THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Cognitive Automation in Mixed-Model Assembly Systems

- Current and Future Use in Automotive Industry

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Cover: A mobile ICT tool used to meet the demands from mass customization.

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Abstract

Customization and personalization of products and services has become the new standard of doing business. In order to provide highly customized products at a reasonable price flexible processes are needed. One example of how a company may supply its customers with variation is VOLVO where the C30 model can be configured to as many as 56 million unique variants. Increased variants puts great strain on the production and assembly system. The product variation creates a vast need for information to support the assembly operators working in the final assembly. As an increased number of choices are required, support by cognitive automation for assembly operators working in a mixed-model assembly environment is needed. In production, especially in an assembly context, cognitive automation aims to support decision making in order to ensure production of error-free products. Increased cognitive automation could improve the operators' work situations and decrease their workload while retaining the same physical automation. However, cognitive automation tends to be less developed than physical automation.

The objective of this Licentiate thesis is to examine how cognitive automation can best be used to support operators in mass customized assembly. Three case studies were carried out at two companies, aimed at identifying their needs concerning cognitive automation. Results of these studies showed that increased product variance caused by mass customization creates a complexity, which may impact the number of assembly errors. One cases study aimed to develop a mobile ICT tool based on a smartphone application and test its possible implementation and benefits. The use of cognitive automation such as a mobile ICT tool can reduce the error rates in complex assembly environments. Although high levels of cognitive automation exists, the actual use of such support can be low, which might be a result of support not designed for the end user. Therefore an increased level of automation does not always provide more support. By altering the carrier and content, the cognitive support can be enhanced to fit the context e.g. mobile information carriers in large assembly stations. Providing more precise cognitive automation can thus target the challenges of more parts and procedures associated with mass customization.

Keywords: Cognitive Automation, Information, Assembly Systems

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Tommy Fässberg

Gothenburg, September 2012

List of Appended Papers

Paper A **Relations between Complexity, Quality and Cognitive Automation in mixed-model assembly** (Submitted)
Fässberg, T., Fasth, Å., Hellman, F., Davidsson, A. and Stahre, J.

Submitted for publication in *Journal of Manufacturing Systems, Special Issue on Assembly Technologies and Systems*

Contribution: Fässberg, T., Fasth, Å. and Hellman, F. initiated and wrote the paper with Davidsson, A. and Stahre, J. as reviewers. Fässberg, T. and Hellman, F. gathered and analyzed the empirical data. Fässberg, T. was the corresponding author.

Paper B **iPod touch - an ICT tool for operators in factories of the future?**
Fässberg, T., Nordin, G., Fasth, Å. and Stahre, J.

Proceedings of 43rd CIRP International Conference on Manufacturing Systems, 2010, Vienna, Austria

Contribution: Fässberg, T., Nordin, G. and Fasth, Å. initiated and wrote the paper. Fässberg, T. and Nordin, G. gathered and analyzed the empirical data. Fässberg, T. presented the paper at the conference.

Paper C **Cognitive automation in assembly systems for mass customization**
Fässberg, T., Fasth, Å., Mattsson, S. and Stahre, J.

Proceedings of the 4th Swedish Production Symposium, 2011, Lund, Sweden

Contribution: Fässberg, T. initiated and wrote the paper with Fasth, Å., Mattsson, S. and Stahre, J. as reviewers. Fässberg, T. was the corresponding author and presented the paper at the conference.

Paper D **A classification of carrier and content of information**
Fässberg, T., Fasth, Å. and Stahre, J.

Proceedings of the 4th CIRP Conference on Assembly Technologies and Systems, 2012, Ann Arbor, MI, USA

Contribution: Fässberg, T. and Fasth, Å. initiated and wrote the paper with Stahre, J. as reviewer. Fässberg, T. was the corresponding author and presented the paper at the conference.

List of Additional Papers

Interaction between Complexity, Quality and Cognitive Automation
Fässberg, T., Fasth, Å., Hellman, F., Davidsson, A. and Stahre, J.

Proceedings of the 4th CIRP Conference on Assembly Technologies and Systems, 2012, Ann Arbor, MI, USA

Development of production cells with regards to physical and cognitive automation – A decade of evolution
Fasth, Å., Mattsson, S., Fässberg, T., Stahre, J., Höög, S., Sterner, M. and Andersson, T.

Proceedings of the International symposium on Assembly and Manufacturing, 2011, Tampere, Finland

An empirical study towards a definition of production complexity
Fässberg, T., Harlin, U., Garmer, K., Gullander, P., Fasth, Å., Mattsson, S., Dencker, K., Davidsson, A. and Stahre, J.

Proceedings of the 21st International Conference on Production Research, 2011, Stuttgart, Germany

Towards a production complexity models that supports operation, re-balancing and man-hour planning
Gullander, P., Davidsson, A., Dencker, K., Fasth, Å., Fässberg, T., Harlin, U. and Stahre, J.

Proceedings of the 4th Swedish Production Symposium, 2011, Lund, Sweden

Production complexity and its impact on manning
Harlin, U., Bäckstrand, G., Fässberg, T., Brolin, A. and Gullander, P.

Proceedings of the 28th International Manufacturing Conference, 2011, Dublin, Ireland

Measuring interaction using levels of automation over time
Mattsson, S., Fässberg, T., Stahre, J. and Fasth, Å.

Proceedings of the 21st International Conference on Production Research, 2011, Stuttgart, Germany

iPod touch – an ICT tool for assembly operators in factories of the future – Technical concepts and requirements
Nordin, G., Fässberg, T., Fasth, Å. and Stahre, J.

Proceedings of the 3rd CIRP Conference on Assembly Technologies and Systems, 2010, Trondheim, Norway

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1 Introduction

This introductory chapter describes the background and challenges of the targeted research area and states the aim and research questions of the thesis.

1.1 Challenges of Mass Customization

An increasing number of customers are requiring highly customized products tailored to fit their varying needs for design, function, taste and lifestyle. One example of how companies supply their customers with customization is the VOLVO C30, which can be configured to 56 million unique variants. Production of this sort, mass customization, sets high demands on the entire production system, e.g. shorter product life cycles and high degrees of flexibility (Chryssolouris 2006; Koren et al. 1999; Pollard et al. 2008). Mass customization has been recognized as the new production paradigm (Jovane et al. 2003; Pine 1993) and relates to companies' abilities to provide customized products and services through flexible processes in high volumes and at reasonably low costs (Da Silveira et al. 2001).

In order to handle the variety in a final assembly context, mixed-model assembly lines are being used. This approach makes it possible to produce different customized models on one assembly line, which results in unique products but also a more complex work environment for the operator assembling the products. Assembly lines require flexibility, which are beneficial for human operators. Case studies show that 80 % of final assembly tasks are still performed by humans despite trends towards automation (Fasth et al. 2010).

Numerous product variants increase the amount of information to and from the assembly personnel since information regarding each product variant must be available. Previous research has shown that the amount and content of information are contributors to production complexity (ElMaraghy and Urbancic 2004; Urbanic and ElMaraghy 2006). In an assembly environment, new and effective information flows are required to handle the vast amount of information available due to the high variety of products and parts. Also, the amount of information needed by the operators is individual and dependent on their level of expertise (Fjällström et al. 2009).

Product variation caused by mass customization creates a vast need for information to support operators working in final assembly. More variants and parts to handle means more decision making and therefore better decision support is required for assembly operators working in mixed-model assembly.

1.2 Cognitive Automation to Support Assembly Operators

In an assembly context automated solutions no longer only consider mechanical tasks; they also concern cognitive support for information and control tasks. A transition has been made from tools such as electric screwdriver (that only provided mechanical assistance) to "smart" tools which also provide cognitive support. Hence the scope of automation has widened through the use of Information Technology (IT). Today automation has an impact on the cognitive functions of the operators, on their thinking as well as on their doing (Hollnagel 1995).

"*Cognitive automation is software intended to automate cognitive activities, such as situation assessment, monitoring, and fault management, that are currently performed by human operators*." (Thurman et al. 1997)

In production, especially in an assembly context, cognitive automation is aimed at supporting decision-making ensuring that error-free products are produced. Choices that an assembly operator is faced with are typically parts, fixture, tool, and assembly procedure choices (Zhu 2009). An increased cognitive Level of Automation (LoA) (i.e. more decision-making tasks are performed automatically) could improve the operators' work situation and decrease their workload while the same physical automation is maintained (Fasth and Stahre 2010). This encourages a shift in focus from physical to cognitive automation.

To develop precise automation that targets the complexity of modern assembly, existing needs and problems must be understood. When the complexity of the assembly task is better understood, adapted solutions can be developed.

1.3 Aim

The aim of this Licentiate thesis is to contribute to a better understanding of how cognitive automation can be used to support operators working in mass-customized assembly.

1.4 Research questions

To fulfill the aim, two research questions have been formulated. The first research question addresses the challenges in industry today while the second question addresses how these challenges can be met.

RQ1: What are the needs for cognitive automation in semi-automated assembly systems?

One challenge in modern production systems is the increasing number of variants and parts. The focus of this question is to understand how the challenges of mass customization relate to the level and use of cognitive support.

RQ2: How can the needs for cognitive automation in semi-automated assembly systems be addressed?

When the needs for cognitive automation in semi-automated assembly systems have been understood, they will have to be addressed. Research question two aims to map important parameters which need to be acknowledged when designing cognitive automation, and how different design parameters can affect the use and precision of cognitive automation.

1.5 Delimitations

The scope of this thesis is limited to final assembly and mixed-model production system. Within the assembly system, focus has been on a task and station level since this is where cognitive automation is used, although the effects are related to higher system levels. The effects on task and station level have mainly concerned quality and time parameters. No cost calculations have been made to quantify the effects of cognitive automation. Furthermore, cognitive automation will not be discussed from a psychological perspective.

The product-development phase and its interactions with production have not been included. However, the complexity of the product and requirements on quality and traceability are acknowledged as drivers for increased use of cognitive automation.

1.6 Structure of the thesis

In Chapter 1 an introduction to the research area has been given, along with the research questions. In *Chapter 2* the research approach and methods used are described. *Chapter 3* provides the frame of reference while *Chapter 4* summarizes the appended papers, mainly focusing on the results. Discussion of the methodology, results and future research is covered in *Chapter 5*. The conclusions of this thesis are presented in *Chapter 6*.

2 Research approach

This chapter describes the process, the methodology and methods used to meet the aim of the thesis.

2.1 Research design

There is more to a research design than the outlining of a work plan. The main purpose of the design is to help avoid situations where the collected evidence does not address the initial research questions (Yin 2003). Therefore, the design needs to originate in the research questions and provide a number of steps to reach the answers, or as Yin (2003) puts it "a logical plan for getting from here to there".

A research question can be answered using a deductive or inductive approach. The deductive approach is based on theoretical considerations where theory is tested empirically while the inductive approach develops theory based on empirical findings (Bryman 1997). The deductive approach is associated with quantitative research while an inductive approach is associated with qualitative research (Starrin and Svensson 1994). Both approaches have their merits and drawbacks, and a combination of the two is argued to accomplish a wider picture of the studied subject (Bryman 1997). In this thesis a combination of the two approaches have been used to fulfill the aim.

