①. In parallel to these meetings, workshops are arranged. These workshops ② are not dedicated to a specific research project, instead, all project partners from the contributing research projects are invited. The scope of the workshops is knowledge transfer from both previous and ongoing research and is based on the aims and needs of the participating project partners. In parallel to the workshops, university courses ③ that specially address the needs of industry are arranged. When a need of further knowledge has been identified after a workshop, the participants are invited to a course that addresses the need ④, and prepares them for future workshops and tasks within ongoing projects.

### 8.6.2 Results from a user group

The participating companies of the ‘user group’ all have their individual aims and starting points, which of course affects the outcome when the research projects are concluded. Four of the participating companies in this example are identified by A, B, C & D (Figure 61). Companies A and B have previously been involved in several research projects and, hence, start off at different levels of comprehension, due to their previous knowledge and maturity, compared to companies C and D.

![Figure 61. Starting points and expected knowledge outcomes for different companies in an ongoing ‘user group’.](image-url)
Company A, which is a multi-national company with several thousand employees, is a long-term research partner whose staff members are able to discuss research questions directly with academics. They are able to focus on the core of a research project as well as directly utilise and implement the outcomes of a project, as they already have an organisation and work approach that apply the methods and techniques investigated. Company B, which can also be considered a large company, has a similar organisational structure and work approach that utilise the investigated techniques. However, in contrast to company A, the personnel of company B working with the investigated methods and techniques are still limited to a few experts. Companies C and D, on the other hand, have not participated in any research collaboration before and, hence, must start to learn about the scope of the project by introduction and tutoring classes that teach the knowledge, technology and scope to their organisations. However, in contrast to companies A and B, companies C and D only aimed to apply and test the latest research in the form of demonstrators or test cases at their companies, due to their low level of maturity regarding involvement in research projects as well as prior knowledge. Their aim was to gain more knowledge and experience before implementing research results in real production processes.

Decision support technologies used for the ‘user group’ are related to simulation-based optimisation, data mining and techniques for extracting knowledge from the optimisation results. One of the current research projects features the two latter subject areas and another project’s focus is the development of optimisation algorithms. Knowledge about discrete-event simulation and simulation-based optimisation is needed when engaging in the projects. However, despite the prerequisites for these two projects, companies start with different levels of understanding and maturity, depending on previous collaboration within research projects and their own experience. Typically, larger enterprises have more experience with research collaboration compared to SMEs.
The initial status of the companies A-D in the ‘user group’ regarding the scope of the project is shown in Figure 61 (before-bar). Company A participants already master modelling and simulation and are skilled in optimisation. They have tested data mining and knowledge extraction and are becoming aware of possible opportunities for using such techniques. Companies C & D, on the other hand, do not have any previous practical knowledge concerning simulation-based optimisation but have an awareness of the technology and what can be achieved by implementing it in their organisation. The knowledge outcome after finalising the ongoing research projects for companies A-D is shown in Figure 61 (after-bar). Each project partner sets its own aims, which of course affects the expected level of maturity achieved after the completion of the three year project period.

8.7 Conclusions and key results

It is essential to engage new companies to participate in research, so that knowledge gained not only benefits a few organisations but is instead spread to, understood and implemented by many others. To be one of the organisations that builds and extends our knowledge society is an important task for academia. Many research funding agencies require that industry related projects conduct cutting edge research and, at the same time, emphasise the importance of engaging SMEs in research projects. Although size does not define a company’s ability to adopt research outputs, a national or international company usually has available staff with research experience who can engage in research projects, compared to a SME. To meet the requirements of cutting edge research, SME engagement and knowledge transfer in one project is not always easily achieved, due to the diversity of research maturity, the participating companies’ prior experience and the lack of a suitable method. Our previous experience has shown that interaction within a research project is usually limited to company – researcher and very little interaction between the participating companies is initiated and supported. Researchers engaging companies that have no prior research experience often face a situation where the partners within a project have different starting points regarding their ability to adopt the research outputs or even know what to expect from a research programme.

The introduced method of ‘user groups’ provides tools that enable cooperation between the experienced research partner and the novices, despite their different levels of engagement in the same project, without dividing them into separate groups. The ‘user group’ case study described has shown that companies widely diverse in both prior experience and levels of engagement are able to cooperate, reach their own objectives and, at the same time, both jointly and individually, contribute to the overall project goals. The transfer of knowledge to
companies and facilitating the exchange of knowledge both between the companies and the researchers and between the companies within the ‘user group’ are essential for building and maintaining the market competitiveness of the companies. The ‘user groups’ method facilitates both the inexperienced and the research mature companies to gain new knowledge and by doing so extends the Knowledge Society.

