THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Towards increasing operator wellbeing and performance in complex assembly

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Cover:
Two actions are presented that can increase operator wellbeing and performance, see section 5.1 Two actions: supporting cognition and emotion.

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ABSTRACT

This thesis provides insights on complex assembly issues and presents pragmatic models, methods, measurable parameters and prototypes that can be used to support operators in complex assembly. Assembly systems are complex partly because of a high degree of product variety and the strategy of having mass-customised products. Complex assembly causes product quality issues, uncertainties and poor ergonomics. Since stress and psycho-social health are emerging problems, it is important to further investigate how complexity affects operator wellbeing and how this and performance can be increased.

The aim of this thesis was to investigate and suggest actions that can increase operator wellbeing and operator performance in complex assembly. This was achieved by first **identifying** and **assessing** factors influencing operator wellbeing and performance. Five factors were identified as such: work variance, disturbance handling, job satisfaction, motivation and operator emotion. Empirical studies were carried out to investigate what measurable parameters could be used to assess operator wellbeing and performance. The assessment of physiological data in real-time was identified as relevant. Two prototypes were **developed** to support the factors that were discovered: the DFIP prototype was used to design work instructions to support operator cognition and the DIG IN prototype was used to support operator emotion. The tests and evaluations of the prototypes showed that operator wellbeing and performance can be supported through these prototypes.

Two actions were suggested to increase operator wellbeing and performance in complex assembly: 1) supporting cognition through improved assembly instructions and 2) supporting emotion through physiological measurement and environmental data in real time. If these actions are carried out in collaboration with operators (in regard to implementation and usability for example) and do not disrupt the operator workflow, then complexity can be reduced, performance can be increased and a more satisfying and attractive workplace can be created.

Keywords: Complex systems, assembly, operator wellbeing, performance, smart wearables.

LIST OF APPENDED PAPERS

This thesis is based on the work contained in the following papers. These are referenced in the text by Roman numerals:

I Fast-Berglund, Å., **Mattsson, S.** & Bligård, L-O. (2016) Finding Trends in Human-Automation Interaction Research in Order to Formulate a Cognitive Automation Strategy for Final Assembly. *Internationel Journal of Advanced Robotics and Automation,* vol. 1 (2), pp. 2473-3032.

Mattsson initiated the paper and did the empirical collection and analysis. Fast-Berglund finalised the paper and wrote the conclusions.

II **Mattsson, S.,** Tarrar, M., & Fast-Berglund, Å. (2016) Perceived Production Complexity – understanding more than parts of a system. International Journal of Production Research. vol. 54 (20).

Mattsson initiated and wrote the paper. The empirical analysis was done with Tarrar and Fast-Berglund.

III **Mattsson, S.,** Fast-Berglund, Å & Åkerman, M. (2017) Assessing operator wellbeing through physiological measurements in real-time - towards industrial application. Technologies special issue, Personal Health and Wellbeing Intelligent Systems Based on Wearable and Mobile Technologies. vol. 5(4), pp. 61.

Mattsson initiated and wrote the major part of the paper. Fast-Berglund and Åkerman wrote parts of it.

IV **Mattsson, S.,** Fast-Berglund, Å., & Thorvald, P. (2016) A relationship between operator performance and arousal in assembly. In 6th CIRP Conference on Assembly Technologies and Systems (CATS); 16-18th May 2016 2016, Gothenburg, Sweden. Elsevier.

Mattsson initiated the paper and did the empirical collection and analysis with Fast-Berglund (now Tarrar). Thorvald wrote parts of the paper. Mattsson was the corresponding author and Fast-Berglund presented the paper.

V **Mattsson, S.,** Fast-Berglund, Å. & Thorvald, P. (2017) Forming a cognitive automation strategy for Operator 4.0 in complex assembly. *Submitted to* Computers & Industrial Engineering special issue the Operator 4.0: Towards Socially Sustainable Factories of the Future (in progress).

Mattsson and Fast-Berglund initiated the paper, while Mattsson wrote the major part of it.

LIST OF ADDITIONAL PAPERS

1. Fast-Berglund, Å. & Mattsson, S. (2017) Smart automation - Metoder för slutmontering. Lund: Studentlitteratur AB.
2. Falck, A.-C., Tarrar, M., Mattsson, S., Andersson, L., Rosenqvist, M. & Söderberg, R. (2017) Assessment of manual assembly complexity: a theoretical and empirical comparison of two methods. International Journal of Production Research, vol. May 2017, pp. 1-14.
3. Mattsson, S., Li, D., Fast-Berglund, Å. & Gong, L. (2017) Measuring Operator Emotion Objectively at a Complex Final Assembly Station. Advances in Neuroergonomics and Cognitive Engineering pp. 223-232.
4. Tarrar, M., Harari, N. S. & Mattsson, S. (2016) Using the CompleXity Index to discuss improvements at work: A case study in an automotive company. In 7th Swedish Production Symposium; 25-27th October 2016, Lund, Sweden.
5. Johansson, P. E. C., Mattsson, S., Moestam, L. & Fast-Berglund, Å. (2016) Multi-Variant Truck Production - Product Variety and its Impact on Production Quality in Manual Assembly. In Procedia CIRP; 29-30th June 2016, Gjøvik, Norway. pp. 245-250.
6. Mattsson, S., Fast-Berglund, Å. & Li, D. (2016) Evaluation of Guidelines for Assembly Instructions. 8th IFAC conference on Manufacturing, Modelling, Management & Control (MIM 2016). Champagne, France.
7. Mattsson, S., Partini, J. & Fast-Berglund, Å. (2016) Evaluating four devices that present operator emotions in real-time. In 26th CIRP Design Conference; 15-17th June 2016, Stockholm, Sweden.
8. Mattsson, S. & Fast-Berglund, Å. (2016) How to support intuition in complex assembly? In 26th CIRP Conference; 15-17th June 2016, Stockholm, Sweden.
9. Mattsson, S., Karlsson, M., Fast-Berglund, Å. & Hansson, I. (2014) Managing production complexity by empowering workers: six cases. In Variety Management in Manufacturing. Proceedings of the 47th CIRP Conference on Manufacturing Systems; 28-30 April, 2014 2014, Windsor, Ontario, Canada. Elsevier. pp. 212-217.
10. Mattsson, S., Fast-Berglund, Å. & Stahre, J. (2014) Managing Production Complexity by Supporting Cognitive Processes in Final Assembly. In Swedish Production Symposium 2014, SPS14; September 16-18 2014, Gothenburg, Sweden.
11. Mattsson, S., Bligård, L.-O., Fast-Berglund, Å. & Stahre, J. (2013) Using Usability to Measure Interaction in Final Assembly. In 12th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design, and Evaluation of Human - Machine Systems; 2013, Las Vegas, USA. pp. 64-69.

12. Tarrar, M., Mattsson, S., Fast-Berglund, Å. & Stahre, J. (2013) Could the use of ICT tools be the way to increase competitiveness in Swedish industry? In 12th IFAC Symposium on Analysis, Design, and Evaluation of Human-Machine Systems; August 11-15 2013, Las Vegas, NV, USA. Elsevier. pp. 179-186.
13. Mattsson, S., Fasth, Å. & Stahre, J. (2012) Describing Human-Automation Interaction in production. In 12th Swedish Production Symposium 6-8 November 2012, Linköping, Sweden.
14. Mattsson, S., Fasth, Å., Berlin, C. & Stahre, J. (2012) Definition and Use of Interaction-Time in Final Assembly. In 12th Swedish Production Symposium 2011; 6-8 November 2012, Linköping, Sweden.

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LIST OF DEFINITIONS

Arousal. An individual's activity and alertness (Mehrabian and Russel, 1974).

Automation. The execution, by a machine agent, of a function previously carried out by a human (Parasuraman and Riley, 1997).

Mass-customised. The strategy of delivering customised products at a cost similar to those that have been mass-produced (Coletti and Aichner, 2011).

Perceived production complexity. The interrelations between product variants, work content, layout, tools and support tools, and work instructions from an operator's point of view (based on Mattsson (2013).