The research process is centered around three case studies, A, B and C, visualized in Figure 1. The three case studies have been performed within the framework of two research projects. Case A was performed within the Complex Project and the results from this case are presented in appended Paper A. Cases B and C were carried out in the project Flexible assembly Process for the Car of the Third Millennium (MyCar). These cases are presented in appended Papers B and C. A more thorough description of the research projects covering their aims and scope, follows in *Section 3.7*. The methods used and the rationale behind the choices of methods will be described briefly below. More detailed information regarding the use of the methods is found in *Chapter 4* Summary of Appended Papers.

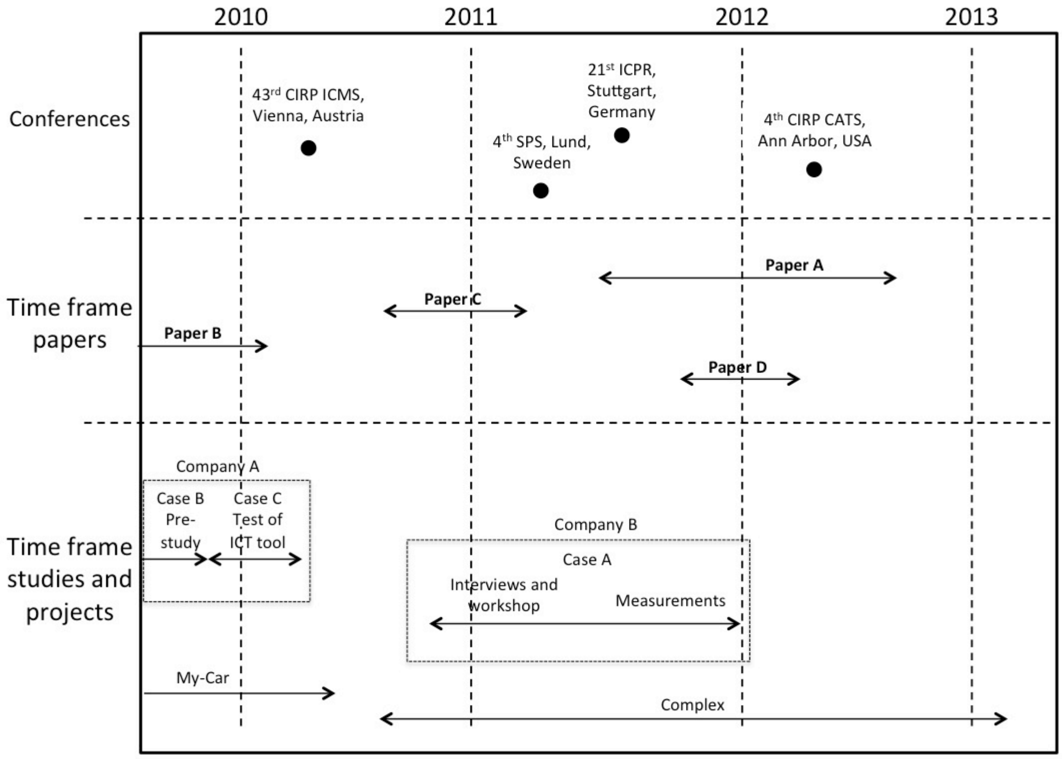

Figure 1. Overview of studies and papers over time

2.2 Methods

Different methodologies and methods have been used to answer the formulated research questions. In this thesis the term methodology refers to a framework or guiding system for solving a problem using a collection of methods in a structured manner, in accordance with the Oxford dictionary definition *"a system of methods used in a particular area of study or activity"*[1]. In this section the methodology and methods used will be described and related to the performed studies.

2.2.1 Case Study

The case study methodology allows for an explored issue to be viewed through a variety of lenses (Baxter and Jack 2008), revealing the complexity of the problem. According to Yin (2003) a case study approach is preferred if the study wants to answer "how" and "why" questions or wants to explore contextual conditions and characteristics of real-life events. The approach is flexible and allows the usage of many different data sources (Baxter and Jack 2008) which need to converge (Yin 2003). The mix of data and/or methods and a combination of quantitative and qualitative methods can be used to let diverse viewpoints cast light upon a topic (Olsen 2004). If the aim of the case is to evaluate an unknown outcome, the study needs to be of an exploratory type (Baxter and Jack 2008). If the case sample selection is chosen strategically, forming a critical case, it can be used for hypotheses testing (Flyvbjerg 2006).

[1] http://oxforddictionaries.com/

Three case studies have been performed at two companies. All studies have covered line segments and station at mixed-model assembly lines producing complex products for the automotive industry. In case study A, the case selection was based on the complexity of the line segment forming an extreme or deviant case in accordance with (Flyvbjerg 2006). In Case study B, stations from two different assembly lines were chosen to gather a broad representation of the studied area forming a current state analysis. In case C, the sample selection was chosen to form a critical case, meaning that if the results are valid for the selected case it is valid for all or many other cases.

2.2.2 Interviews

To gain access to how people perceive their surroundings, why not talk to them (Kvale 1997: 9). Interviews are commonly a meeting between two persons, but they can also be performed in groups e.g. forming a workshop. An interview can be structured similar to a survey, unstructured or somewhere in-between (Merriam 1994). A structured interview permits comparisons between interviews without losing the depth of a personal interview (Flynn et al. 1990). The unstructured interview is often used to explore something new in order to gather data to base new questions on (Merriam 1994). One interview can include both structured and unstructured elements. The structured part is to verify, and the unstructured part can provide uncovering insights.

Interviews and/or workshops have been performed during all case studies to gather the views of assembly operators and other personnel. In study A, on-site interviews were carried out with operators regarding views on complexity and support systems. In study B, interviews were done with assembly operators and different functions supporting the assembly system, interviews focused on the existing information-support system. In study C, both interviews and a workshop were held to gather opinions on the use of a tested mobile ICT tool.

2.2.3 Measure and Analyze Levels of Automation

In order to measure and analyze the Level of Automation (LoA) of the studied system and to suggest new solutions the Dynamo++ methodology has been used. The aim of the Dynamo++ is to provide a structured approach to task allocation within a span of LoA. The Dynamo++ is a development (Fasth et al. 2008) of the Dynamo methodology developed by Granell et al. (2007). The development from Dynamo to Dynamo++ mainly focused on the analysis phase of the methodology.

The methodology consists of 12 steps divided into four phases, each containing three steps visualized in Figure 2. Phase one and two concern the current state of the studied system while phase three and four concerns development and implementation of a new solution.

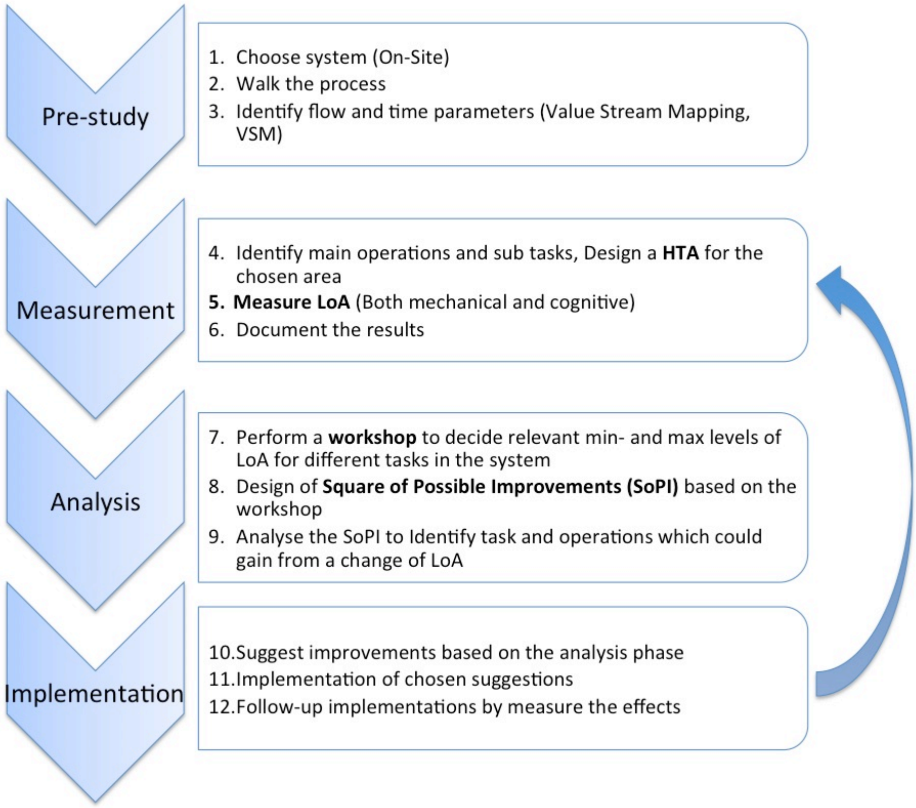

Figure 2. Phases and steps in the Dynamo++ methodology

The Dynamo++ has been used in cases B and C. During case A, the LoA measurement method, step 5 from the measurement phase has been used separately. The key methods used, marked bold in Figure 2, are further described below.

Hierarchal Task Analysis and LoA Assessment, step 4 and 5

In the measurement phase of the Dynamo++ methodology, a LoA assessment method was used to visualize the current LoA for one or several operations. The operations were decomposed into sub-tasks by performing a Hierarchical Task Analysis (HTA) (Shepherd 1998). The decomposition can be done by observations and/or be based on existing work instructions. Each task is then assessed according to Frohm's (2008) LoA taxonomy covering both physical and cognitive automation. The assessment is visualized in a matrix as seen in Figure 3.

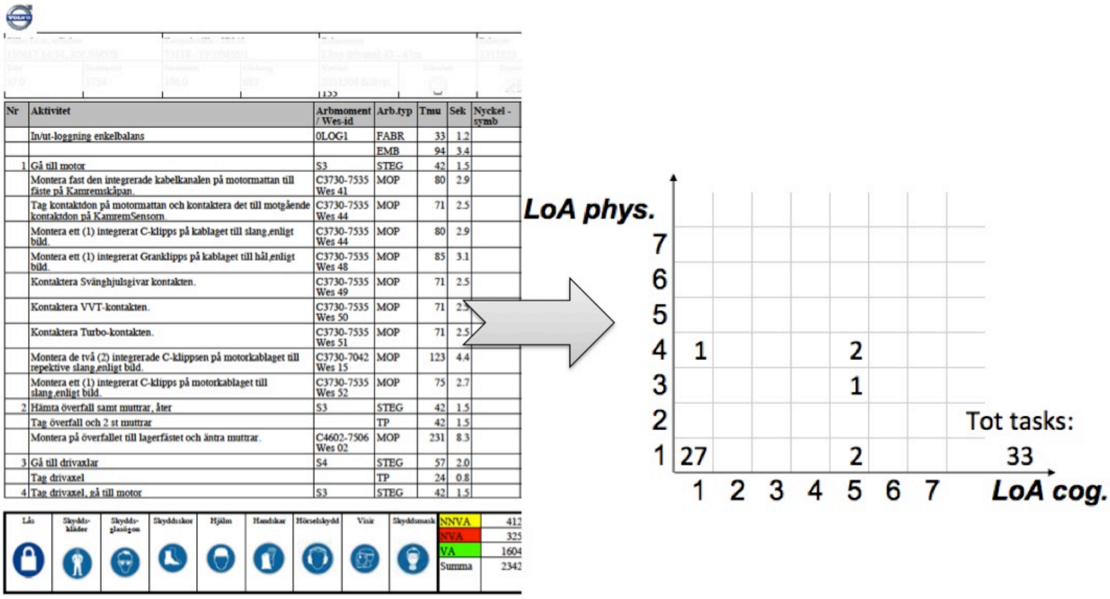

Figure 3. Creation of LoA matrix from a work instruction

Workshop and Square of Possible Improvements, step 7 and 8

The LoA assessment and matrix visualizes the current state of the studied system. A workshop with operators, production engineers, quality representatives and management functions is used to assess feasible boundaries of automation. Plotting these boundaries for each task or clusters of tasks in the matrix yields a Square of Possible Improvements (as seen in Figure 4), that shows the allowed action space, or room for improvements i.e. the Square of Possible Improvements (SoPI).