The research literature and the results from the ‘user group’ study undertaken indicate the following results:

- It is important for researchers to initiate cooperation with new partners to enhance the arena for knowledge transfer.
- The method of ‘user groups’ devised has proven to facilitate knowledge transfer for research partners with diverse research backgrounds.

The final Chapter of the dissertation discusses and evaluates the design science approach applied, the results emerging during the research study, and presents overall conclusions and possible areas of future work.
9 Discussions, conclusions and future work

This Chapter discusses the results evolving from the presented research that aims to define a framework for an Adaptive Decision Support System. Guidelines for assessing design science research are used as a basis for the discussion. In addition, the overall conclusions of the dissertation are presented together with ideas on future work.

9.1 Discussions

As previously described in Chapter 1, the essence of design science research is utility. Design science addresses research through an iterative process of building and evaluating artefacts, instantiations in this case, to meet the identified needs. Fundamental questions to be answered when applying design science research, according to Hevner et al. (2004), are:

- What utility does the new artefact provide?
- What demonstrates the utility?

Seven guidelines for assessing research using design science methodology are presented by Hevner et al. (2004) (Table 11) and further elaborated in Hevner and Chatterjee (2010), Arnott and Pervan (2012) and in Drechsler et al. (2016). This Chapter also includes a description of the use of the guidelines when the design science process is applied. The seven guidelines have achieved a high level of acceptance within the research community as “integral to top quality design research” (Hevner and Chatterjee, 2010). The individual design science research project should address each of the guidelines, but each of them may not necessarily be given the same focus.
Table 11. Guidelines for evaluation of design science research according to Hevner et al. (2004).

<table>
<thead>
<tr>
<th>Guideline</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Design as an artefact</td>
<td>Design science research must produce a viable artefact in the form of a construct, a model, a method, or an instantiation.</td>
</tr>
<tr>
<td>2 – Problem relevance</td>
<td>The objective of design science research is to develop technology-based solutions to important and relevant business problems.</td>
</tr>
<tr>
<td>3 – Design evaluation</td>
<td>The utility, quality, and efficacy of a design artefact must be rigorously demonstrated via well-executed evaluation methods.</td>
</tr>
<tr>
<td>4 – Research contribution</td>
<td>Effective design science research must provide clear and verifiable contributions in the areas of the design artefact, design foundations, and/or design methodologies.</td>
</tr>
<tr>
<td>5 – Research rigour</td>
<td>Design science research relies upon the application of rigorous methods, in both the construction and evaluation of the design artefact.</td>
</tr>
<tr>
<td>6 – Design as a search process</td>
<td>The search for an effective artefact requires utilising available means to reach desired ends while satisfying laws in the problem environment.</td>
</tr>
<tr>
<td>7 – Communication of research</td>
<td>Design science research must be presented effectively both to technology-oriented as well as management-oriented audiences.</td>
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The numbering of the guidelines does not coincide with the sequence in which they are applied by Hevner et al. (2004) in three examples given, when evaluating design science research. Subsections 9.1.1 – 9.1.7 use the alternative sequence of the three examples. In each Subsection is Hevner et al. (2004) and Hevner and Chatterjee (2010) initially view of each guideline discussed. They are then each followed by a discussion about the presented research.
9.1.1 Problem relevance
To acquire knowledge and understand enabling design, development and implementation of constructions of innovative artefacts for identified problems are the objectives of design science research. It is not enough to solely address technical issues, also organisational and user-based approaches need to be addressed, to overcome acceptance problems predicted (Hevner et al., 2004, Hevner and Chatterjee, 2010).

The overall aim of the research presented is to define a framework for an Adaptive Decision Support System, to address the scope and demands of the future shop-floor, as indicated in the research literature, and confirm its relevance, as well as further elaborate it on the basis of the interviews with production managers and HR specialists.