Triangulation. To increase reliability, validity and interpretation of data by collecting different types of data (Olsen, 2004).

LIST OF ABBREVATIONS

CXI	The CompleXity Index method
EDA	ElectroDermal Activity
DFIP	Design principles For Information Presentation
DIG IN	DIGitalised well-beINg
INUS	Insufficient but Necessary part of an Unnecessary but Sufficient condition

1 INTRODUCTION

This chapter describes the operator's role in complex assembly systems. It identifies research gaps relating to complex assembly, operator wellbeing and performance and operator support. Furthermore, the aim and research questions are presented alongside the direction of the thesis.

1.1 Background

It has been predicted that assembly work will change dramatically in the future. Digitalisation (keywords: the internet of things, big data, automation) is gradually transforming the traditional working environment into something more adjustable and personalised (Whitmore et al., 2015); where operator needs and requirements are considered. It is believed that operators' work tasks will change and that operators will be proactive, managing many different tasks and technologies (Griffin et al., 2007, Toro et al., 2015, Weyer et al., 2015). Operators will collaborate symbiotically with higher levels of automation, such as cobots and support systems (cobots are robots that perform a task together with an operator (Colgate et al., 1996))(Romero et al., 2015, Straeter and Arenius, 2015, Banks et al., 2014, Fereidunian et al., 2015). This will increase the level of complexity in production systems which, in turn, increases the need for knowledge and understanding of the operator in such systems (Brinzer et al., 2017, Griffin et al., 2007, Toro et al., 2015). However, assembly work is already complex.

1.2 Complex assembly

In an assembly system, material is transformed into a product through manual operations or by automated process (Bellgran, 1998, Andreasen et al., 1983, Rampersad, 1994, ElMaraghy et al., 2010). The tasks in final assembly are often manual (Fasth et al., 2010b, Michalos et al., 2010, Battini et al., 2015), limited to specific task times and follow a sequence of operations (Ghosh and Gagnon, 1989). The main part of the assembly work is when the operator monitors machines, does manual assembly, handles small disturbances, handles materials and orders and does set-up or maintenance (Sheridan, 1987, Stahre, 1995a, Stahre, 1995b).

Assembly work is complex, partly because of major product variety (Orfi et al., 2011, Schleich et al., 2007, Hu et al., 2008, MacDuffie et al., 1996) and the strategy of creating mass-customised products (Coletti and Aichner, 2011). Complexity in a system can be defined as something that is "difficult to understand, describe, predict or control" (Sivadasan et al., 2006). Complexity affects ergonomics (Battini et al., 2015), quality (Falck and Rosenqvist, 2012, Fässberg et al., 2012a), production reliability and uncertainty (Grote, 2004), performance (Guimaraes et al., 1999, Perona and Miragliotta, 2004) and production time (Urbanic and ElMaraghy, 2006, Lokhande and Gopalakrishnan, 2012). In this system, the operator is affected by disturbances, demands, product variants, environment, tools and support tools, instructions and components, see Figure 1.

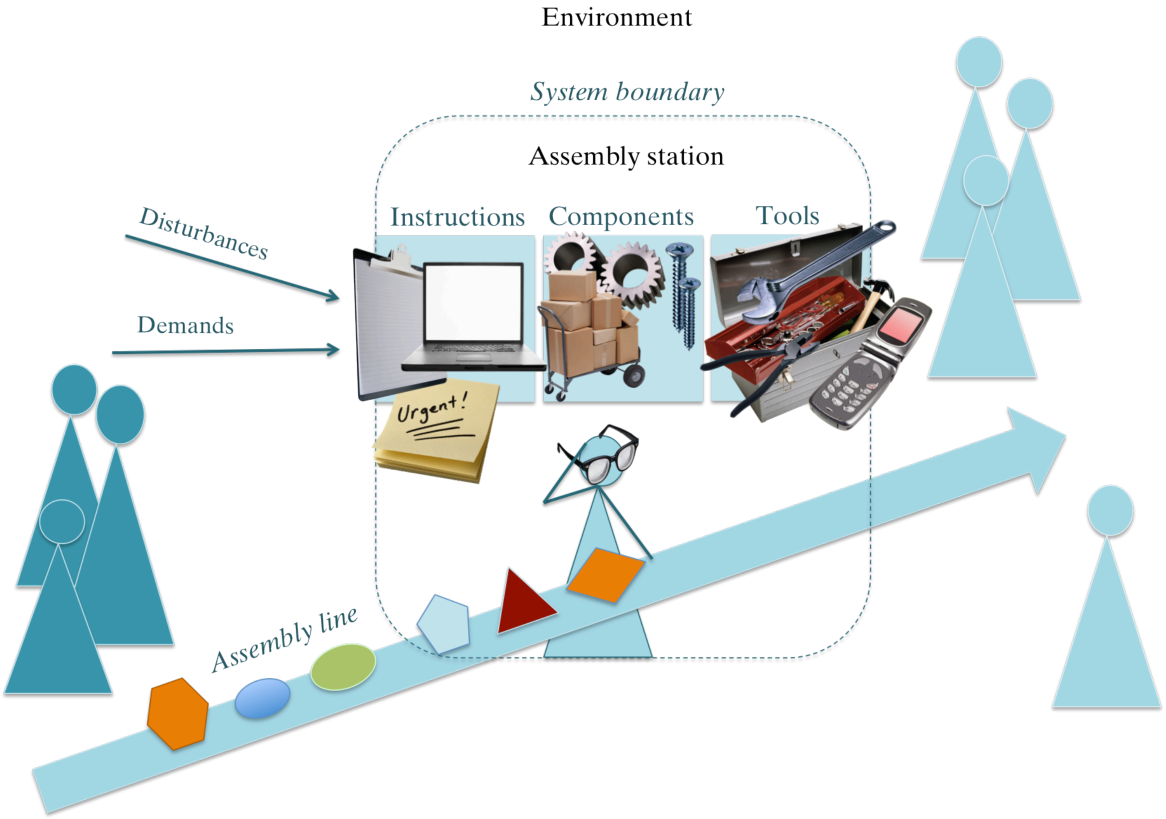


Figure 1: The operator is affected by disturbances, demands, product variants, environment, tools and support tools, instructions and components.

Methods of reducing complexity in assembly are needed urgently, if predictability and productivity in production are to be increased (Falck et al., 2017). Existing methods and models use objective data to assess complexity (or objective production complexity) (Mattsson et al., 2014c). Objective data is often studied by focusing on calculation or determining the probability of mistakes by using methods such as those of MacDuffie et al. (1996), Frizelle and Suhov (2001), Zhu et al. (2008), Abad (2010). Studying perceived production complexity means using *subjective dat*a, in other words data as perceived by the participants. When subjective data is used within existing methods, complexity is studied from the perspective of controller, management or team-leader; in other words, it does not assess the workers' perception.

Personnel working with the assembly system may perceive an objectively simple system as very complex. For example, a car may have a small number of similar parts but still be complicated to assemble (Gullander et al., 2011). This thesis uses a method of assessing perceived production complexity called the CompleXity Index (CXI, see Frame of reference). *Perceived production complexity* is defined as the interrelations between product variants, work content, layout, tools, support tools and work instructions from an operator' s point of view (based on Mattsson (2013)).

In a complex system, the operators remain an invaluable resource (Griffin et al., 2007, Toro et al., 2015). This is because operators are flexible and can manage the rapid, dynamic changes that complexity causes (Billings, 1997, Jensen and Alting, 2006, Fasth et al., 2009). Serious demands are placed on operators to manage many different tasks (Falck et al., 2017). To stay competitive, production companies must therefore be attentive to operator wellbeing and subjective experience (Grote, 2004, Mavrikios et al., 2007).