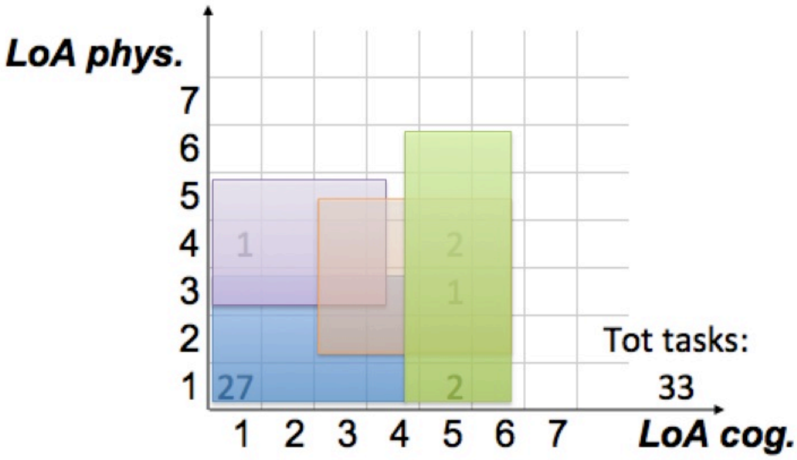

Figure 4. Example of a Square of Possible Improvements (SoPI)

2.2.4 Operator Choice Complexity

Case study A examined if there existed a relation between complexity and the level of assembly errors. The measure of Operator Choice Complexity (OCC) was used as an objective measure for complexity. OCC is a measure developed to quantify human performance when making choices (Zhu 2009). The measure is based on an entropy function and is defined as: "*Choice complexity is the average uncertainty or randomness in a choice process, which can be described by a function H in the following form*" (ibid):

$$H(X) = H(\rho 1, \rho 2, \ldots, \rho M = -C \cdot \sum_{m=1}^{M} \rho m \cdot \log \rho m \qquad \textit{Equation 1.}$$

In the equation, C is a constant dependent on the base of the chosen logarithmic function, and ρm is the probability of a choice taking the m^{th} outcome. In case study A, this measure was used to capture an objective measure of complexity. By assessing the number of possible variants at a given assembly station and the given demand for each variant, the probability for each variant was given. This probability was then used in equation 1, and a complexity measure for the station was given based on the variance of variants. This reasoning can be expanded to include choices of fixtures, tools and parts.

3 Frame of reference

This chapter provides the frame of reference on which the thesis and appended papers are based. First, theory related to mass customization, assembly systems and the role of complexity are presented and then the role and importance of information systems and automation in assembly systems are dealt with.

3.1 Mass Customization

The foundation for advanced production systems was created during the 19th and 20th century. Since the industrial revolution, the prevailing production philosophy has shifted a number of times. A shift from craftsmanship to mass production occurred in the early 20th century, and in the early 21st century mass customization was recognized as the new paradigm for production (Jovane et al. 2003; Pine 1993). Mass customization influences the entire production system in its ambition to provide each customer with a unique product or service since "*Mass customization relates to the ability to provide customized products or services through flexible processes in high volume and at reasonably low cost*" (Da Silveira et al. 2001).

The justification of a transition to mass customization is mainly based on three factors. First, customers are becoming more difficult to generalize, which creates a fragmentation on the market. Also, customers are demanding more variety and features that personalizes the products. Second, a shortening of products' life cycles, faster technological change and increased industrial competition are expected. Third, new advances in manufacturing technology make extreme flexibility possible for example by the use of IT (Hart 1995; Kotha 1995).

Several different strategies can be used to achieve mass customization. In a classification by Gilmore and Pine (1997), four strategies were mentioned; *adaptive*, *transparent*, *cosmetic* and *collaborative*. In *adaptive* customization customers are offered a standard product, which they can customize themselves; *transparent* customization means that customers are provided with a unique product without this being explicitly told. *Cosmetic* customization is when a standard product is promoted differently to different customers. In *collaborative* customization the end user helps to define the end product. In the automotive business, mass customization is achieved collaboratively (MacCarthy et al. 2003). Although automotive companies have a limited model program, they can offer an extensive number of options for the customers to choose from, for example the BMW 7 series can be modified to reach 10^{17} variants[2].

[2] http://www.bmwgroup.com

3.2 Assembly Systems

The assembly system is an integrated part of the production system and can be defined as *"An arrangement of facilities that is utilized for the assembly of a product or products. Examples are assembly stations, assembly cell, assembly line, etc."* (CIRP 2012). In this thesis the production system is superior to the manufacturing system, and covers all steps from raw material to end customer (Groover 2001). The production system can be characterized as a transformation system, transforming input to output. In the assembly system, transformation is achieved by putting parts together (Mattson and Jonsson 2003), where parts can be joined together either into subassemblies or finished products (Bellgran 1998). A simplified model of a transformation process (Hubka and Eder 1988) is expressed in Figure 5. The model consists of four parts, which all supports the transformation: human, technical, information, and management system. The human and technical systems constitute the execution part of the system, and the information and management systems govern the knowledge and supervision of the transformation. It is mainly how the information system supports the human system that is of interest for this thesis. As in the socio-technical system view, the operator is seen as an integrated part of the system rather than as a component i.e. the human system is complementary rather than only an extension of the machine system (Trist 1981).

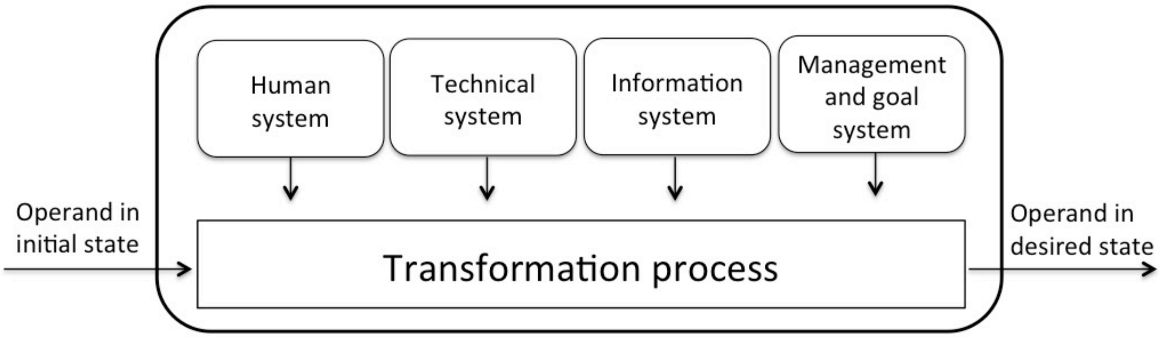

Figure 5. Simplified model of Hubka and Eders' (1988) transformation process

An assembly systems layout can be arranged in many different ways. The relationship between layout, product and process has been visualized by Hayes and Wheelwrights (1979) in their product-process matrix which can be seen in Figure 6. According to Da Silveira et al. (2001) mass customization is found below the main diagonal in the product-process matrix due to its characteristics of high volume and high variety. The dominating layout in automotive companies are the assembly line, which has been defined as "*An assembly system in which several work stations are linked together in the sequence of operations required*" (CIRP 2012).

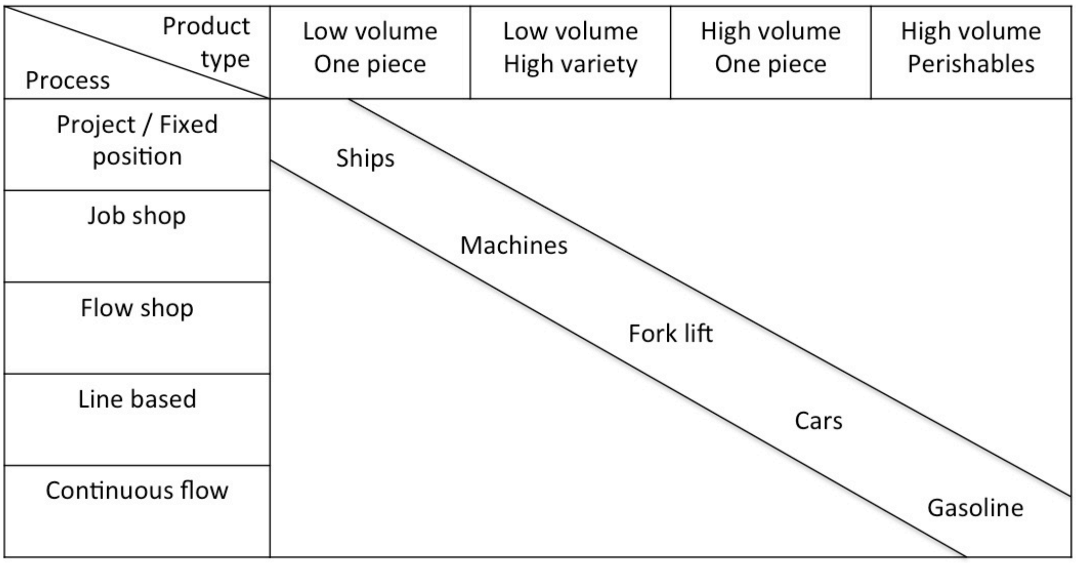

Figure 6. Product process matrix (Hayes and Wheelwright 1979)

In order to handle the variety of mass customization within a factory while achieving volumes, a mixed-model assembly system is used. In such a system, many different models are being assembled at the same assembly line forming a mixed-model assembly line represented in Figure 7. The mixed-model assembly line is recognized as an enabler to handle variety in production (Zhu et al. 2008). Although mixed-model assembly systems enable high variety, such systems tend to get very complex as variety increases (Hu et al. 2008). The complexity ranges from planning aspects on a managerial level down to increased assembly choices on an operator level.

Figure 7. Example of the principle of a mixed model assembly line

Delayed product differentiation is a strategy in mixed-model assembly to move the point of differentiation as late as possible in the system and thus be more cost efficient by avoiding unnecessary inventory and Work-In-Process (WIP) (Hu et al. 2008). Assembly precedes the sales process, but succeeds fabrication (Hu et al. 2008) which means that products have accumulated value before the assembly process, making assembly errors expensive. This motivates a special focus on error-free processes in assembly.

3.3 Complexity in assembly

The increasing complexity is one of the main challenges for production companies (ElMaraghy et al. 2012). The term complexity is, however, rather vague and can be ambiguous. Weaver (1948) defines complexity as the degree of difficulty to predict the system properties given the properties of the systems parts. Previous research has identified several factors causing production complexity. Calinescu and colleagues (1998) presented six categories of factors causing complexity, namely: product, plant/shop, planning, information, other, and environment. Urbanic et al. (2006) introduced a model of complexity where quantity, diversity and information content are directly associated with complexity. MacDuffie and colleagues (1996) made use of four measures to capture variety related to complexity within the automotive industry: model mix, part variation, level of content and variability of options. The relationship between complexity, and variety of products and parts has been investigated by several authors (Hu et al. 2008; MacDuffie et al. 1996; Schleich et al. 2007) and has been referred to as the main cause of complexity within the automotive industry (Schleich et al. 2007). The complexity in mixed-model assembly caused by a high level of variety is by Hu and colleagues (2008) called "choice complexity", which concerns all choices that the assembly operator can make and the risk for errors associated with these choices. One way to measure complexity in a production context is to use Shannon's information entropy function, developed to measure uncertainty and randomness of a variable in a system (Abad 2010; Frizelle and Woodcock 1995; Zhu et al. 2008).