The evolution of the industrial shop-floor operator, as presented in the research literature, indicates that the future shop-floor will have an intense and dynamically changing environment, with stochastic events negatively affecting the production system. It will not be possible for any human to process or evaluate, in real time, the amount of information available on the future shop-floor. In addition to the scope and demands, the interviewees predicted the use of ICT-devices on the shop-floor, as a part of a decision support system that is able to handle vast information in real time, in dynamically changing production situations. Although research focusing on decision support systems has been undertaken for several years, the research literature indicates that further research and development is needed, to facilitate an adaptive and dynamic decision support system that addresses the demands of the future industrial shop-floor.

The artefact, the Adaptive Decision Support System, addresses the predicted demands raised by the research literature and the interviewees. Furthermore, it also strengthens the research on decision support systems for the industrial shop-floor. The design of the Adaptive Decision Support System focuses on the improvement of productivity and decision quality for shop-floor operators. In addition, it supports interpersonal communications, organisational control and improved skills in decision-making.
9.1.3 Research rigour

Research rigour addresses how research is conducted and it requires the use of well-defined and motivated methods, both during development and evaluation. Instantiations used should be tested and evaluated within an appropriate environment, meaning as close as possible to expected real-life situations. For the studies to be conducted, appropriate subject groups should be obtained. It is further discussed in Hevner et al. (2004) and Hevner and Chatterjee (2010) that if research aimed at implementations in real-life environments has an overemphasis on research rigour, it might lessen the relevance of the research, and vice versa. However, as argued by Applegate (1999), it is both possible and necessary, in design science research, to have both relevance and rigour in the research programme.

The work on the Adaptive Decision Support System uses a pragmatic or mixed-method approach, in applying the design science research methodology. It is a widely used methodology with a strong link to research on decision support systems (Arnott and Pervan, 2012).

The Adaptive Decision Support System has been developed using the design science research process. Studies made have used subject groups and environments for testing and evaluation that are as close as possible to the real industrial environments. Future shop-floor operators, high school students of today, have been engaged to evaluate the developed instantiations, using demonstrators based on real-world production scenarios.

The presented work is based on the design science research methodology and motivates the methods used for the performed studies in developing, testing and evaluating the instantiations. Relevant evaluations have been made within a close-to-real industrial context and have focused on utility: usability, quality and productivity.

9.1.4 Design as a search process

Design science is an inherently iterative process used to discover a solution to a problem. A tentative design is tested and evaluated, thus generating an updated design which is again tested and evaluated. Simplifications of the problem at hand are commonly used in design science explicitly to represent only a subset of the whole. However, the scope of the iterative design science process should be expanded and refined during the cycles, in addition to the artefacts becoming more realistic and relevant to real-world applications (Hevner et al., 2004, Hevner and Chatterjee, 2010).
The development process of the research presented initially used theories and instantiations that focused on separate subject areas such as function blocks, Augmented Reality and demands of the future shop-floor. Tests and evaluations of the initial instantiations and theories led to the design and formulation of a framework that enables adaptive decision support and adaptive system control. With the framework as a basis, dynamic shop-floor instructions using Augmented Reality were developed, tested and evaluated, which led to an Adaptive Decision Support System. The capabilities of the proposed Adaptive Decision Support System have been revealed in two extensive studies using demonstrators to represent real-life production environments.

9.1.5 Design as an artefact
Artefacts of design science research are conceived as interdependent on the people, organisation and social context in which they are used. Perception and suitability for the organisation are crucial for the successful development and implementation of design science research artefacts. However, artefacts constructed in design science research are usually not systems or devices ready to be sold and implemented in a real-life environments. An artefact usually demonstrates ideas, capabilities and practices (Hevner et al., 2004, Hevner and Chatterjee, 2010).

Artefacts, in the form of instantiations, with different scopes have been developed and evaluated. An instantiation for assessing the Adaptive Decision Support System as a complete entity as well as instantiations focusing on one of its modules or underlying functionalities have been developed, tested, evaluated and implemented in close-to-real life production environments, in close cooperation with its future shop-floor users.

9.1.6 Design evaluation
The answers to the fundamental questions of design science research cannot be found if evaluation is left out of the research process. It is important that well-executed evaluation methods demonstrate the utility and quality of the artefact, as evaluation is a crucial component of the design science research process. The evaluation should include the integration of the artefact within the targeted environment or infrastructure (Hevner et al., 2004, Hevner and Chatterjee, 2010).