1.3 Operator wellbeing and performance

Since stress and psycho-social health are emerging problems in Sweden and Europe (Swedish Work Environment Authority, 2016, Buffet et al., 2013), it is important to further investigate how complex assembly affects operator wellbeing and how operator wellbeing and performance can be improved (Muaremi et al., 2013, Li et al., 2014). Operators are human beings with moods, emotions and subjective experiences that influence their communication, decisions, actions and motivations (Horlings et al., 2008). By studying operators' emotions in connection with the task or system, it is possible to detect stress, anxiety frustration and boredom among operators. Accordingly, the kind of errors that emanate from these emotions may be reduced (Hudlicka, 2003, Bohgard et al., 2009). The fact that many choices are made under time pressure increases the risk of assembly errors (Zhu et al., 2008, Battini et al., 2015). Moreover, subjective wellbeing can negatively influence physiological function and serve as an early indication of poor health (Kuykendall and Tay, 2015).

It is generally rare for wellbeing to be defined or operationalised (Schulte et al., 2015, Salanova et al., 2014). Wellbeing at work is "a summative concept that characterises the quality of working lives, including occupational safety and health (OSH) aspects" (Schulte and Vainio, 2010) and a survey of wellbeing at work (conducted within the European Union) showed no consensus of wellbeing at work (Buffet et al., 2013). The most commonly used terms were job satisfaction, good/fair working conditions, quality of work and health at work (Buffet et al., 2013). In this thesis, *operator wellbeing* is defined as job satisfaction and work-related affect (as according to Page and Vella-Brodrick (2009)). *Job satisfaction* is defined as the satisfaction one gets from work (Jernigan et al., 2002) and *work-related affect* is defined as operator emotion towards or during work (Diener and Seligman, 2004, Page and Vella-Brodrick, 2009). Furthermore, in this thesis operator performance is defined as the number of products assembled correctly (by defining performance in terms of quality (Park, 1987)).

1.4 Supporting operators in complex assembly

Support systems can help operators to cope better with complexity demands (Holm et al., 2014, Posada et al., 2015). Rapid technological advances offer potential solutions by supporting operators who use automated devices (such as smart wearables and augmented reality) (Whitmore et al., 2015, Guler et al., 2016). These smart technologies can collect data in real-time (Carpanzano and Jovane, 2007) and be analysed with intelligent software (Vogel-Heuser et al., 2015); something which could be used to support an operator. However, although these smart technologies exist, they are not adapted to the manufacturing industry (Weyer et al., 2015). Examples of industrial applications must therefore be presented and evaluated.

Design is crucial if there is to be any benefit from the opportunities afforded by new technologies (Chui et al., 2012, ElMaraghy et al., 2012). In complex assembly few assembly workstations are designed on principles that support operator capabilities (Thorvald et al., 2014, Bäckstrand et al., 2010, Mattsson and Fast-Berglund, 2016). New technologies must become human-centred and better fit the operators' capability to handle uncertainties (instead of being technology-centred) (Endsley, 2016, Ropohl, 1999, Trist, 1981, Hendrick and Kleiner, 2001, Trist and Bamforth, 1951). A *human-centred system* should support both human physical and cognitive capabilities (Romero et al., 2016a). The benefits of designing a more usable system are: increased productivity, fewer errors, reduced training and support, improved acceptance, enhanced reputation, improved satisfaction and motivation (Maguire, 2001).

1.5 Aim, research questions and objectives

This thesis aims to investigate and suggest actions that can increase operator wellbeing and performance in complex assembly. Firstly, this aim is achieved by **identifying** and **assessing** factors that influence operator wellbeing and performance. Secondly, prototypes are **developed** to test and evaluate whether these factors can support operators in industry. Three research questions, RQ1-3, are as follows:

RQ1: What influences operator wellbeing and performance in complex assembly?

RQ2: How can operator wellbeing and performance be assessed in complex assembly?

RQ3: How can results from RQ1-2 be used to design prototypes that support operators in complex assembly?

The objective of RQ1 is to identify relevant factors that influence operator wellbeing and performance and then form a conceptual model. Once these influencing factors have been identified, it is important to know what measurable parameters that can be used to assess this in industry. RQ2 therefore deals with how operator wellbeing and performance can be assessed. The objective of RQ2 is to identify measurable parameters from RQ1 and give examples of how they can be used to assess operator wellbeing and performance. Finally, RQ3 is based on how the results from RQ1 and RQ2 can be used to support operator performance and wellbeing at work. The objective of RQ3 is to design and evaluate prototypes and discuss industrial implications.

1.6 Scope and delimitations

This thesis is intended to support practitioners in assembly systems who wish to increase operator wellbeing and performance.

The thesis has the following delimitations:

- Objective production complexity in assembly systems is not studied in this thesis. Complexity in a system is viewed from the operator's perspective (the perceived production complexity).
- Logistics, product development and organisational management are not covered in this thesis, although they do affect complex assembly. Assembly work is studied at station level.
- Physical and cognitive automation levels are not investigated in this thesis. Automation levels are discussed in terms of how operators perceive automation in general and how operators interact with the specific automation solutions at an assembly station.
- Human-machine interfaces and the design of automation in general are not included in this thesis. Human-robot interaction is mentioned briefly.
- Safety and trust in automation are not included, although they are important aspects of wellbeing at work and Human-Automation Interaction.
- Individual and performance-shaping factors are not included in this thesis.
- Physical wellbeing, psychosocial work environment and ergonomic methods are not included in this thesis. Some aspects of physical wellbeing are discussed.
- The causes of stress, in terms of psychological or physiological aspects, are not included in this thesis.

1.7 Thesis outline

1. **Introduction** describes the operator's role in complex assembly systems. Research gaps are identified in connection with complex assembly, operator wellbeing and performance and operator support. Furthermore, the aim and research questions are presented alongside with the direction of the thesis.
2. **Research methodology** presents the pragmatic mixed-method research approach. This is followed by methods used, purpose and data collection for the appended papers.

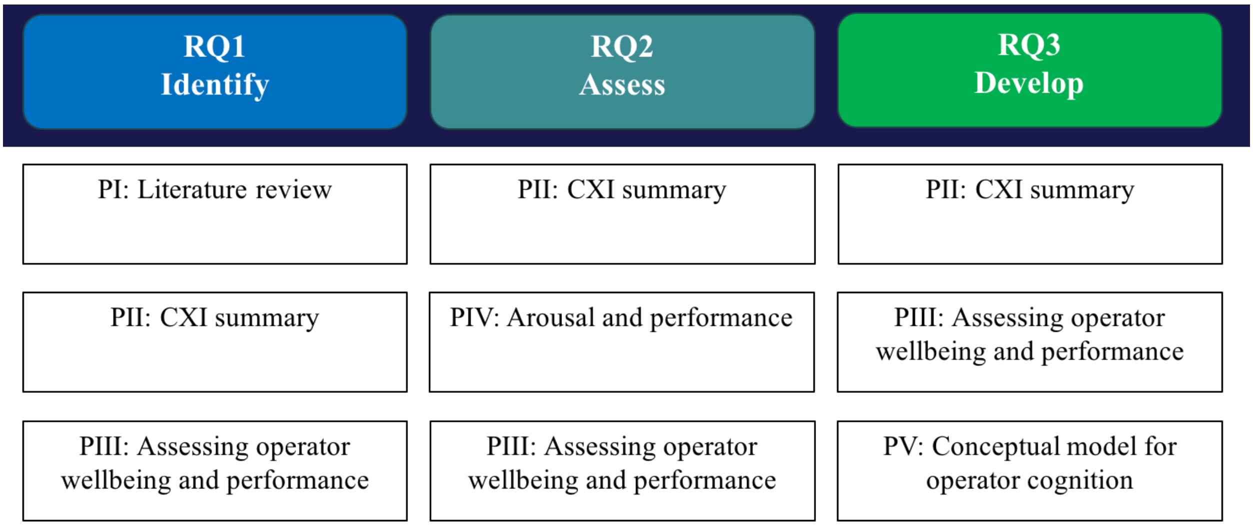
3. **Frame of reference** further presents complex assembly in terms of perceived production complexity and the CompleXity Index method. Relevant ways to assess the impact of complex assembly are presented from the perspective of Human-Automation Interaction and operator wellbeing. There is a presentation of theory on supporting operator cognition, in context of managing complexity in a system.
4. **Summary of the appended papers** presents the summarised results from the five appended papers. The focus is on what each paper contributes to answering RQ1-3 respectively. There is also table of industrial and research contributions.
5. **Discussion** combines and discusses the results from the appended papers. Research quality, reflections and limitations, and future work are then presented.
6. **Conclusion** presents the connected to the two suggested actions.