Rouse and colleagues (1980) differentiated between objective complexity which can be quantified and subjective complexity. To understand operators perceived complexity it is important to have a holistic view of complexity, including subjective complexity (Gullander et al. 2011). Concerning perceived complexity Li and Weringa (2001) presented a conceptual framework for supervision and control where the technical-system complexity and task complexity are seen as the main contributors to perceived complexity. It is believed that task complexity and perceived complexity can be targeted by using cognitive automation. Better support is important since human cognitive skills are increasingly crucial when manufacturing systems become increasingly complex and subjected to changes and uncertainties (Grote 1994).

3.4 Information Systems in Assembly

According to Hubka and Eder (1988) an information system is a vital part of a technical system, as previously visualized in Figure 5. The role of an assembly line information system is to provide assembly operators with appropriate information that allows an assembly of products at the right time and quality (Case et al. 2008), thus, reducing the perceived complexity for assembly operators. Designing such information systems is difficult. According to Hollnagel (1987), an information system should provide the right information (what), at the right time (when), in the right way (how).

-*What* information to present	contents, meaning.
-*How* it should be presented	format, context and receiver characteristics.
-*When* it should be presented	timing in relation to the decision, whether it should be presented automatically or on request.

To decide what information to present is difficult, as Endsley (2000) claimed in her information-gap theory. More data does not necessarily result in more information. The problem with today's systems is not the lack of information, rather finding what is needed when it is needed (ibid). This was similarly stated by Hollnagel and Woods (2005) as "*The belief that more data or information automatically leads to better decisions is probably one of the most unfortunate mistakes of the information society.*"

According to Kehoe (1992), it is the quality rather than the quantity of information that is of importance. He presented six qualitative criteria for how to create efficient information: relevance, timeliness, accuracy, accessibility, comprehensiveness and format (ibid). Hollnagel (1987) argued that quality is not necessarily a feature of the information itself, but rather of the interaction with information, and stressed the importance of *how* and *when*. Further, there is a potential risk of cognitive overload if the operator is surrounded by much information, which creates stress (Wilson 2001). One way to cope with information overload is to filter the information (Hollnagel and Woods 2005). However, it can be difficult to decide what information is relevant (Parasuraman and Wickens 2008). This highlights the importance to present quality information rather than quantity. Also the amount of information needed by an operator is individual and dependent on their level of expertise (Fjällström et al. 2009).

It is important that information is presented in a way that considers the different possible roles of an assembly operator. According to Rasmussen (1983), operators performance is based on three different types of behavior, skill, rule and knowledge-based behaviors, known as Rasmussen's SRK-framework. Skill based behavior represents sensory-motor performance of actions, which take place without conscious control. Rule based behavior refers to a task being performed according to a stored rule, which is based on previous successful behavior used to achieve this task. Knowledge-based behavior is used when the operator is faced with a new problem where old strategies do not apply; the task is resolved by combining new and old information. In the SRK-framework the perception of information will differ depending on behavior category. The boundaries between the behaviors are not distinct and the behavior is dependent on the attention and competence of the operator. In an assembly setting a majority of tasks are done in a skill or rule-based fashion.

Situation Awareness and Human Error

Situation awareness (SA) is defined as "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*" (Endsley 1995), or simply put: "*knowing what is going on around you*" (Endsley 2000). SA consists of three levels: level 1 is the perception of elements, level 2 concerns the comprehension of the current situation, and level 3 is the projection of a future state as illustrated in Figure 8. Many of the errors recognized by human operators originate from errors in their situation awareness (Endsley 1999).

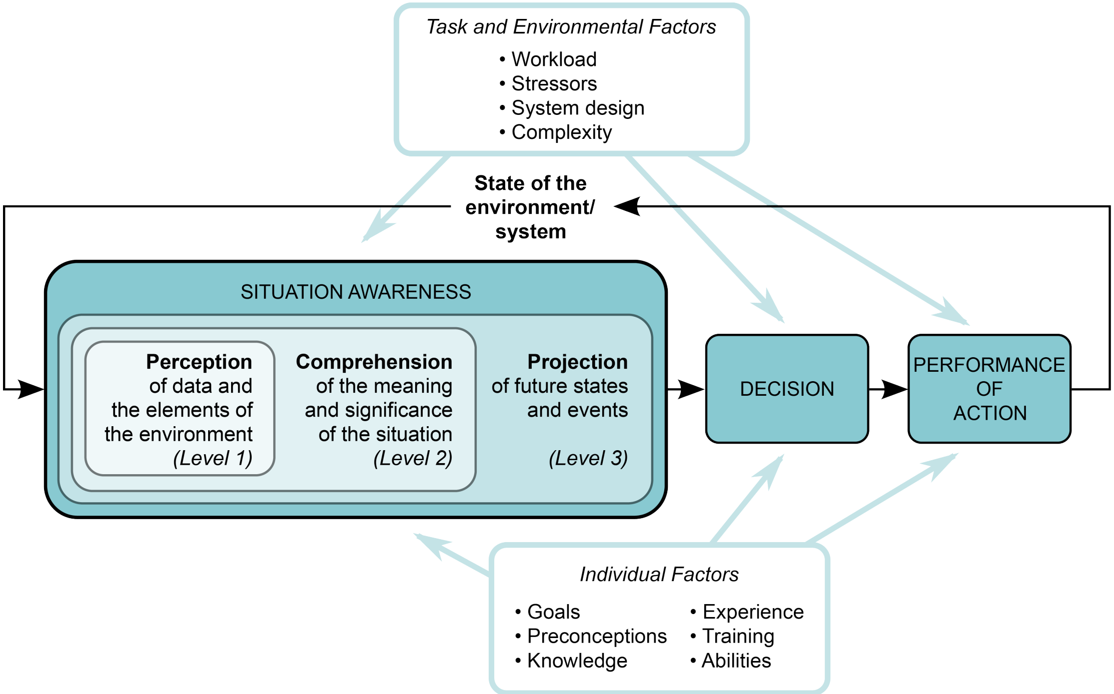

Figure 8. A model of situation awareness (Endsley 1995)

A system which fails to trigger operators' attention has an increased risk for errors (Endsley 1999). Information triggers can be used to make operators aware that information may be needed to avoid error related to SA level 1. The assembly operators' needs and demands for information create four possible situations, which are illustrated in Table 1. In situations where a need of information exists, but no demand for information is given, attention triggers are needed. Attention triggers used to create a demand for information seeking have proven to have positive effects regarding the internal quality in an assembly setting (Bäckstrand et al. 2010).

Table 1. Evaluation of need and demand of information, adapted from Case et al. (2008)

	Need of information	**No need of information**
Demand for information	This is the preferred situation. Low risk for errors due to lack of information. Information matches the need.	This situation can be frustrating for the operators'. A need have been identified, but they are not provided with the information they feel they need.
No demand for information	An error will eventually occur. A solution might be to introduce a trigger to create a demand.	Trivial situation

The information system aims to prevent human errors to ensure products of high quality. However, errors can be defined in many ways. The failure of a planned action can either be a slip or a mistake (Reason 1995). It is termed a slip if the plan of execution is adequate, but the action does not turn out as intended.

The failure to execute is associated with lack of attention. If the action goes as intended, but the plan is inadequate, it is termed a mistake. Mistakes can be divided into rule and knowledge based mistakes (Reason 1995), as the failure lies within the planning and mental process. Both slip and mistake can be avoided if there is support, in the planning of the action to avoid a mistake or the use of attention trigger during the execution to avoid a slip.

The effectiveness of an information system can be altered by manipulating the *what*, the *how* and the *when* of the system or of the carrier and content of information. For example, by changing *how* information is presented, reduced content has been shown to have an effect on internal quality in assembly operations (Bäckstrand et al. 2010). Further, Thorvalds et al. (2010) showed that quality can be greatly improved when information is provided by a mobile information source i.e. change in carrier of information. Guimaraes and colleagues (1999) showed that effective man/machine interfaces can reduce the negative impact complexity has on performance. It is believed that mobile ICT tools can remove the information access gap which can exist on a shop floor level (Emmanouilidis et al. 2009).

Learning in automotive industry

Skill and knowledge is acquired in a learning process that consists of three phases: the cognitive, the associative and the autonomous phases (Fitts and Posner 1967). The skill behavior is established first when the operator reaches the autonomous learning phase (Malmsköld et al. 2007). Malmsköld *et al.* (2007) presented a framework to understand the learning process in the automotive industry. Two training types, cognitive (computer based) and associative and autonomous (physical components) were mapped to four knowledge phases as seen in Table 2. Many of the skills described in the framework e.g. sequence of variants can be supported during the work cycle and not only during training. Information during the work cycle regarding assembly sequence and quality demands could be of great use for the operator.

Table 2. Knowledge phase framework for automotive assembly operation according to Malmsköld (2007).

Knowledge phases	Cognitive Learning (computer based training)	Associative & Autonomous Learning (Training with physical components)
Product	Product shape, special features, differences between different variants, used fasteners	How to handle, i.e. grip positions
Process	Interface parts, "third hand", placement in car, needed tool/equipment and where/how they interact with part, functionality of equipment & tools, quality of safety demands, tightening sequence demands.	Fitting in, adjustment, assembly path, tool path handling of tool.
Assembly sequence	Knowledge about valid sequences for different variants on different stations.	Performance of operations in right sequence with right quality within available cycle time.
Finesse	Knowledge about quality issues, i.e. things to have in mind when performing and why it is important to perform the operations in a certain way.	Performance of operations in right sequence with right quality within available cycle time but also with finesse care included.

3.5 Automation and Levels of Automation

Automation in its widest meaning refers to: *i.* the mechanization and integration of the sensing of environmental variables (by artificial sensors), *ii.* data processing and decision making (by computers), *iii.* mechanical action (by motors or devices that apply forces on the environment, and/or *iv.* "information action" by communication of processed information to people (Sheridan and Parasuraman 2006). In this thesis, the assembly operator has a central role in the system reflected in the view on automation, which can be defined as a device or system that accomplishes (partly or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator (Parasuraman and Riley 1997). Automation can also be seen as the allocation of physical and cognitive tasks between humans and technology, described as a continuum ranging between totally manual and totally automatic (Frohm 2008). This task division between human and machine can be termed "Level of Automation" (LoA). Frohm (2008) defined LoA, both the physical and cognitive parts, in seven different grading levels, from totally manual to totally automatic, as seen in Table 3.