Recurrent evaluations have been an important component during the development and research undertaken for the Adaptive Decision Support System. Instantiations and test cases embracing a smaller scope (e.g. the production cell controlled by function block technology presented in Chapter 2), as well as instantiations and test cases with an extensive scope (e.g.
the complete systems presented in Chapters 6 and 7), have been evaluated to demonstrate utility and quality. The evaluation results presented indicate, for example, that dynamic shop-floor instructions using Augmented Reality (ARES) achieve higher usability scores compared to the existing spreadsheet-based instructions at the quality control station on site. The evaluations made also show that the developed ARES outperforms the existing information system in facilitating quality and productivity.

9.1.7 Research contribution

Based on the novelty, generality and significance of the developed artefact, design science research identifies the potential of three types of research contribution: The design artefact, Foundations, and Methodologies. In any design science research project, at least one of these contributions must be found. Most often, the artefact itself is the main contribution of the design science research undertaken, facilitating a solution of an identified problem. Implementing and exercising artefacts in real-life environments contribute significant value to the research community (and hopefully best practice in achieving wider societal benefits) (Hevner et al., 2004, Hevner and Chatterjee, 2010).

As with most design science research, the Adaptive Decision Support System formulated is the main contribution, but not solely, as a design artefact. Implementations and evaluations of the instantiations in close-to-real life production environments have strengthened the bridge between decision support system research and the industrial shop-floor while demonstrating the Adaptive Decision Support System’s ability to facilitate shop-floor work. Performed tests show that that glasses implementing Augmented Reality employ a promising technology, but evaluations indicate that further developments is needed before such technology can be applied at the industrial shop-floor on a daily basis. The presented research on ARES, using available technology - a tablet, demonstrates high usability facilitating quality and productivity enabling implementation of the framework presented.

In parallel, the research has also resulted in several publications, as cited in this dissertation. The performed research has also contributed by examining the demands of the future shop-floor and its operators. It has obtained the response to such demands from the expected future shop-floor operators. In addition, the research programme has devised and implemented a methodology for technology transfer, enabling research inexperienced companies to become active research partners, and proven its capabilities.
As indicated in the research literature and confirmed by members of the ‘user group’, several research questions have emerged, forming new research projects. Common for most of these projects is the shop-floor and how the performance of shop-floor operators and supporting tools can enhance productivity. As described in Chapter 8, the research has contributed to several companies gaining advances in production in general and on the shop-floor in particular. The presented research has impacted ongoing and planned research and development, especially involving both Volvo Cars and Volvo GTO Powertrain.

9.1.8 Communication of research

The guidelines state that design science research should be presented to audiences with both technical orientation as well as management orientation. The technical participants should be given sufficient technical details and organisational context to enable them to construct and implement further work based on the performed research. The managerial participants should be given sufficient details to enable them to commit the organisation to further development and implementation (Hevner et al., 2004, Hevner and Chatterjee, 2010). In parallel, the level of practical impact achieved by the recipient organisation is defined as “research resonance” by Drechsler et al. (2016).

The research programme on the Adaptive Decision Support System has been developed, tested and evaluated together with industrial partners of ongoing research projects. In establishing the scope and direction of the research, indicated and initiated by the research literature and confirmed by industry, demonstrators that represent real-life production environments have been used for tests and evaluation. The results have periodically been presented to both the managers and technical staff of the industrial partners during the ongoing research. The developed ‘user group’ methodology has played a substantial role in reaching and communicating with industrial partners that are either more or less engaged, facilitating both continuous research and the engagement of new industrial partners.
9.1.10 Concluding discussion

The most common drawbacks (low relevance, low level of evaluations and a mediocre methodology), identified in research on decision support systems by Arnott and Pervan (2012), have been avoided during this research on the Adaptive Decision Support System. The industrial research partners have played an active role during the different phases of the research process, which has ensured the relevance of the performed research. Making recurrent evaluations has been an important part of the research process, which has followed the design science process as presented in the research literature. All of the seven guidelines have been addressed with an emphasis on the relevance of the problem, design, development and evaluation of the instantiations and, finally, the communication of the research.

9.2 Conclusions

Referring to the objectives in Chapter 1, the major conclusions that can be drawn in this dissertation are summarised as follows:

1. Through an appraisal of the research literature and the current state of industrial practice, investigate event-driven function block technology and shop-floor decision support as a basis of adaptive decision support for shop-floor operators.