2 RESEARCH METHODOLOGY

This chapter presents the pragmatic mixed-method research approach. This is followed by methods used, purpose and data collection for the appended papers.

2.1 Overview

The five appended papers, I-V, and research activities are connected to the research questions in Figure 2.



RQ1 **Identify**	**RQ2** **Assess**	**RQ3** **Develop**
PI: Literature review	PII: CXI summary	PII: CXI summary
PII: CXI summary	PIV: Arousal and performance	PIII: Assessing operator wellbeing and performance
PIII: Assessing operator wellbeing and performance	PIII: Assessing operator wellbeing and performance	PV: Conceptual model for operator cognition

Figure 2: Research activities connected to appended papers and the contribution of research questions.

2.2 Research philosophy and approach

This thesis has taken a pragmatic, mixed-method research approach (Morgan, 2007, Waal, 2005, Mills, 1969, Johnson and Onwuegbuzie, 2004). A *mixed-method approach* uses a combination of quantitative and qualitative methods to find a deeper understanding of a phenomenon (for instance, how to assess operator wellbeing in industry) (Östlund et al., 2011, Zohrabi, 2013). This can highlight relationships that are not visible when using only one type of data (Eisenhardt, 1989, Williamson, 2002, Yin, 2009).

The aim was to build theory based upon theoretical constructs which have been further developed in empirical studies (Flynn et al., 1990). Table 1 presents an overview of the research approach.

Table 1: Appended paper's aim, type and approach.

Appended paper	**Aim**	**Type**	**Approach**
I	To present a review of the development of Human-Automation Interaction and see the trends of interaction between humans and automation.	Theoretical	Explanatory Abductive
II	To measure and analyse perceived production complexity from an operator perspective and discuss how the result can be used to manage complex stations.	Empirical	Explanatory Abductive
III	To investigate empirically how operator wellbeing can be assessed, what devices can be used for such assessment and how this can be implemented in an industrial context.	Empirical	Exploratory Abductive
IV	To investigate if there are correlations between operator performance and arousal. Operator emotion is studied by looking at subjectively and objectively measured arousal.	Empirical	Exploratory Inductive
V	To answer how cognitive automation solutions can be designed to support Operator 4.0 in complex assembly.	Theoretical	Exploratory Deductive

Initially, *explanatory research* was used. This tries to describe a phenomenon by using theoretical constructs and was used in Paper I. Empirical data was then used to find causal relations that could further explain the phenomenon (Paper II). *Exploratory research* was conducted in Papers III-V, which aims to find preliminary results or suggest working hypotheses.

The chosen research approach included abductive, deductive and inductive elements. *Abductive research* means that theoretical and empirical research are alternated in order to draw conclusions from the studies (Alvesson and Sköldberg, 2008). This was used in Papers I-III, where constructs were tested and formed using empirical studies. In Papers I-III, theory was built by iterating between theory and finding empirical evidence (Eisenhardt, 1989). This is different from *deductive research*, where conclusions are drawn from logical statements (Thurén, 2002). In other words, the answers to the research questions were formed by studying theory (Starrin and Svensson, 1994), used in Paper V. *Inductive research* was carried out in Paper IV, where conclusions are drawn from empirical data (Thurén, 2002).

2.3 Data collection

Methods of data collection in the appended papers are presented in Table 2. *Triangulation* is used to increase reliability, validity and interpretation of data. This means collecting different types of data by such methods as combining interview and laboratory results (Olsen, 2004, Zohrabi, 2013). Four basic types of triangulation have been used in this thesis: *data triangulation* (different types of data at different times), *method triangulation* (different methods), *theory triangulation* (different research disciplines) and *investigator triangulation* (multiple researchers involved in the investigation) (Denzin, 1970, Denzin and Lincoln, 1998).

Table 2: Data collection in the appended papers (method type, method(s), data collected and triangulation type).

Appended paper	Method type	Method(s)	Data collected	Triangulation type
I	Literature review	Grounded theory	107 articles	Theory and investigator
II	Survey	CompleXity Index method	112 survey responses	Investigator
III	Mixed-method approach	Literature review, laboratory tests, case studies and workshop	73 experiment participants, 10 operators in case studies and 15 workshop participants	All types
IV	Laboratory experiment	Repeated experiments	(same as above for experiment participants)	Data, method and investigator
V	Theoretical analysis	Literature study	-	Theory and investigator

The data collection will now be described for each paper in turn.

In Paper I, a five-stage systematic literature review was conducted, based on Grounded Theory (Corbin and Strauss, 1990). The five stages were: define, search, select, analyse and present (inspired by Rutter and Francis (2010)). 107 articles were included in the sample and 690 key elements (to describe HAI) were found (define, search and select). Based on a previous literature study (Mattsson et al., 2012), the analysis stage used two types of categorisation to structure the elements that had been found. The elements were then coded into one of three HAI paradigm categories: Human-centred, Automation-centred or Interaction centred. The type of system element was then: input, system processes or output element. The results were presented using tables (in percentages).

Paper II assessed perceived production complexity at 36 stations in seven large companies (1000-6000 employees), using the CXI method. 112 surveys were performed at 70% of assembly and 30% of machine supervision stations (only data from assembly stations were included in Summary of the appended papers). The industry types were distributed as follows: automotive industry 45.8%, powered appliances 25%, tooling 12.5%, medical appliances 8.3% and bearings 8.3%. The sample from supervision stations (number of respondents) was larger than that of assembly stations (56% compared to 44%). On average, the respondents had worked at the station for more than 5 years. Of the 36 stations that were measured, 31 were perceived as complex (as assessed by the respondents).

Paper III used a mixed-method research approach to answer the two questions in the paper: (1 "What physiological measurements can be used to assess operator wellbeing in real time?" and 2) "What risks and possibilities are connected to assessing operator wellbeing in real time in industry?"). Since physiological measures are uncommon in industry and new devices are being developed continously, long-term studies are not possible. This meant that a more exploratory approach was suitable. The paper details the literature study, laboratory experiments, case studies and workshop that were used (Laboratory Test A is explained below).

In Paper IV, 60 participants were recruited (mainly via campus message boards) at Chalmers University of Technology. Participation was voluntary, with each participant studied separately. Participants assembled 5 + 5 Lego gearboxes during two different assemblies, A and B. A lasted 70 seconds and B lasted 50 seconds. To avoid experiment bias, the participants were divided into two groups: Group AB and Group BA. The component shelf was optimised according to the picking order. Operator performance was assessed as the number of correctly assembled products during a cycle at an assembly station. Operator emotion was assessed using subjectively rated arousal, valence and dominance according to the Self-Assessment Manikin (SAM, see Figure 5) (Bradley and Lang, 1994) with Likert scales ranging from 1-5. Electrodermal activity (EDA) was measured using the Qsensor and analysed by comparing the number of non-specific skin conductance responses (NSCR) per minute to operator performance (as described in Mendes (2009)). Three types of NSCR peaks were calculated: down peaks, flat peaks and up peaks, see Figure 3. *Flat peaks* were defined as down peaks that were longer than 2 seconds. To increase data reliability, all calculations involved multiple researchers. Following assembly, an interview was carried out to validate findings. Participants were then shown their EDA graph; their views on the data were not captured.

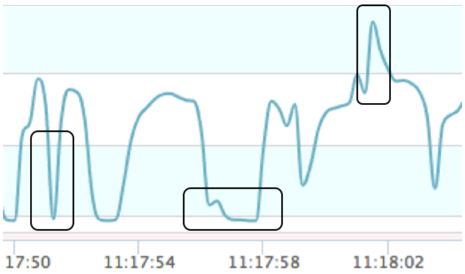


Figure 3: The three types of EDA NSCR peaks assessed in Laboratory Test A: down peak, flat peak and up peak (left to right in figure).

In Paper V, a theoretical analysis was performed in which a model of assembly work phases was combined with a model of cognitive processes published in Mattsson et al. (2014a). A conceptual model of cognitive support was developed in the paper.