Table 3. LoA taxonomy for computerized and mechanized tasks in manufacturing (Frohm 2008)

LoA	Mechanical and Equipment	Information and Control
1	**Totally manual** – *Totally manual work, no tools are used, only the users own muscle power.*	**Totally manual –** *The user creates his/her own understanding of the situation and develops his/her course of action based on his/her earlier experience and knowledge.*
2	**Static hand tool –** *Manual work with support of a static tool.*	**Decision giving –** *The user gets information about what to do or a proposal for how the task can be achieved.*
3	**Flexible hand tool –** *Manual work with the support of a flexible tool.*	**Teaching –** *The user gets instruction about how the task can be achieved.*
4	**Automated hand tool –** *Manual work with the support of an automated tool.*	**Questioning –** *The technology questions the execution, if the execution deviates form what the technology considers suitable.*
5	**Static machine/workstation –** *Automatic work by a machine that is designed for a specific task.*	**Supervision –** *The technology calls for the users´ attention, and directs it to the present task.*
6	**Flexible machine/workstation –** *Automatic work by a machine that can be reconfigured for different tasks.*	**Intervene –** *The technology takes over and corrects the action, if the execution deviates from what the technology considers suitable.*
7	**Totally automatic –** *Totally automatic work. The machine solves all deviations or problems that occur by itself.*	**Totally automatic –** *All information and control are handled by the technology. The user is never involved.*

Automation has foremost been used with three main purposes (Hollnagel, 2003);

- To ensure a more precise performance for a given function
- To improve the stability of the performance by relieving people from repetitive and monotonous tasks, which are poorly performed.
- To overcome the capacity limitations of humans when they act as control systems thereby enabling processes to be carried out faster, more efficient and possibly also more safely.

In a questionnaire-based delphi study, Frohm (2006) inquired companies and experts regarding their view on automation in manufacturing. One result was that companies perceived a difficulty to handle many products or variants by automation.

In Figure 9, factors influencing the choice of degree of automation is presented including variety and flexibility. In the final assembly, automated solutions aim to support assembly operators rather than replace them and only limited degree of automation can be implemented in the automotive final assembly (Benders and Morita 2004). A high diversity of products exists in final assembly and a high level of flexibility is needed. Hence, a majority of the work is performed “manually”. To find the “right ” level of automation in final assembly is not a simple task.

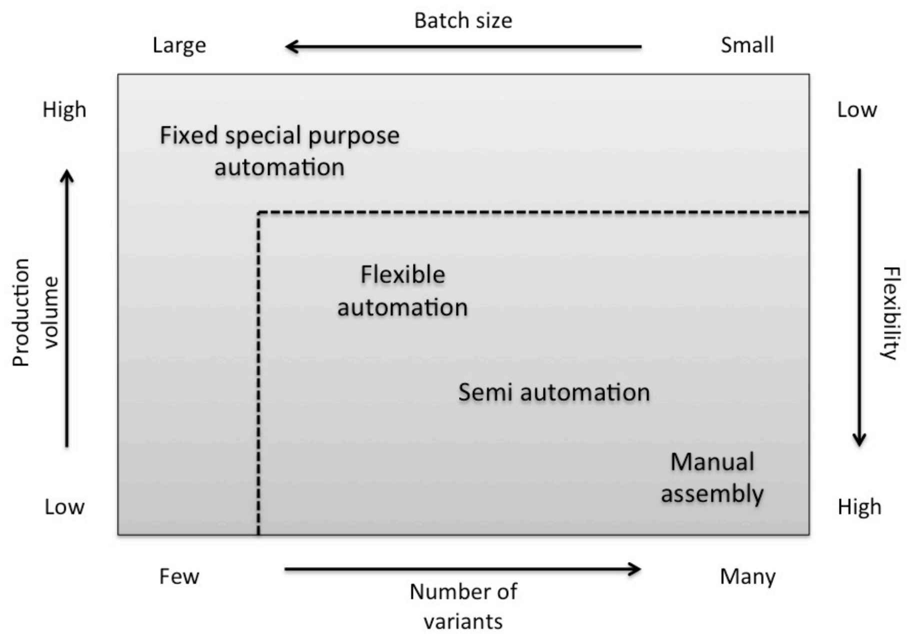

Figure 9. Factors influencing automation and assembly principle modified from (Rampersad 1994)

To address this difficult problem a concept model was constructed as a further development of the Dynamo++ methodology (Fasth and Stahre 2010). The aim was to visualize relationships between different areas and actions within a company when redesigning a system with focus on LoA through task allocation. The model is presented in Figure 10 and consists of two loops. The loop on the left-hand side is a quantitative way of describing the task allocation between operators and technique. The loop on the right-hand side describes areas of importance when performing a task allocation. Level of Competence (LoC) and Level of Information (LoI) are two important factors to consider which are related to the cognitive LoA in the studied system (Fasth et al. 2009). The role of the information system is highlighted in the concept model concerning *how* information is presented to the operators i.e. carrier and content of information. However, the concept model lacks guidelines for how to include the concepts of carrier and content in the task-allocation process.

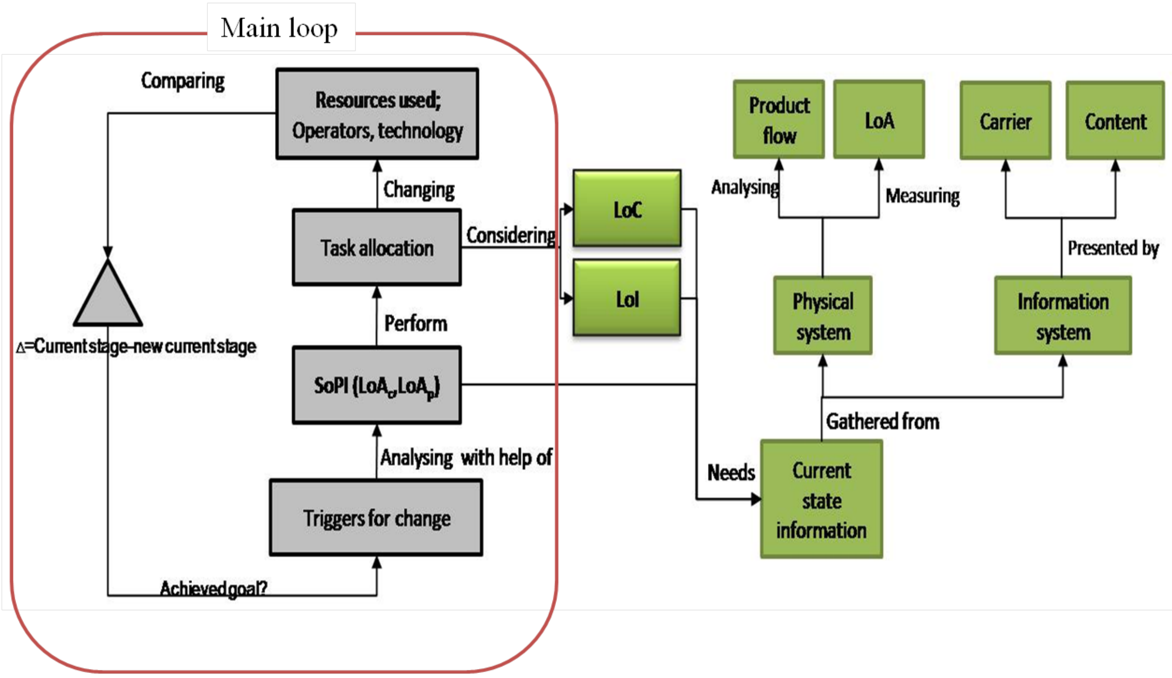

Figure 10. Concept model for task allocation (Fasth and Stahre 2010)

3.6 Cognitive Automation

As previously discussed, automation does not only consider mechanical tasks it also concerns cognitive support for control and information. In an assembly context, the support functions for operators are increasing. Thus, the scope of automation has broadened through the use of IT. One definition of cognitive automation has been provided by Thurman and colleagues (1997) "*Cognitive automation is software intended to automate cognitive activities, such as situation assessment, monitoring, and fault management, that are currently performed by human operators*". Automation has an impact on the operators' cognitive functions, his/her thinking as well as doing (Hollnagel 1995).

Parasuraman et al. (2000) introduced a LoA scale, which emphasizes the information and control side of automation as shown in Figure 11. This scale consists of four stages. *i. Information Acquisition*, which involves the acquisition, registration, and position of multiple information sources, *ii. Information analysis* refers to conscious perception, selective attention, cognition, and the manipulation of processed information, *iii. Decision selection* refers to automation as being able to make decisions based on information acquisition, analysis and integration, *iv. Action implementation,* the final step, where automation may execute forms of action. The acquisition and analysis automation is also referred to as information automation (Parasuraman et al. 2000). Frohm's (2008) definition of cognitive automation is linked to the three first stages *acquisition*, *analysis* and *decision selection*. Furthermore the four different stages of automation in Figure 11 maps the levels described in Endsley's SA model previously described in Figure 8. The first two stages of automation support the operator in the first two levels of SA, perception and comprehension of the situation.

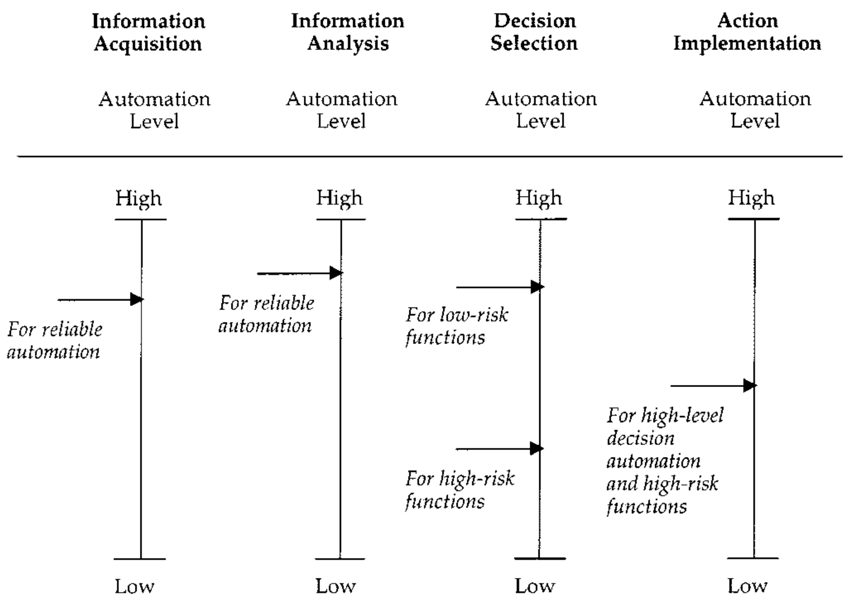

Figure 11. Levels of Automation with emphasis on information and control (Parasuraman et al. 2000)

In Figure 12, Frohm's (2008) taxonomy is presented through a matrix (Fasth et al. 2009) visualizing three different areas: *human assembling and monitoring*, *machine/technique monitoring*, and *machine assembling*. In the *human assembling and monitoring* area, cognitive automation ($LoA_{Cognitive}$) could be described as the amount of technique and information provided to the operator in order to know what, how and when to do a specific task in the most efficient way. When a tool or machine is performing the task i.e. higher physical automation ($LoA_{Physical}$ = 5-7), the cognitive automation is mainly used for control and supervision ($LoA_{Cognitive}$ = 4-7). As the focus in this thesis is on final assembly and mainly *human assembling and monitoring*, i.e. the entire matrix will not be utilized.