An investigation of function block technology, through an appraisal of research literature and the current state of industrial practice, has formed a foundation for the presented Adaptive Decision Support System. The presented work extends the scope of function blocks beyond industrial process measurement and system control, as defined by the international standard IEC61499, and bridges the gap between decision support systems research and the industrial shop-floor. In parallel, decision support systems and the industrial shop-floor have been studied in the research literature and the current state of industrial practice. These areas together form the basis for the research on adaptive decision support for shop-floor operators.

Function block technology can facilitate online abilities for emerging shop-floor support systems, as the presented Adaptive Decision Support System. Adaptive control in distributed manufacturing environments and cloud environments can eventually be enabled through function block technology.
2. Through interviews with production managers and shop-floor operators, in combination with a literature review, establish the requirements of the future shop-floor and its operators, as well as identify the properties needed for shop-floor decision support to enhance production output.

Predicted requirements of the future shop-floor and its operators have been established, in addition from the literature review, through interviews with production managers and HR specialists. The results indicate that future shop-floor operators can expect to face extensive demands for both technical and interpersonal skills. Shop-floor decision support systems adaptable to changing production situations and able to handle vast amounts of information in real time will be required.

The response from the future shop-floor operators to the interviewees’ predicted shop-floor environment indicates a positive attitude to shop-floor work. To seize this opportunity, companies need to arrange shop-floor work according to future requirements, not past ones.

Building the future shop-floor can include a more extensive use of ICT, which eventually will affect whole production systems, and especially human machine interfaces (HMI). The design of the HMIs has not changed significantly during the past 20-30 years. Although the previously physical lamps, buttons and handles are today virtual on a touch screen, the main concepts are the same. Skilled operators with much ICT experience in general and with high expectations of shop-floor integrated ICT are expected to emphasise the development of not only the HMIs but of the whole shop-floor.
3. Design, test, implement and evaluate a framework, using event-driven function block technology, for an adaptive decision support system for shop-floor operators.

A framework, based on function block technology, enabling dynamic and adaptive decision support for shop-floor operators has been presented. It has been implemented, tested and evaluated in two extensive studies using demonstrators based on real-life production environments. The results from the studies have

- presented the Adaptive Decision Support System and demonstrated the full functionality of its three main modules, Adaptive system control, Adaptive decision logic and the Operator device, confirming that the underlying precepts and concepts are sound.

- demonstrated that the Operator device of the Adaptive Decision Support System, implementing the developed system ARES, enabling context-driven dynamic and adaptable instructions to shop-floor operators using Augmented Reality, facilitates shop-floor work.

The presented framework of the Adaptive Decision Support System has been developed together with industrial partners. The results have been positively received. Volvo GTO Powertrain has invested in rebuilding machine equipment for data collection to enable live tests during 2017 and further development on ARES is ongoing together with Volvo Cars R&D. This work and these investments at Volvo GTO Powertrain and Volvo Cars have been planned and implemented during 2015-2016 and demonstrate the interest of the companies to invest in shop-floor decision support.
4. Develop, test and implement a methodology for knowledge transfer between academia and industry, facilitating the implementation of research results for industrial partners with less prior research experience.

A method facilitating research collaboration that includes both less experienced and well-established industrial partners has been presented. The method focuses on the transfer of knowledge and technology in collaborative research programmes. This method named ‘user group’, which has been implemented with 10+ participating industrial partners, provides tools for cooperation and facilitates bi-directional transfer of knowledge. It also offers a tool for the researchers in engaging new research partners.

The presented results from an ongoing ‘user group’ show how research partners with diverse backgrounds have used and implemented research results, especially successful for less experienced industrial partners. The research presented in this dissertation has extensively used companies engaged in the ‘user group’ for development and communication of results.

During the period of the presented research (2010 – 2016), I have engaged eight “new” SMEs and one “new” international company to participate in our division’s research programmes. One major reason why these companies want to join as industrial research partners is the ‘user group’. Through the ‘user group’, they are able to interact with the researchers and the other partners, facilitating their own growth through seminars, courses and meetings. Each company usually has 2-4 representatives and generally 50+ persons attended different ‘user group’ meetings during a year.
The companies’ engagement in the ‘user group’ has formed a basis for several research projects in which I have had, or continue to have, a role:

- **Wise-ShopFloor (2011-2014)** – National project, led by the University of Skövde, where I have engaged two companies.
- **YOU2 (2013-2017)** – National project, led by the University of Skövde, where I have engaged five companies. I defined the research question and have the role of operational project leader.
- **IDSS (2013-2017)** – National project, led by the University of Skövde, where I have engaged three companies.
- **Dynamite (2014-2016)** – National project, led by Chalmers University of Technology, where I have engaged two companies.
- **SYMBIO-TIC (2015-2019)** – EU project, led by KTH Royal Institute of Technology, where I have engaged one company and lead one of the work packages.
- **MANUWORK (2016-2020)** – EU project, led by LMS (Greece), where I have engaged two companies. I led and compiled “the Skövde” part of the application (of a total of 4.8 million Euros, the University of Skövde together with the two companies from Skövde received 1.2 million Euros).
- **KDISCO (2013-2015)** – Postdoctoral project. I engaged two companies to support the postdoctoral researcher.
- **E3 (2016-2018)** - Postdoctoral project. I engaged two companies to support the postdoctoral researcher.
- **2 PhD students (2015-2020)** – I established the projects and formulated the research questions. In addition, I engaged one company that is working with the students. The company is investing a considerable amount of money in these two PhD projects.
Besides contributing to bridging the gap that is indicated in the research literature, the research performed also contributes value to the industrial partners. Adaptive and dynamic decision support and system control able to process vast amounts of information in real time demonstrates utility for shop-floor operators. The research presenting the Adaptive Decision Support System has demonstrated, in extensive studies based on real-life production environments, the provided utility for the shop-floor and its operators. For example:

- The framework enables dynamic and adaptive decision support for operators working in an information intensive shop-floor environment.
- The operators’ learning processes are facilitated and, especially for inexperienced operators, knowledge gain and decision-making are improved.
- By applying chosen decision rules, shop-floor teams can steer how incoming events should be processed.
- A decision support system focusing the demands and needs of the future shop-floor.
- Results indicate that ARES, implementing Augmented Reality technology, has the potential to outperform the at-site used information system, facilitating quality and productivity. In parallel, ARES has also received higher usability ratings compared to the at-site used information systems.
9.3 Future work
There are several possible areas which could benefit from further refinement and reassessment, following the presented research on the Adaptive Decision Support System:

- Glasses that can be used on a daily basis, implementing ARES, are a promising technology for the shop-floor. No available devices have yet proven full functionality in displaying dynamic information. More research and development on adapting emerging devices and technology is needed. In parallel, investigating how instructions should be designed for correct interpretation and how such instructions could be displayed on an Operator device implementing ARES, for use on a daily basis by shop-floor operators, is also required.

  Research and development is planned (2016-2017), together with Volvo Cars R&D, for the ARES to be implemented with Hololens from Microsoft. The current level of Hololens’ functionality does not fully meet the requirements for an Operator device that will be used during a full working day on the shop-floor, but it is a big step forward. Emerging technologies beyond Hololens should be further elaborated when available.

- Collaborative robots, Cobots (humans and robots collaborating without barriers in between), is an emerging field for the shop-floor. Future research on adapting the Adaptive Decision Support System to a shop-floor environment with Cobots is emphasised. The Adaptive system control module needs further research and development for robot control.

  The research project SYMBIO-TIC will further elaborate collaborative robotics. It uses adaptive system control based on function block technology to enable adaptive robot control. Such research will continue at the University of Skövde in cooperation with European partners for the next 2.5 years.
• The whole Adaptive Decision Support System should be further developed, tested and evaluated in the real production facilities of our industrial partners and should cover the user, organisational and social context. The scope should not be limited to the presented Adaptive Decision Support System alone. It should, for example, include ongoing research covering Cobot programming through speech recognition and haptic control, as well as interface design. Such tests would possibly generate new research questions and also form a foundation for the development of a commercial Adaptive Decision Support System.

The Adaptive Decision Support System (all three modules) will be tested on a real production line at Volvo GTO Powertrain during 2017. The production line has 20+ stations, mainly machining, but also some manual stations. The results will be further elaborated in research projects planned to start during 2017.
Publications of Magnus Holm

This is the complete list of publications having Magnus Holm as one of the authors.

2017


2016


SYBERFELDT, A., AYANI, M., HOLM, M., WANG, L. & LINDGREN-BREWSTER, R. Localizing operators in the smart factory: A review of existing techniques and systems. 2016 International Symposium of Flexible Automation, 2016a Cleveland, Ohio, USA


2015


2014


2013


2012


2011


2010


2009

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CONFALONIERI, M., BARNI, A., VALENTE, A., CINUS, M. & PEDRAZZOLI, P. An AI based decision support system for preventive maintenance and production optimization in energy intensive manufacturing plants. 2015 IEEE International Conference on Engineering,
DAI, W. & VYATKIN, V. A case study on migration from IEC 61131 PLC to IEC 61499 function block control. 7th IEEE International Conference on Industrial Informatics, 2009.