2.4 Research quality

Validity means that the method or technique measures what it is intended (Williamson, 2002, Yin, 2009). This can be evaluated by studying the construct, internal, external and contextual validity (Yin, 2009, Ihantola and Kihn, 2010). To ensure validity, a *theory building approach* was followed; the studies were described in a logical and consistent way (contextual validity) (Flynn et al., 1990). *Multiple cases* were used to increase the external validity. In other words, studying different types of companies to see if the same results are found (also by data triangulation). Internal validity was increased by validating the quantitative findings using qualitative data (semi-structured and unstructured interviews and methodology triangulation) (Eisenhardt, 1989). Internal validity was also increased by supporting the findings with theory.

To secure the *reliability* of empirical data (meaning that the data that was discovered is stable and did not occur by chance) it was stored and structured so that it could be re-visited (Williamson, 2002, Yin, 2009). Lastly, transferability was also used to ensure research quality in empirical studies (Ihantola and Kihn, 2010). This was achieved by providing links between theory and empirical data and showing the practicality of the results.

3 FRAME OF REFERENCE

This chapter further presents complex assembly in terms of perceived production complexity and the CompleXity Index method. Relevant ways to assess the impact of complex assembly are presented from the perspective of Human-Automation Interaction and operator wellbeing. There is a presentation of theory on supporting operator cognition, in context of managing complexity in a system.

3.1 Complex assembly

In everyday language, "complexity" is often used of the difficulty of understanding or analysing a system. Weaver stated that, given the system's parts, *complexity in a system* is the difficulty in predicting that system's properties (1948). From a production system perspective, the ability to predict system behaviour is crucial. Checkland's definition of a complex system and the Systems Theory view of complex systems are therefore relevant. Checkland defined a *complex system* as: "a set of elements connected together which form a whole; thus showing properties which are properties of the whole, rather than properties of its component parts" ((1993), p. 3). A similar view is seen in Systems Theory, which states that the sum of a system's elements is greater than the sum of its parts (Skyttner, 2001). A definition of production complexity, suggested by Zeltzer et al, states that complexity is the sum of all possible aspects and elements that make a task mentally difficult, error-prone, requiring thought, vigilance and induces stress (2012).

Perceived production complexity

This thesis uses perceived production complexity in context of assembly systems. Perceived production complexity is affected by interactions between the human-automation system, the task and systems complexity, manufacturing strategy and personal factors. These, in turn, affect performance (Li and Wieringa, 2001, Brolin et al., 2011, Guimaraes et al., 1999, Urbanic and ElMaraghy, 2006). Perceived production complexity depends on subjective factors such as knowledge, training, personality type, willingness and background (Gullander et al., 2011). Moreover, aspects of motivation, past experiences, stress levels, error culture and competences could affect the perceived production complexity (Brinzer and Banerjee, 2018). This thesis defines perceived production complexity as the interrelations between product variants, work content, layout, tools and support tools and work instructions, as perceived by the operators (presented in the introduction). The definition is based on empirical work that was used to develop the CXI method. In the context of assembly systems, *complex assembly* is therefore defined as: stations perceived as complex by the operators working there, as assessed using the CXI method.

The system elements in complex assembly systems can be divided into cause variables, system processes and effect variables. *Cause variables* are elements in a system that can be designed or influenced, while *effects variables* are aspects that can be measured (in theory) (Mattsson et al., 2013a). Although the main cause of complexity in a production system is usually given as product variants (Orfi et al., 2011, Schleich et al., 2007, Hu et al., 2008), additional causes have been suggested such as product structure, structure of plant/shop, planning and scheduling, information flow, dynamic variability and uncertainty of the environment (Calinescu et al., 1998) as well as information and material flows (Sivadasan et al., 2006, Urbanic and ElMaraghy, 2006). The cause variables in the perceived production complexity definition are described through an INUS-condition which is an "Insufficient, but Necessary part of an Unnecessary but Sufficient condition" (Mackie, 1965). An INUS-condition means there are necessary conditions or elements which make a system complex. However, if only some of them are present, the system will not be perceived as complex.

The CXI method was used to investigate the relationships between the system elements and identify complex assembly stations.

The CompleXity Index method (CXI)

CXI is a questionnaire, developed to give an index for the complexity at a production station (Mattsson et al., 2014c); the survey is presented in full in Appendix A (current version). CXI includes 22 statements presented using Likert scales (on a scale of 1-5 with some statements reverse-coded (see Appendix 1 in Paper II)). There is also one tick-box question and one comment field. The method was developed in 2011 and has been validated empirically using different kinds of triangulation (Mattsson et al., 2011, Fässberg et al., 2011, Mattsson, 2013, Mattsson et al., 2013b). CXI was further validated through principal component analysis (Paper II, 21 statements/questions).

The statements are divided into three areas: A) Station design, B) Work variance and C) Disturbance handling. *Station design* covers how well the station is designed in terms of layout and tools and support tools. Layout means the structure of the plant or shop (Calinescu et al., 1998). Station design also includes ergonomic issues such as accessibility and physical load. Tools and support tools are assessed according to the number of operator choices or the probability of making mistakes (MacDuffie et al., 1996, Frizelle and Suhov, 2001, Zhu et al., 2008, Abad, 2010, Zeltzer et al., 2013). *Work variance* covers variance in both product variants and work content. Product variance is a known cause of complexity, as indicated by such researchers as Orfi et al. (2011), Schleich et al. (2007), Hu et al. (2008) and Falck and Rosenqvist (2012). Work content variance means the tasks connected to the tool, fixture, part and procedure connected to the product variant (Zhu et al., 2008), which are important considerations (Zeltzer et al., 2013). Work variance also deals with competence which, in terms of development and proactivity, is a relevant aspect of handling assembly systems (Fasth et al., 2010a, Mårtensson and Stahre, 2003). This is connected to humans' ability to handle the dynamic situation caused by complexity (Billings, 1997, Jensen and Alting, 2006, Fasth et al., 2009). *Disturbance handling* covers aspects of work content associated with handling disturbances, such as product variants that do not occur frequently. Disturbances are an important aspect of complexity since complex systems often are connected to uncertainties

(Grote, 2004). This complexity area also includes the extent to which operators are part of planning their work. The way information is presented (such as paper, screens, mobile devices etc.) and how it is presented (text, pictures, audio, film) is vital in decreasing perceived production complexity (Fast-Berglund and Blom, 2014, Fast-Berglund et al., 2013).

The CXI for a station is calculated using a formula. CXI per respondent is calculated using the formula (1), while the CXI for a station is calculated using formulas (2) and (3):

$$\mathrm{CXI_p} = \frac{\sum_{e=1}^{k} \mathrm{M_{ep}}}{k} + \frac{\max_{e=1..k} \mathrm{M_{ep}}}{4} \qquad (1)$$

$$\mathrm{CXI_e} = \frac{\sum_{P=1}^{n} \mathrm{M_{ep}}}{n} \qquad (2)$$

$$CXI = \frac{\sum_{p=1}^{n} CXI_p}{n} \qquad (3)$$

Where:

CXI is the total complexity index for the station
CXI_p is the total complexity index for the station for respondent p
CXI_e is the complexity index for complexity element e for the station
M_{ep} is the median of the questionnaire answers for complexity element e for respondent p
k is the number of complexity elements, i.e. 3
n is the number of respondents

A higher score on the scale indicates a higher level of complexity. The score is divided into three complexity levels and colours: low complexity, green < 2; moderate complexity, yellow ≥ 2 but < 3.5; high complexity, red ≥ to 3.5. The output of the method is a colour carpet, which visualises the areas and statements that contribute to increased complexity at a station.

CXI has been used as a current state tool in empirical studies, such as those by Johansson et al. (2016), Mattsson and Fast-Berglund (2016) and Tarrar et al. (2016). 464 participants have so far answered the questionnaire and CXI has been assessed at 178 stations. 14 different companies were included in the studies. The studies were mostly carried out in the automotive industry (43%) but a number have also been held in other industries (pharmacy 14%, machining 29%). CXI was used in disassembly[1] (two companies, 14%).