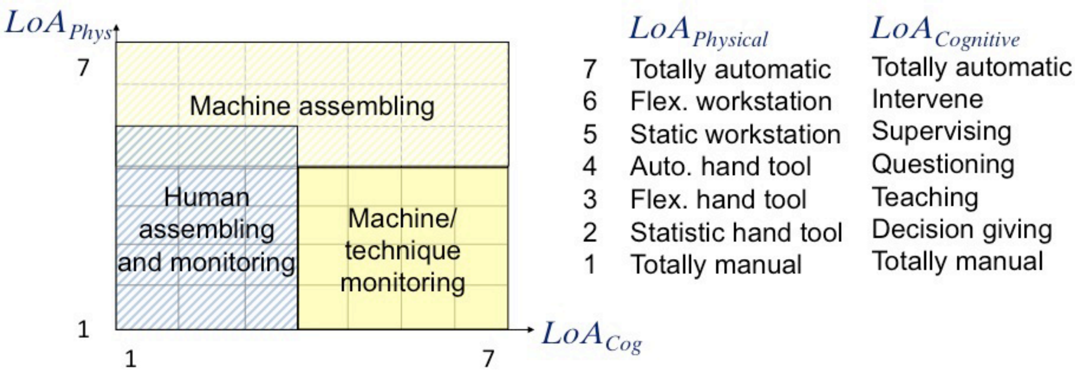

Figure 12. LoA matrix and taxonomy (Fasth et al. 2009 ; Frohm et al. 2008)

Case studies have shown that tasks in final assembly have low physical and cognitive automation (Fasth et al. 2010; Fässberg et al. 2011a; Fässberg et al. 2012). When companies redesign their systems, they often only consider the physical LoA and the cognitive LoA is solved afterwards. There is also a tendency in manufacturing companies for the cognitive LoA to be low when the physical level is low (ibid). Case studies show that over 80 % of final assembly tasks are performed by operators based on their own experiences (Fasth et al. 2010) i.e. without any decision support ($LoA_{Cognitive}$ = 1). This implies that information support could be insufficient for operators in final assembly contexts.

When implementing cognitive automation in final assembly, it is preferable to provide information rather than decisions (Parasuraman and Wickens 2008). Implying that it is better to support operators with good information rather than telling them what to do without explaining the rationale behind the decision. Human actions are determined by their understanding of the situation, not on how the designer expects or assumes the user to act (Hollnagel 1997). This sets high demand on the system to be sufficiently transparent and adaptable to the user's needs (Hollnagel 1987).

3.7 Research context

To understand the background and nature of this thesis work, the research projects and sources of funding are presented below.

3.7.1 Flexible Assembly Processes for the Car of the Third Millennium (MyCar)

MyCar, an EU project was initiated in 2006 and ended in 2011. One of the objectives was to develop an information system for human-centered assembly. In order to support assembly workers' information seeking behavior, mobile information sources were used aiming to improve productivity, quality and reduce environmental impact. A second aim was to explore and create new ways to present correct information to assembly operators when and where needed. Papers B and C are based on this project.

3.7.2 Complex

The Complex project aimed to develop generic models and methods to support strategies, planning, managing and optimizing of complex production. Complexity was studied, a definition was developed along with methods for measuring and managing complexity. Results have also contributed to IT-support tools for calculation of the total requirement of indirect and direct man-hours in production. Paper A is a result of this project.

4 Summary of Appended Papers

This chapter presents a summary of the appended papers highlighting methods, results and conclusions.

In Table 4 below, a brief summary of the four appended papers' research questions and results are presented.

Table 4. Relation between research questions and appended papers

	RQ1: What are the needs for cognitive automation in semi-automated assembly systems?	*RQ2: How can the needs for cognitive automation in semi-automated assembly systems be address?*
Paper A	A relation between complexity and assembly errors was observed. Cognitive support was low, 60 % of all tasks were performed by own experience. Errors were more common for tasks performed without cognitive support.	Cognitive automation can be used to reduce the negative effects of increased choices thus reducing the negative effects of complexity. Increased and more precise usage of cognitive automation targeting stations when complexity is high can reduce assembly errors in the final assembly.
Paper B	The usage of existing cognitive automation was found to be low. This was due to that excessive assembly related information being presented. The number of internal rejects caused by assembly mistakes was considered high.	To address the problems with low usage of instructions a concept of a mobile ICT tool based on a smartphone was introduced as an information carrier.
Paper C	Assembly information must be adapted to fit individual needs including the use of attention triggers.	The implementation of the concept developed in Paper B and further developed in (Nordin et al. 2010), shows that a mobile carrier gives more flexibility and accessibility than fixed screens. Adjustable content, e.g. text, pictures and films, were used to support individual needs. Attention triggers were introduced on tasks with high quality demands.
Paper D	Marginal contribution.	To achieve precision in cognitive automation, the concepts of carrier and content should be used in a task allocation model. When designing cognitive automation, contextual parameters such as cycle time and station size should be included.

4.1 Paper A: Relations between Complexity, Quality and Cognitive automation in mixed-model assembly

Aim and method

The aim was to investigate if cognitive automation can be used to increase quality in complex final assembly contexts. An industrial case study was carried out to study the relationships between three parameters, namely, cognitive automation, quality and choice complexity. Different methods were used to analyze the parameters. The study was carried out at a line section at Volvo Cars Corporation (VCC) final assembly factory at Torslanda in Sweden. The section was selected based on its high complexity, regarded by the company as one of the most complex in the factory. Of a total of 16 stations, covering two team areas, 7 stations were included in the study. The complexity parameter was measured using the entropy function; Equation 2 Operator Choice Complexity (OCC). The probability, P, was calculated for each variant j and for each station i. The total OCC was calculated using the entropy function. The demand for each variant was based on one week of production, 3835 products.

$$Hi(\rho i1, \rho i2, \ldots, \rho iMi) = -C \cdot \sum_{j=1}^{Mi} \rho ij \cdot \log \rho ij \qquad \textit{Equation 2.}$$

The parameter "quality" was measured by extracting errors reported to the internal quality system ATACQ. Errors were extracted for a period of 16 weeks and sorted by station. The errors caused by material and parts defects were excluded i.e. only assembly errors were included in the study. To analyze correlations between assembly errors and choice complexity parameters, a bivariate correlation analysis was done using the software JMP 9.0.0[3]. Regarding the third parameter, cognitive automation, a LoA assessment method was used. Both cognitive and physical LoA were assessed for two product variants at each station; using the most common variant regarding demand and the heaviest variant regarding time. Input to the assessment was Assembly instructions provided by Standardized Operations Procedure (SOP) sheets.

Results and conclusions

When examining the relation between OCC and assembly errors, it was evident that a positive linear correlation exists between the two parameters as illustrated in Figure 13. The correlation coefficient was 0.819, showing a significant positive correlation between OCC and assembly errors, meaning that an increase of OCC resulted in more assembly errors. Further, analysis was carried out on three stations of interest: the station with the lowest complexity and the lowest number of assembly errors (*station 13*); the station with the highest complexity and the highest error rates (*station 23*); and *station 11,* which deviated the most from the linear correlation.

[3] http://www.jmp.com/

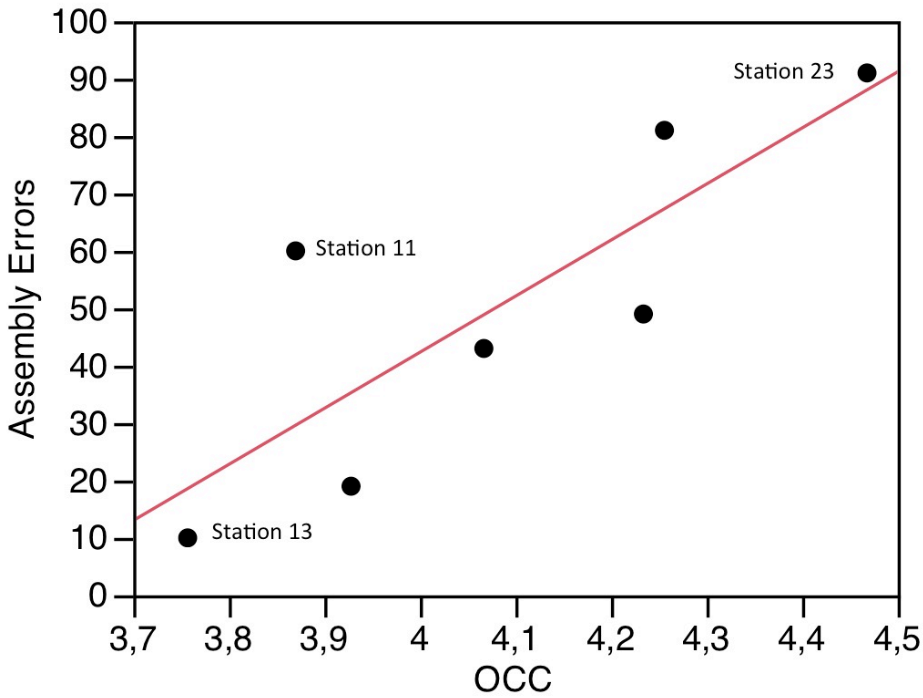

Figure 13. Relation between assembly errors and complexity (original in Paper A, figure 8)

At *station 11,* a total of 60 assembly errors were measured during the investigated period. A total of 63 % (38) of the errors were classified as “not connected”, meaning that a signal cable had not been connected. One specific part and task accounted for 38 % (23) of the total errors. The LoA of this specific task was assessed $LoA_{Cognitive}$=1 and $LoA_{Physical}$=1, meaning that the operation was performed without any support.

A total of 91 assembly errors were measured, and 60 % (54) of the errors were classified as “incorrectly fitted” in *station 23*. One single part and task accounted for 51 % (47) of the total errors. The part was either placed in the wrong position or missing. The LoA of this specific task was assessed $LoA_{Cognitive}$=1 and $LoA_{Physical}$=1, meaning that the operation was performed without any support.

At *station 13,* a total of 10 assembly errors were measured during the investigated period. They were all classified as “not connected”. The low error rate at this station could be explained by most operations at the station being associated with a high LoA. Part assurance was done with a hand scanner, and the tightening operations were counted by the system to match the number of tasks planned for.

Over 60 percent of all tasks were done using one’s own experience according to the LoA assessment and “incorrectly fitted” and “not connected” were the most common errors at the investigated stations (11,13 and 23). This can be an indicator that there is a need for more cognitive support at these stations. A distribution of the most common error types covering all stations is shown in Table 5.

Table 5. Distribution of assembly errors per type (original in Paper A, table 1)

Error type	Number of errors	Percentage of total errors
Not Connected	106	30 %
Incorrectly fitted	82	23 %
Missing	51	14 %
Not tightened	38	11 %
Loose	29	8 %
Disassembly	28	8 %
Broken	8	2 %
Wrong type	7	2 %
Other	4	1 %
Total	353	100 %

An increase in models, parts and tools will increase the choices. The OCC measure cannot be directly reduced by cognitive automation since it does not influence the actual number of parts to choose from. However, cognitive automation can reduce the perceived complexity caused by the increased OCC. A significant positive correlation was observed between OCC and assembly errors, meaning that increased choices led to more assembly mistakes. Several examples of cognitive support were identified although over 60 % of all tasks were performed relying only on one's own experience. The classification of assembly errors showed that errors were more common for tasks performed manually and without any cognitive support. Cognitive automation can be used to reduce the negative effects of increased choices thus reducing the negative effects of complexity. Increased and more precise usage of cognitive automation targeting stations with high complexity can reduce assembly errors in the final assembly.

4.2 Paper B: iPod touch - an ICT tool for operators in factories of the future?

Aim and method

The aim was to assess the need and benefits of cognitive support represented by a mobile ICT tool. To fulfill the aim a case study was carried out in the final assembly at a Swedish production company operating in the automotive industry. To paint a broad picture, two sections were chosen as a case sample, chosen from two different mixed-model final assembly lines within the same factory. The two assembly lines differed mainly in terms of the parameters cycle time and number of variants produced. Both assembly and control stations were investigated in the study making a total of four stations, two assembly and two control stations.