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WIEDENMAIER, S., OEHME, O., SCHMIDT, L. & LUCZAK, H. 2003. Augmented reality (AR) for
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VYATKIN, V. 2011. IEC 61499 as enabler of distributed and intelligent automation: State-of-
the-art review. *Industrial Informatics, IEEE Transactions on*, 7, 768-781.

VYATKIN, V., DUBININ, V., VEber, C. & FERRARI, L. Alternatives for execution semantics of

VYATKIN, V., PANG, C. & TRIPAKIS, S. Towards Cyber-Physical Agnosticism by Enhancing IEC
61499 with PTIDES Model of Computations. 41th Annual Conference of the IEEE
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instructor for hierarchical structures. Proceedings of the 2nd IEEE/ACM International

Appendix 1 – Questions during interviews

These are the questions asked during the interviews with the production managers and HR specialists (translated from Swedish).

**Background**

1. Current position? Duties?
2. How long have you been with the company?
3. Training?

**General questions**

4. Generally describe your production, various steps?
5. What different roles are there in production? How do they differ?
6. How do you define shop-floor operators in your production?
7. What are the shop-floor operators’ main activities / tasks in the production?
8. What skills are required to work as a shop-floor operator in production?
9. How do you organize the shop-floor work? Teams / group / individual / cross-functional teams?
10. What decisions are taken by the operators / team?
11. What information are needed to make these decisions?
12. What technologies / tools (support functions) are used by the shop-floor operators today?
13. What authority does the operators have at fault / downtime for resetting and start-up?
14. How do you engage all shop-floor staff in shop-floor development?
15. What do you do to get a common / holistic approach at the shop-floor?

**Vision of the future**

16. How has your industry changed during the past 20 years?
17. How do you think it will evolve in the future? 5 -10 years? The shop-floor operators? 10-15 years?
18. What trends do you predict?
19. If any, what will be the new competences required for future shop-floor operators?
20. What competences do you consider to be crucial for future shop-floor operators?
21. How do you think shop-floor supporting systems / tools will need to develop if the teams’ / operators’ tasks increases?
22. What plans or visions are there within the company, in terms of technology and organization?
23. What specific techniques do you think will change your production?
24. How does the company develop new supporting systems for the shop-floor operators?
25. How are the shop-floor operators engaged in this development?
26. What is your strategy for recruiting young shop-floor operators in the future?
27. What obstacles do you identify in attracting shop-floor staff in the future?
28. How do you get "older" employees to keep up with shop-floor evolution? How do you motivate them?

Skills development, improvement and development

29. What kind of skills do you predict to be required of the future shop-floor operators?
30. Do you train the shop-floor operators continuously? Long-term / short term?
31. How do you support the shop-floor operators in developing their skills?
32. Has the attitude to learning and development within the company changed over time?
33. What do you consider to be the critical factor for success when developing shop-floor skills?
34. Have the possibilities of learning for the shop-floor operator decreased / increased during recent years?
35. How are shop-floor operators supported in developing their skills?
36. How do you train and develop the necessary "non-technical" skills? (Language, analytical skills, holistic understanding, etc.)
37. What does your approach towards continuous improvements include? How do you engage the shop-floor operators?
Concluding questions

38. Are there anything in particularly interesting you want to highlight?

Other questions

39. Have you within the company implemented any management concepts / practices?
   Which? When?

40. Which management trends have affected the company? What about the future?
Appendix 2 - Questionnaire

This is the questionnaire used in the second study presented in Chapter 3 (translated from Swedish).

The future operator

Future operators, namely those who are employed in our manufacturing industry within 5-10 years, you are today is a teenager. In our research we interviewed production managers and HR specialists who gave his view of the competence requirements of future operators. Now we want your opinion on the manufacturing industry as a workplace and especially the work as operator.

1. Have you in any way come in contact with a manufacturing company? Select one or more options that apply to you.
   - [ ] I have a family member / friend working in the manufacturing industry.
   - [ ] I have been on field trips to a manufacturing company.
   - [ ] I have worked in a manufacturing company.
   - [ ] Other: _______________________________________________________________
   - [ ] I have not been in contact with a manufacturing company at all.