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[1] Within the research project EXPLORE, founded by MISTRA. http://www.ivl.se/toppmeny/pressrum/pressmeddelanden/pressmeddelande---arkiv/2016-05-25-mistra-explore-utforskar-framtidens-fordonsatervinning.html

3.2 Assessing relevant factors in complex assembly

This section presents relevant factors used to assess the effects of complex interactions and human behaviour. Although the level of automation in assembly is generally low, the term “level of automation” (LoA) has been used to assess and describe the tools used in final assembly by such researchers as Fasth et al. (2008), MacDuffie (1995), Lind et al. (2008). Research from the HAI area has been used to describe the interactions in complex assembly because future trends relate to increases in complexity as well as automation level.

Human-Automation Interaction

Human-Automation Interaction (HAI) can be defined as the way a human controls and receives information from automation (Sheridan and Parasuraman, 2005) while performing a task. *Automation* is defined as the execution by a machine agent of a function previously carried out by a human (Parasuraman and Riley, 1997). An example of this is an operator in final assembly who uses an screw driver to mount a generator on an engine. The operator is affected by the construction of the screw driver, by its weight and haptics. The operator controls the screw driver and is given information as vibration while performing the assembly task (such as pre-set draw).

The effects of HAI are still hard to predict (Sheridan, 1995, Bustamante et al., 2009, Lee, 2008, Parasuraman and Riley, 1997, Merritt and Ilgen, 2008, Sarter et al., 1997, Prewett et al., 2010). A number of reasons for problems with HAI have been identified: awareness and situational awareness (Sarter et al., 1997, Endsley, 1996), performance (Endsley and Kaber, 1999, Parasuraman and Riley, 1997), feedback (Endsley, 1996, Norman, 1990) and levels of automation (Endsley and Kaber, 1999, Endsley, 1997, Parasuraman and Riley, 1997). The most common effects assessed in recent HAI research are (Paper I): performance, workload, additional subjective ratings/perception, trust/reliability, levels of automation and error types. The number of occurrences appears in Table 3.

Table 3: Common measurements used to assess effects in recent HAI research (2000-2014).

Measurement	**Number of papers**
Performance	23
Workload	16
Subjective ratings/perception	14
Trust/reliability	13
Total	*66**

* Of 88 measurements in total. Measurements that were seldom used are not included in this table.

Both performance and workload are relevant factors in HAI, and subjective ratings and perception are often used. This is illustrated further in the next section.

Operator wellbeing

Russell's circumplex model of emotion has been used to assess occupational wellbeing (Mäkikangas et al., 2015, Bakker and Oerlemans, 2011). The model describes the relationship between the affect states of arousal and valence, as shown in Figure 4. *Arousal* is an individual's activity and alertness, according to scales such as wide-awake/sleepy and excited/calm (Mehrabian and Russel, 1974). *Valence* is described using bipolar adjectives such as happy/unhappy and pleasant/unpleasant (Russell, 1980, Posner et al., 2005). Aspects of occupational wellbeing were also included in the model: workaholics, engaged, burned-out and satisfied (Mäkikangas et al., 2015, Bakker and Oerlemans, 2011). Both the affective states and the different aspects of wellbeing at work connect with the chosen definition of operator wellbeing. In other words, relating to both work-related affect and job satisfaction (Page and Vella-Brodrick, 2009, Jernigan et al., 2002).

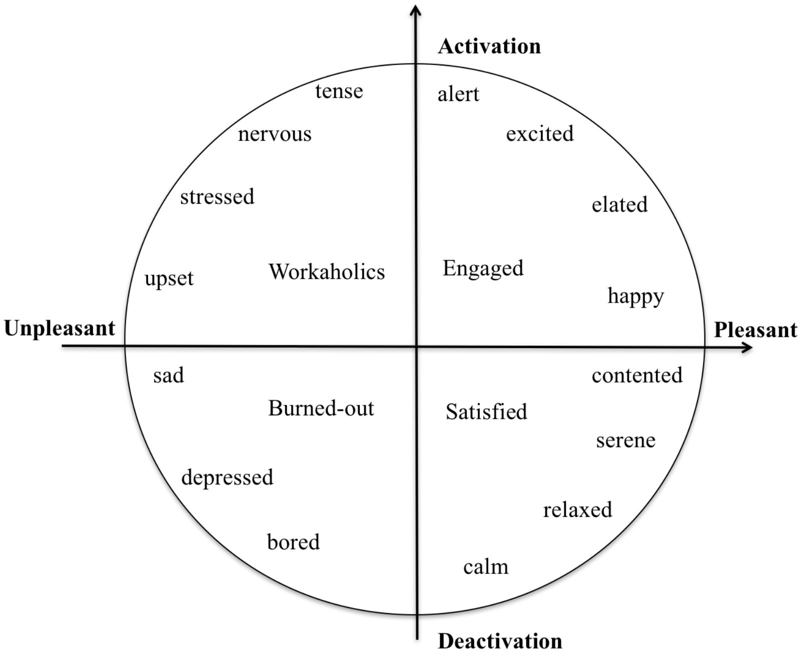


Figure 4: Russell´s Circumplex Model of emotion, adapted from Posner et al. (2005), Bakker and Oerlemans (2011), Mäkikangas et al. (2015).

When studying operator emotion the subjective difficulty of assessing and describing one's own emotions has been noted by many researchers (Saarni, 1999). These difficulties suggest that emotions lack distinct borders, making it hard for individuals to discriminate one emotion from another (Posner et al., 2005). For example, subjects rarely explain one positive emotion without also mentioning their experience of other positive emotions (Watson and Clark, 1992). Although it is difficult to distinguish the valence of an emotion, it can be captured by using self-report measures such as rating scales (Figner and Murphy, 2011, Kallus et al., 1998). One example of self-reports assessing arousal, valence and dominance is the Self-Assessment Manikin (SAM) (Bradley and Lang, 1994). SAM incorporates a third dimension to describe affect. This third dimension is *dominance* and is defined as the extent to which an individual feels free to act or is unrestricted (Mehrabian and Russel, 1974, Stamps, 2005). Figure 5 illustrates the self-ratings using a scale of 1-5 (Likert scale). This was used in experiments in this thesis.

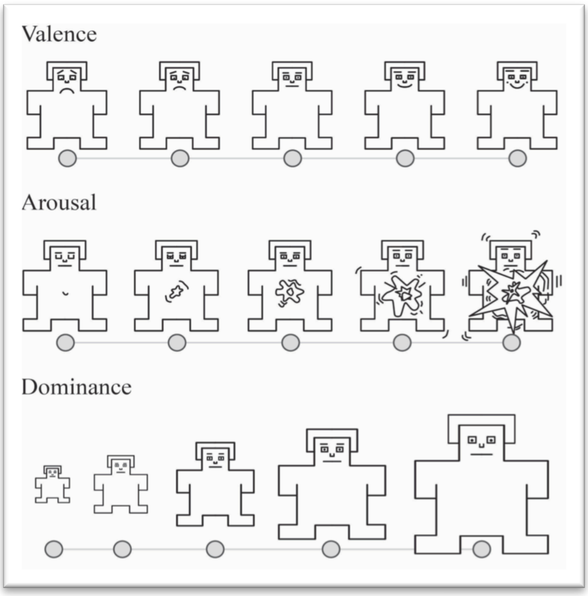


Figure 5: The Self-Assessment Manikin (SAM), adapted from Bradley and Lang (1994). The figures represent the self-assessed valence (ranging from unhappy to happy), arousal (ranging from relaxed to excited) and dominance (ranging from little control to control).

When conducting self-assessments and interviews, it is important to take subjective reconstructions into account (Kallus et al., 1998); specifically, cross-validation is needed. Because subjective reconstructions are more often used than real-time explanations, it is important to report emotions as they happen and in direct connection to actual experience. In other words, not just in terms of what the participant felt (Kahneman and Krueger, 2006). This is because past experiences are often connected to systematic biases; that is, connected to a situation or subjective reconstruction (Posner et al., 2005, Kallus et al., 1998). Schwarz et al. saw that when making judgments as to how happy and satisfied they were with their lives, subjects would rely on their momentary affective states (1983). In other words, whether they felt positive or negative in that moment (Diener and Seligman, 2004). Moreover, if they were unhappy, they would try to explain their state more than those who were in pleasant affective states (Schwarz and Clore, 1983). Another way of minimising bias is to capture real-time data (Kahneman and Krueger, 2006, Frey and Stutzer, 2002).