The focus of this paper is on the three first phases of the Dynamo++ methodology thus providing a current-state analysis. A total of seven interviews were carried out with personnel representing assembly, quality and management. The current information and communication flow were mapped focusing on the final assembly operators; both the carrier and content of information were mapped. The existing LoA, cognitive and physical, was assessed for the selected case stations. Assembly quality was assessed using reject figures from one of the lines covering a 3-month period and 2568 products.

Results and conclusions

Information and communication mappings revealed that there existed many carriers of information and redundancy of information, seen in Figure 14. Information regarding unexpected events did not have a standard channel for communication, which caused a risk of miscommunications.

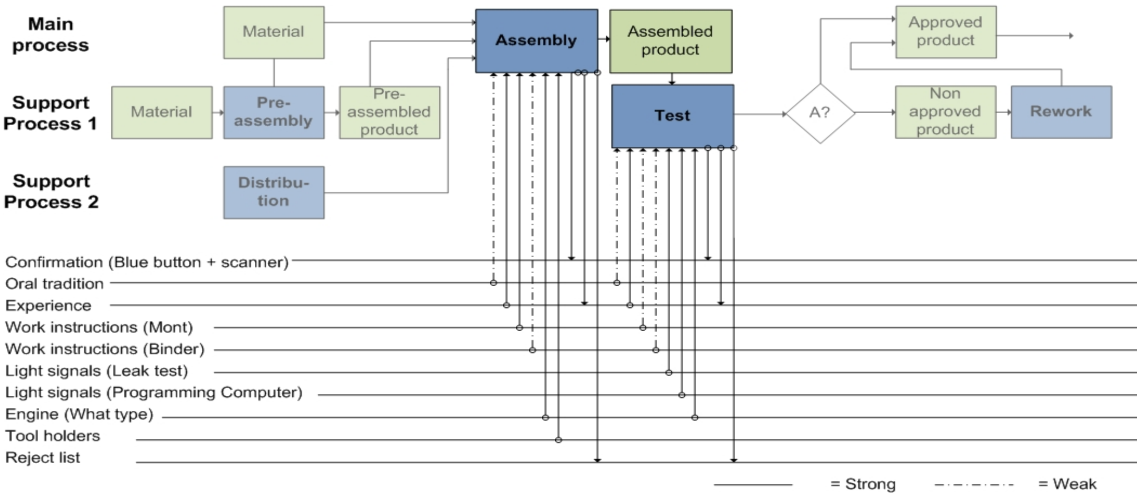

Figure 14. Information mapping for one assembly and test station showing the direction and carrier of information.

A LoA assessment showed that the available cognitive support provided by the current system was not fully utilized as visualized in Figure 15. As seen in the figure the main part of all tasks were performed using one's own experience, $LoA_{Cognitive}$ = 1. In the interviews operators stated that they did not use the information presented and experienced that too much information was provided.

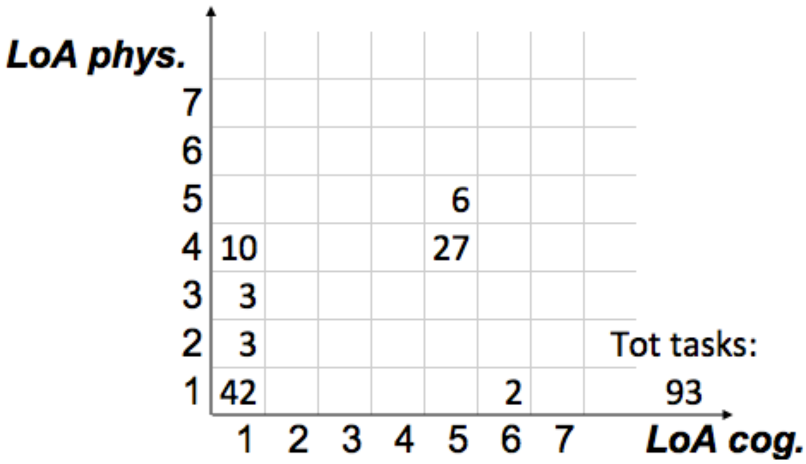

Figure 15. LoA assessment of one product, at one assembly station (original in Paper B, figure 3)

The operators described that assembly information was only needed when unusual product variants occurred. The only information operators required were the unique features of the products. The identification of what to assemble was decided by visual inspection of the products rather than by instructions, causing a risk for misinterpretations and that one error upstream possibly leading to several errors downstream.

An analysis of internal reject data revealed that approximately half of the total errors were due too assembly errors. Each assembly error was transported to the reject area where they were corrected. This is a time-consuming activity making quality a key parameter to consider. The cycle time was expected not to be affected at station level; on the contrary, it may be prolonged if more instructions are to be used. But the total lead time for the line will be positively affected if a more efficient flow could be accomplished by using cognitive automation thus reducing the need for rework in the flow.

The low use of cognitive automation was due to presentation of excessive information, mainly by assembly instructions. Half of the number of errors originated from assembly errors and caused a need for rework, which motivates efforts to increase the use of cognitive automation using a mobile ICT tool. This enables the potential to enhance the quality and improve the productivity of the entire flow.

4.3 Paper C: Cognitive automation in assembly systems for mass customization

Aim and method

The aim was to test if a developed mobile ICT tool based on a smartphone application (Nordin et al. 2010) could reduce perceived complexity for the assembly operators. The test took place at a station selected to represent the entire assembly line. Focus in this paper was on the fourth implementation phase of the Dynamo++ methodology. Four operators tested the mobile application for ten assembly cycles each, which was approximately one hour of production per operator. The station had six different variants with 25 to 29 components to assemble. The mobile device was attached to the forearm of the operator while the previously used information carrier was hidden behind a sheet of cardboard. The interaction with the mobile application was observed and video recorded for latter analysis. The test was followed by a workshop and interviews with each of the subjects.

The mobile smartphone application was based on the existing instruction system, but the carrier was changed from fixed screens to a mobile unit. Based on the findings in Paper B, the content was updated and extended with more support from pictures and videos. The abstraction level of the text-based instructions could be adjusted to suit individual requirements allowing filtering of information. Triggers for attention were introduced by vibrations. In the test study, a trigger was used when a part with a history of quality defects was to be assembled. Other included features were a preview function presenting the next three upcoming products and new communication channels for example regarding rejects of products.

Results and conclusions

The test focused on the instructional part of the mobile ICT tool. Although the size of the station was fairly restricted, a mobile information source was useful. Observations showed changes in the operators' information selecting patterns. For example, assembly-related information was used when picking parts. Previously, it had been difficult to view the information since the operator faced away from the product and source of information, see the ICT tool used when picking parts in Figure 16. Operators expressed that another benefit with the mobile ICT tool was the ability to use the keyboard without superfluous movements.

Figure 16. The use of an ICT tool during test in production

The views gathered through individual on-site interviews and during the workshop revealed that operators experienced that the placement of the device worked well and did not cause restrictions or discomfort. Furthermore, the content was easy to see. However, some concerns were raised such as the risk of banging and breaking the device. What remained an issue was that an unnecessary amount of information was presented. A solution was to only present information regarding parts that differed between variants and nutrunner operations. This solution was positively viewed by the operators. However, when reducing information the full amount of information needs to be accessible, allowing for filtering of information, if requested by the operator. Attention triggers by vibration were positively viewed as long as they were intended to be individual and not overused. Further, it was expressed that triggers should only be used where quality issues had been previously registered or where there existed a risk for confusion e.g. when introducing new products. The preview of the product sequence was considered excessive, as the next coming product was easy to identify from the previous station. New information channels provided the potential to speed up the feedback loop regarding assembly errors.

"Yesterday I made the same error seven times but it took several hours before I received any information regarding it during the lunch through a rumor".

Assembly operator 4

The mobile ICT tool was expected to increase the use of cognitive automation by changing both content and carrier of information. Thus making the information more easily accessible and relevant. A mobile carrier of information has a number of benefits in a final assembly setting due to its flexibility and accessibility. It is important that the content of information is designed to fit the end user, reducing the need to filter redundant information. It is believed that the quality of task-based instructions has an impact on the internal quality of an assembly system. Cognitive automation can be used to create better-designed information on a task level thus reducing the perceived complexity.

4.4 Paper D: A Classification of Carrier and Content of Information

Aim and method

The aim was to develop a classification of carrier and content of information that can be utilized in a task allocation process to support the design of new information systems for an assembly environment. The developed classification is mainly based on a literature review covering how different carriers and contents are used in an assembly context, but also the need of information support systems. The reviewed literature was related to observations done in the industry.

Results and conclusions

It was seen that different parameters cause different needs regarding both content and carrier of information. Parameters such as cycle time, number of tasks, and the range of motion at the workplace are important to consider in the choice of carrier and content. Mobility is an interesting carrier since it allows for information to always be within reach. The content can be presented in many different modes such as text, drawings, pictures and films. As more information needs to be presented, new and efficient ways to present information is sought. Augmented reality is an example of a future way to present content in assembly, which gives the ability to tailor-make information. Depending on how these parameters are chosen, they will affect how efficient the information flow will be.

Cognitive automation is an enabler towards more effective and competitive systems by adapting to fit operators' individual needs. The concept of dividing possible solution into carrier and content makes it easier to make the adaption. The concept provides an opportunity to give a more nuanced view of the information flow within an assembly context.

5 Discussion

This chapter discusses how the main results relate to the research questions. The methodology used is also discussed concerning validity and transferability of the results. Lastly, suggestions for future work is discussed.

5.1 The need for cognitive automation

The need for cognitive automation has been studied in an automotive setting with focus on mixed-model final assembly. The aim has been to understand how the challenge of mass customization relates to the level and use of cognitive support. The studies have been guided by *RQ1:*

What are the needs for cognitive automation in semi-automated assembly systems?

Mass customization and increasing variants have been found to increase perceptions of complexity in production (Fässberg et al. 2011b). It is not only the variety of products and parts that cause complexity, more advanced products such as new powertrains also increase the need of flexibility in manufacturing (Diffner et al. 2011), increasing the complexity of the system.

The complexity caused by variety and the increasing need of choices is observed to correlate with the level of assembly errors (Fässberg et al. 2012). Hence, assembly operators need support in mixed-model environments where a high variety of products and parts exist, and the operator needs to make a lot of choices. According to Reason (2000) "*We cannot change the human condition, but we can change the conditions under which humans work.*" One way to create a change in work conditions is by using cognitive automation to support assembly operators. However, the usage of cognitive automation is low (Fasth et al. 2010; Fässberg et al. 2011a; Fässberg et al. 2012) and many tasks in assembly are performed by one's own experience i.e. no use of cognitive automation. The low usage shows that there is a need for new automation solutions.

It was seen that the use and need of cognitive automation is context dependent. The companies studied had similar contexts regarding product and work tasks. However, due to the fact that cycle times differed, the presentation of information varied. In the short cyclic context, guidance of what to pick and assemble was given by for instance pick by lights. No time was allocated to use instructions for assistance on how to perform a task, while in the long cyclic context how and what information was given by instructions. In both cases, scanning and "smart" tools were used for part assurance and torque assistance. The errors found in the short cyclic context were made in manual tasks, seldom performed, with no cognitive support. To add cognitive automation for manual tasks, which are seldom performed, is difficult. Attention triggers may be suitable for these kind of tasks. By establishing a link between the error log system and attention triggers, attention could be based on individual previous mistakes. Another important context parameter is the size of the station or more generally the distance to information. Mobile information can be essential if the distance to the information is perceived as long, increasing the risk for errors (Thorvald et al. 2010).