2. Have you been able to get a picture of how it is to work at a manufacturing company?
   - [ ] I have a family member / friend working in the manufacturing industry.
   - [ ] I have been on field trips to a manufacturing company.
   - [ ] I have worked in a manufacturing company.
   - [ ] Other: _______________________________________________________________
   - [ ] I have no idea of how it is to work at a manufacturing company at all.

3. What high school programs are you attending?
   - [ ] Technology Program
   - [ ] Volvo High School
   - [ ] Industrial Technical
   - [ ] Other: _______________________________________________________________
4. What words do you fit in to a job as an operator at a Swedish manufacturing company today? Select 3-5 words / statements that you think fit.

Accuracy; Bad working environment; Boring; Career opportunity; Challenging; Clean; Creativity; Development; Dirty; Do not need to think; Engaging; Excellence; Fun; Good salary; Good working environment; High competence; Holistic view; Independently; Innovative technology; Interpersonal skills; Low competence; Messy; Monotonous tasks; Multi-skilled; Old technology; Orderliness; Poor salary; Simple tasks; Teamwork; Working alone

☐ I have no view at all, whether positive or negative, about the work that the operator (no additional options need to be marked).

During the interviews yielded production managers and HR specialists their view of the competence requirements they think will be the future operators. Their words have been compiled in this picture. It’s like you can see quite comprehensive competence requirements they see ahead. We would like to have your opinion on these means.

Put yourself in the situation that you are working as an operator on a production line where there is quite a variety of manual assembly stations and some automated assembly stations with robots.
What does it mean to be a team player with interpersonal skills?

What does it mean to be innovative, creative and get things done?

What does it mean to have a holistic understanding of the production system?

What does it mean to be flexible and multi-skilled?

What does it mean to have IT-knowledge?

What does it mean to work proactively and have an ability to interpret processes and relationships?

If in five years you would be working as an operator in the manufacturing industry, what do you think would be the three most important conditions for you to be happy and do a good job?
Appendix 3 – OpenRules for an Expert System

Figure 61 is an example of OpenRules written using a spread sheet system. More information on OpenRules can be found at www.openrules.com.

Figure 62. Examples of OpenRules written using a spread sheet system.
**Appendix 4 – SUS questionnaire**

The SUS questionnaire. When used it was translated to Swedish.

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<th>Strongly disagree</th>
<th>Strongly agree</th>
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<td>1. I think that I would like to use this system frequently.</td>
<td></td>
<td>![Radio buttons](1 2 3 4 5)</td>
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<tr>
<td>2. I found the system unnecessarily complex.</td>
<td></td>
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</tr>
<tr>
<td>3. I thought the system was easy to use.</td>
<td></td>
<td>![Radio buttons](1 2 3 4 5)</td>
</tr>
<tr>
<td>4. I think that I would need the support of a technical person to be able to use this system.</td>
<td></td>
<td>![Radio buttons](1 2 3 4 5)</td>
</tr>
<tr>
<td>5. I found the various functions in this system were well integrated.</td>
<td></td>
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<tr>
<td>6. I thought there was too much inconsistency in this system.</td>
<td></td>
<td>![Radio buttons](1 2 3 4 5)</td>
</tr>
<tr>
<td>7. I would imagine that most people would learn to use this system very quickly.</td>
<td></td>
<td>![Radio buttons](1 2 3 4 5)</td>
</tr>
<tr>
<td>8. I found the system very awkward to use.</td>
<td></td>
<td>![Radio buttons](1 2 3 4 5)</td>
</tr>
<tr>
<td>9. I felt very confident using the system.</td>
<td></td>
<td>![Radio buttons](1 2 3 4 5)</td>
</tr>
<tr>
<td>10. I needed to learn a lot of things before I could get going with this system.</td>
<td></td>
<td>![Radio buttons](1 2 3 4 5)</td>
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Appendix 5 – SUS scores

There SUS scores from the tests presented in Chapter 6. L1 – L20 and V1 – V23 refers to the individual participants.

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<td>L5</td>
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Appendix 6 – Productivity and Quality variables

The time (in minutes) for finishing the measurement sequence in test cases II (Spreadsheet) and III (ARES) depending on number of errors incurred (presented in Chapter 6). L1 – L20 and V1 – V23 refers to the individual participants.

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