3.3 Supporting operator cognition

Complexity in a system may be managed by removing, simplifying, avoiding or preventing complexity (Corbett et al., 2002, Kaluza et al., 2006, Wiendahl and Scholtissek, 1994). In complex assembly, market demands often make it impossible to remove or avoid complexity. An alternative is therefore to simplify and thus reduce complexity (Wiendahl and Scholtissek, 1994). In today's systems, it is difficult to find information (due to information overload) and operators are therefore less well-informed than before (Endsley, 2000). This is because information is not adapted to the operator's level of experience. Instead, it is text-based and relies on the operator's previous knowledge (Mattsson and Fast-Berglund, 2016). Instructions that are developed without considering active cognitive processes can cause unnecessary cognitive load and lead to poor operator performance (Sheridan, 2002). Therefore, an improvement is needed in the way information is presented (Thorvald et al., 2010, Fässberg et al., 2012b, Bäckstrand et al., 2010, Bäckstrand et al., 2008, Brolin et al., 2011, Thorvald, 2011). One way to reduce complexity could be to introduce cognitive support to filter the information (Fast-Berglund and Stahre, 2013) and present it intuitively, effortlessly and quickly (Mattsson et al., 2014a). If the necessary information is presented to the operator more simply, the operator may save time whilst also increasing performance (Bäckstrand et al., 2008).

How an operator understands a situation, not what it objectively is, governs the operator's actions (Hollnagel, 1997). To support interaction and optimise performance, it is therefore important to understand the operator's cognitive processes (Rasmussen, 1983). *Cognitive processes* are the mental processes by which humans become aware of and process information (Bohgard et al., 2009). There are two types of cognitive process: intuition and reasoning (Smith and Kirby, 2004, Kahneman and Krueger, 2006). *Intuition* is automatic, effortless and fast. *Reasoning* is also known as the "explicit system", "rule-based system" (Evans, 2003) and "analytic system" (Tsujii and Watanabe, 2009). From a cognition perspective, tasks in complex assembly fit within automatic, non-energy-consuming tasks. This means intuition, such as gathering information, recognising elements in a situation and comprehending the situation (more or less aware and/or automatic). Also, intuitive thinking is often the norm; reasoning is less used (Kahneman, 2003a).

Figure 6 presents a model of intuition in which cognitive processes and different knowledge levels are combined (Mattsson et al., 2014a). Intuitive behaviour is connected to *skill-based behaviour*; unconscious behaviour involving very little control to perform or execute an action once an intention is formed (Rasmussen et al., 1990). This automaticity allows operators to free up cognitive resources, which can then be used for higher cognitive functions like problem solving (Wickens and Hollands, 1999). This level could also be referred to as fast and dependent on signals; traffic lights for example (Rasmussen, 1983). *Rule-based behaviour* is a more conscious state of recognition and accesses stored rules from past work scenarios (Schlick, 2000). This behaviour is activated by signs in the environment (Rasmussen, 1983). Unlike signals, *signs* are a state in the environment connected to certain behaviour. Signs are not directly processed and must be activated.

Cognitive processes	Gathering information, forming characteristics, recognising elements in a situation	Comprehending a situation, understand the importance of objects and how they can be used to reach a goal by conforming elements and connecting them to tools
Part of model	**Level 1: Skill-based behaviour, SA Level 1 and System 1**	**Level 2: Rule-based behaviour, SA Level 2**
Characteristics	Unconscious, automatic, fast	Unconscious/conscious, fast/moderate and include causal relations
Activated by what type of information	Signals	Signs

Figure 6: Model of intuition based on Rasmussen's model of SRK-based behaviour (Rasmussen (1983), Kahnemann's model of System 1 and 2 (Kahneman (2003b) and Endsley's model of situational awareness (SA) (1996).

The model does not include Rasmussen's third level, *knowledge-based behaviour*, which include conscious acts that occur when faced with an unfamiliar situation. This behaviour is connected to trial and error or thinking conceptually. According to Rasmussen, knowledge-based behaviour is driven by symbols which are abstract information, variables or properties that must be processed (Rasmussen, 1983). Rasmussen states that, in a complex environment, complex thinking is not preferred since humans focus their attention on a few things at a time. In other words, information must be processed sequentially (since complex thinking is cognitively demanding).

4 SUMMARY OF THE APPENDED PAPERS

This chapter presents the summarised results from the five appended papers. The focus is on the contribution from each paper to answering RQs 1-3. There is also table of industrial and research contributions.

4.1 Overview

The results of the appended papers contribute to the research questions, as in Figure 7.

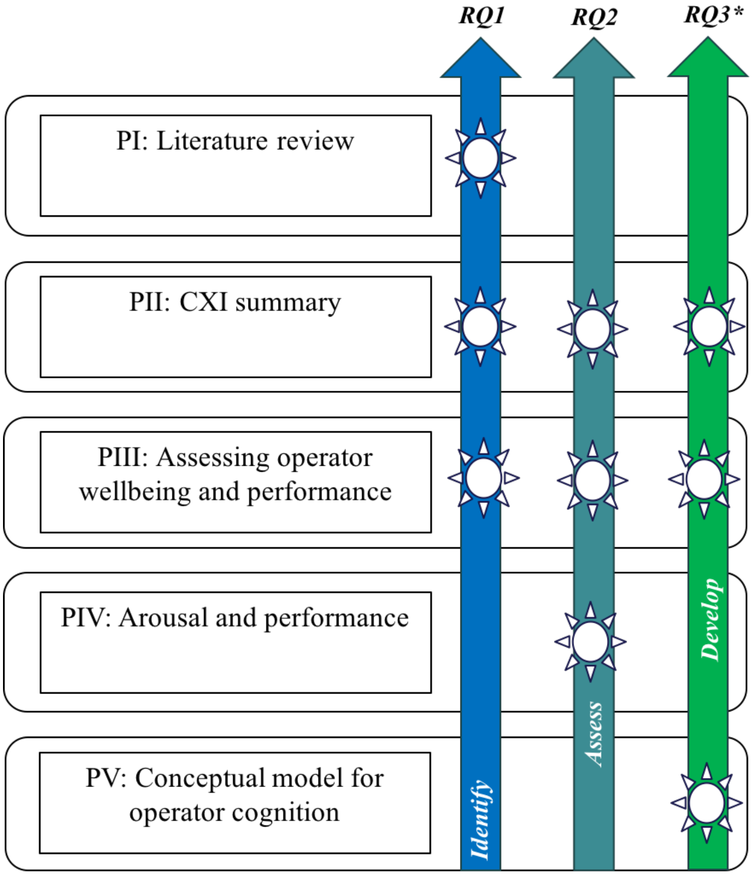


Figure 7: Research activities and contribution to research questions. *RQ3 is also answered by additional unpublished work.

The purpose and research objectives that questions are connected to appear in Table 4.

Table 4: Research questions connected to objectives.

Purpose	Research Question (RQ)	Objective
Identify	RQ1: What influences operator wellbeing and performance in complex assembly?	I) To identify influencing factors and form a conceptual model of system elements.
Assess	RQ2: How can operator wellbeing and performance be assessed in complex assembly?	II) To identify measurable parameters and show examples as to how they can be used to assess operator wellbeing and performance.
Develop	RQ3: How can results from RQ1-2 be used to design prototypes that support operators in complex assembly?	III) To design and evaluate prototypes and discuss industrial implications.

4.2 RQ1: What influences operator wellbeing and performance in complex assembly?

In Paper I a black-box model was used to categorise key elements found in recent HAI literature. The categorisation was based on two things: three HAI paradigm categories and three system element types. By categorising system elements according to type, measurable parameters (effects) could be separated from causes, see Table 5. As an example common causes connected to human factors were identified: work environment and performance-shaping factors.