To what extent cognitive automation is needed in different contexts is not obvious. In Figure 17, the need for cognitive automation has been mapped in relation to the variety of products and on number of tasks to perform on a station level. An increased number of variants create a need for more efficient information flows, highlighting the importance of the content and timing of information. When the number of tasks increases the timing of information within the work cycle becomes more important. As variety and task increases, so does the need of cognitive automation. This illustration is a simplification of reality since the parameter time is only indirectly included. However, the figure illustrates the importance of cognitive automation when variants and number of tasks increase due to mass customization.

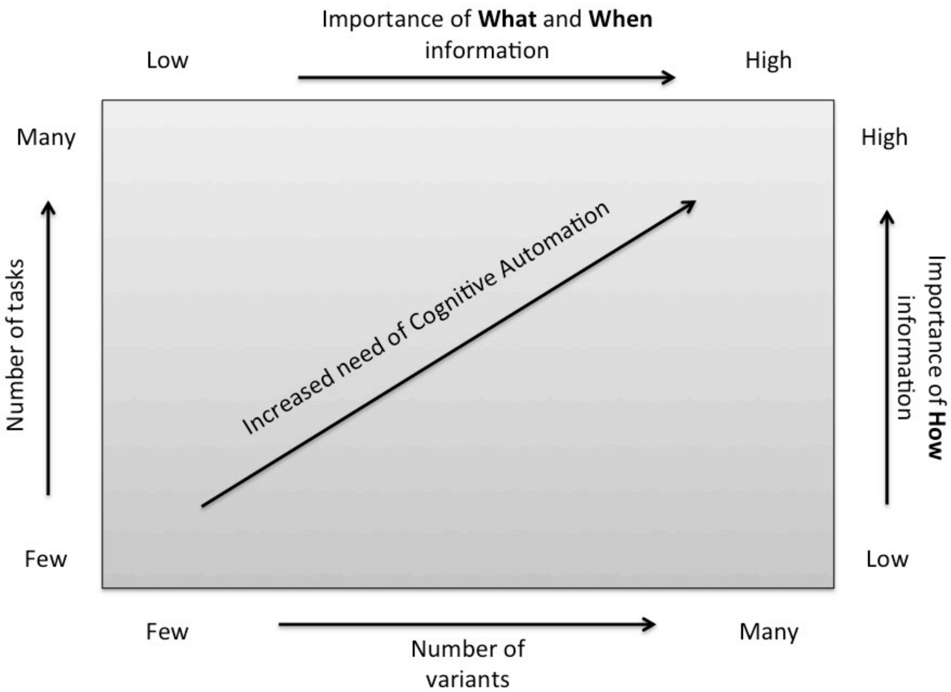

Figure 17. Need of information in relation to variety and number of tasks at one assembly station

Although three decades have passed since Bainbridge (1983) presented the possibility for operators to design their own interfaces in a control room context, this has not yet become a reality in modern information systems for final assembly. It could be argued that individualization of information and instructions in particular would clash with the focus on standardization. Standardization has many positive effects for assembly but the question is if information needs to be presented in a standardized way for a standard to be followed? Cognitive ergonomics is as important as physical ergonomics therefore possibilities for tailor-made information should be as natural as support for physical ergonomics.

An assembly operator performing one task can be seen as the smallest element in an assembly operation. In Figure 18 the importance of sufficient cognitive automation for such a task is illustrated from micro level to a macro level. By providing sufficient task-based support by precise cognitive automation better working conditions and increased quality will benefit the company not only on a shop floor level.

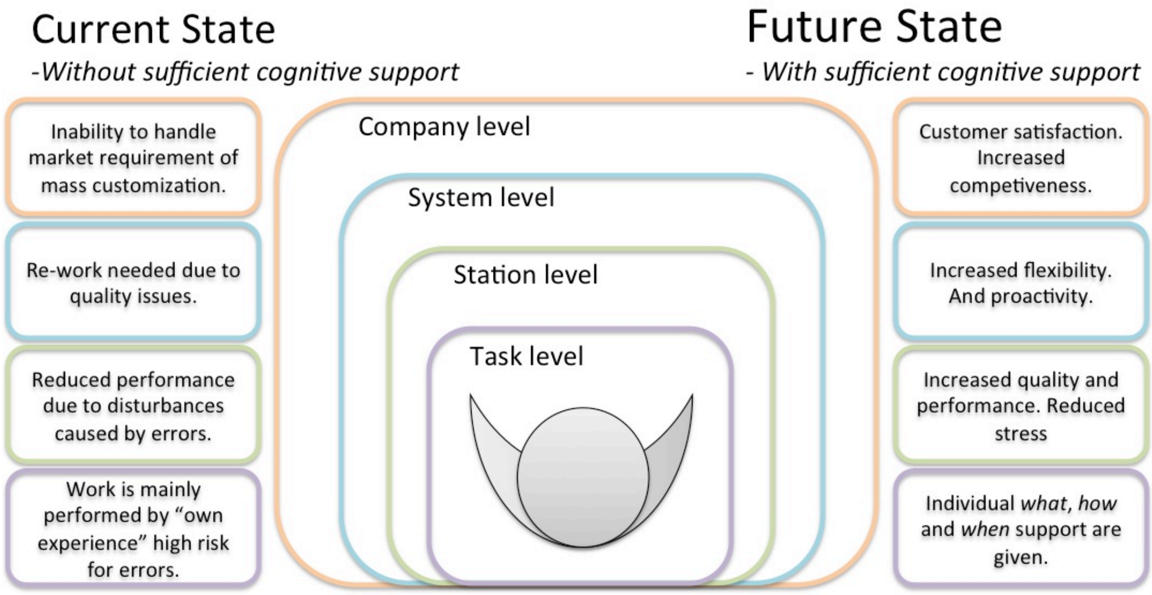

Figure 18. Effects of cognitive automation, a systems perspective

5.2 How to use cognitive automation in assembly

Based on the identified need for cognitive automation, more precise solutions needs to be developed. How to use and implement cognitive automations were the focus of the second research question. *RQ2:*

How can the needs for cognitive automation in semi-automated assembly systems be addressed?

Many cognitive automation solutions are in place in final assembly. To name a few: pick by light systems, work instructions on digital screens or paper, hand scanners for part verification and "smart" tools. However, when broken down to a task level a majority of assembly tasks are performed without any assistance from cognitive automation. This is due to support not being implemented at all possible tasks but also that the existing support is not always used.

When the need for task-based support and cognitive automation is discussed the entire spectrum of automation needs to be considered. From simple light systems, which help with the information acquisition to advanced "smart" tools, which both perform action support and controls that an operation was performed correct. The entire spectrum of cognitive automation is needed in "manual" assembly.

Regarding the low usage of existing cognitive automation, one way to increase the use is by implementing more restrictive automation, $LoA_{Cognitive} = 5$ and above in Frohm's (2008) taxonomy. Another way to increase the use of cognitive automation is individualization of information and the use of attention triggers if the potential of the system is not fully met. A mobile ICT tool based on a smartphone has been shown to have all those benefits including the ability to filter information, trigger for attention and the ability for individuality (Fässberg et al. 2011a). Furthermore, it simplified communication and collaboration between operators.

5.3 Methodological considerations

In Paper A, the LoA assessment method was used separated from the Dynamo++ methodology. In comparison to the other two measurements used, internal quality and OCC, the LoA measure is more difficult to interpret and there exists a degree of subjectivity in the assessment, which may restrict the possibility to compare values assessed by two independent observers. Furthermore, the LoA assessment figures cannot be transferred beyond the single case, which restrict the possibilities for comparisons between stations. However, the LoA matrix provides a visualization of the tasks for one product and no better method or measure for cognitive automation has been found. The Dynamo++ methodology gives a structure to difficult problems and the LoA assessment gives an overview of the problem in a visual current state, which enables for comparisons with a future state.

In Paper B and C many different methods and techniques was used within the frame of the methodology Dynamo++. The use of multiple methods with both quantitative and qualitative character gave a broad understanding of the problem. The Dynamo++ provided guidance for the first three phases, pre-study, measurement and analysis, providing usable methods and structure and room for flexibility. However, in the implementation phase guidance was lacking, especially in the step aiming to suggest new solutions. Techniques and methods from the area of product development were proven to be useful (Nordin et al. 2010).

5.4 Transferability of results

The context of research has been mixed-model assembly of advanced products that have included many components and tasks. The main focus was the cognitive automation for assembly operators. The findings suggest that there exists a need for cognitive automation to handle the increased complexity which is transferable to other areas with a similar context e.g. logistics and maintenance. Logistics stations are in many ways similar to assembly stations, however, with a focus on arranging, sequencing and kitting of parts, with a high need of choice support. Operators working at logistic stations may need more support since they lack the natural connection to the product, which makes errors more difficult to spot. Maintenance operators perform tasks, which are oriented more towards knowledge-based behavior. They are in need of detailed and flexible information and are not restricted by assembly sequence as the assembly operator. Both logistic and maintenance operators covers a large work area, making their need for mobile information potentially greater than for the assembly operator.

The demand of variants causing an increase of parts and components is a phenomenon affecting more fields than the automotive industry. As complexity in manufacturing and assembly increases so does the need for cognitive automation.

5.5 Recommendations for future work

All studies presented in this thesis have been carried out at large companies within the automotive industry. Widening perspectives to SMEs and other branches than automotive is sought after.

Studies measuring the effects of implemented cognitive automation are lacking. Case studies and experiments to quantify the relationships between cognitive automation and effects in quality and time parameters could fill this void.

The concept of a mobile ICT tool showed a potential in assembly but has not yet been implemented. Further developments of this concept, testing and usage in different company settings is key.

Due to increased development of industrial solution aimed for smartphones and tablet (Toijer 2012a), costs for development and end customer can be reduced (Toijer 2012b). Such a development has great potential to create cheap, easy-to-use solutions of cognitive automation. Thus making industrialized cognitive automation easily accessible for companies of all sizes.

6 Conclusions

This chapter concludes the findings of this thesis. The conclusions relate to the two research questions and the aim.

The need for cognitive automation for operators are related with the complexity of the work tasks. The variety and complexity of products, tools and tasks caused by mass customization can have several negative effects, such as assembly errors related to wrong decisions and longer operation times due to increased information and part searching. The findings of this thesis indicate that improved cognitive support can have positive effects on the parameters quality, time, and perceived complexity. Although high levels of cognitive automation exist, the actual usage can be low due to support not being designed for the end user. An increased Level of Automation does not necessarily provide more support per se. The support given must be adapted to fit the context in order to be fully operational and fulfill its purpose. This is key in an environment with a high level of variety of products and tasks to perform. Cognitive automation simplifies coping with the complexity of variants.

Several parameters need to be considered in the design of cognitive automation: mobility, individuality, filtering information and attention triggers. The developed mobile ICT tool for improved cognitive support includes all the above-mentioned parameters. Cognitive automation was introduced by a mobile ICT tool and was found helpful by the operators. By altering the carrier and content (task allocation model) cognitive support can be enhanced to fit the context. By providing more precise cognitive automation, the challenges associated with mass customization can be met.

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