Table 5: System elements were categorised into Human, Automation and Interaction-centred elements (HAI paradigm categories) and system elements (causes, system processes and effects).

System elements /HAI paradigm categories	Causes	System processes	Effects
Human-centred	Work environment, performance-shaping factors	Situation awareness, decision-making, attention	Mental workload, trust, stress
Automation-centred	Level of automation, function allocation	Fault diagnosis, planning, procedure	Quality, time, cost, performance, efficiency
Interaction-centred	Design, role(s), decision support	Authority, communication, coordination	Safety, control

The model in Table 5 is useful because identified system elements could be better understood and communicated (by practitioners and researchers). It was also used to differentiate between elements in complex systems so that relationships could be further investigated.

In Paper II system elements were further investigated. Its empirical data showed the main cause of perceived production complexity to be the dual areas of work variance (41.5%) and disturbance handling (38.3%). Factors connected to these areas, and which influence operator wellbeing and performance include product variance, proactive work, being part of planning and controlling one's work and instructions (CXI statements). Having many product variants may make it difficult for an operator to stay focused on the differences between them. Humans have difficulty holding more than seven ±2 items in the working memory simultaneously (Reisberg (2001). Due to these limitations in working memory, the pressure to reduce times and increase quality makes work variance even more important. However, having multiple tasks to do does not necessarily imply that the work is ill-conceived (even if it may objectively be considered complex). Some operators prefer to work at the same task all the time; they can then focus their attention on other things. Being part of an unpredictable situation also affects the operator in terms of wellbeing and performance. For example, if operators are not included in planning or changing their station, work may become stressful because they do not feel they have enough information.

In Paper III, job satisfaction, motivation and operator emotion were identified as relevant factors for operator wellbeing and performance, due to correlations observed in the literature. Job satisfaction is a common term in the European Union, used to define a sense of wellbeing at work (Buffet et al., 2013). High levels of performance have been connected to having a high degree of job satisfaction and a high level of psychological wellbeing (Wright et al., 2007). Moreover, correlations between motivation and wellbeing have been seen (for example, competence, autonomy and relatedness, which affect intrinsic motivation, self-regulation and wellbeing (Ryan and Deci, 2000)). When these three factors are satisfied, they increase self-motivation and mental health; when they are not, they diminish motivation and wellbeing instead. Operator emotion is relevant due to that boredom, under-stimulation, stress and high demands are connected to both operator wellbeing and performance (Bohgard et al., 2009, Muaremi et al., 2013).

RQ1 results

Five factors were identified as influencing operator wellbeing and performance: work variance, disturbance handling, job satisfaction, motivation and operator emotion. A conceptual model of system elements was also formed using recent HAI literature.

4.3 RQ2: How can operator wellbeing and performance be assessed in complex assembly?

In Paper II, CXI was used to assess the perceived production complexity (and thereby its influencing factors; work variance and disturbance handling). Furthermore, for each of the complex stations, CXI was used to identify bottlenecks and to work with the company on suggested improvements. First, the complexity index is found. Then the colour carpet is used to find the characteristics of the stations. For example, at one station disturbance handling was considered high while work variance was considered moderate, as distinct from a station which was perceived as complex across all complexity areas. It was also found that the statements contributing to the station having generally high levels of work variance and disturbance handling were driven by product variety (statements 1 and 2).

In Paper IV, operator wellbeing was assessed using physiological data, self-reports and interviews. A weak/moderate correlation was found in 1st assembly between operator performance (number of parts assembled correctly) and EDA (the number of flat peaks, see Research Approach). This correlation is presented in Figure 8 and shows an NPAC increase, with an increase in flat peaks. This means that operators whose level of performance in assembly was high also had more flat peaks, whilst those with generally lower levels of performance had fewer flat peaks. No other significant correlations were seen; specifically, no correlations between performance and self-assessed arousal, valence or dominance were seen (using SAM).

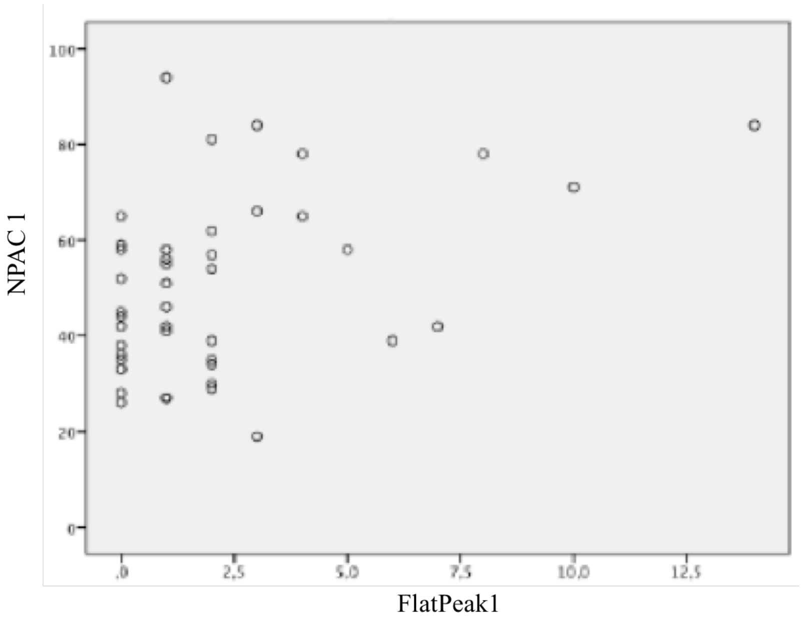


Figure 8: Correlation between number of correctly assembled parts and flat peaks/min. in 1st assembly.

The covariance results could be due to reactivation. In other words, participants in the 1st assembly having to concentrate to learn the job and handle the stressful situation, thus producing flat-peaks before reactivation (Fowles, 1980, Bradley and Lang, 2004). Some support is seen in the interviews, where 1st assembly was generally perceived as stressful (40%) and difficult (28%) while the 2nd assembly was seen as better (35%) and less stressful (22%). However, the cause of the correlation was not visible in the experiment. This might be due to such things as cognitive or physical reactivation.

Paper III identified additional physiological data types as promising for assessment of operator wellbeing in real-time; Table 6 shows a summary of the results.

Table 6: Summarised findings from Paper III.

Physiological measurements	Research methods	Findings	Sources
EDA	Literature study	EDA was identified as useful in assessing stress, changes in emotion and motivation.	Literature data
	Laboratory study A (Paper IV)	Weak correlation with operator performance (significant correlation)	Quantitative data
EDA and HRV	Laboratory study B	50% of the participants thought it was the most reliable, 50% preferred HRV.	Qualitative data
EDA and HRV	Case study A	Participants positive towards the graphs	Qualitative
EDA and BVP	Case study B	Project leader thought it was crucial in understanding interaction	Qualitative

EDA was considered reliable and useful in assessing operators' wellbeing at work, which was seen both in the experiments and case studies. EDA is useful for assessing changes connected to emotional and cognitive states since it is not affected by parasympathetic activity (unconscious bodily actions, such as digestion and salivation (Braithwaite et al., 2013)) and is measured as current in the skin (which increases when an operator produces sweat) (Mendes, 2009, Boucsein, 2012). Moreover, the sensors are cheap and reliable (Figner and Murphy, 2011).

HRV was seen as reliable by operators in the assessments (Laboratory Study B and Case Study A). HRV measures are useful since, when a person is exposed to stress, the autoimmune nervous system triggers stress hormones that change both the heart rate and HRV (Taelman et al., 2009). Studies show that HRV levels are high when a person does not feel stressed, while low HRV levels are an indicator of a higher perceived stress levels (Peper et al., 2007). BVP was also combined with EDA to give new information in a human-robot collaboration (covering operator wellbeing and understanding of the interaction).

Further studies are needed to identify the relationship between EDA, BVP, HRV and operator performance. The advantages of combining different types of data have been seen in several studies, such as EDA, HRV, self-ratings, behaviour and personality traits. These can be used to detect anomalies (Hernandez Rivera, 2015, Hairong Yan, 2015, Sandulescu et al., 2015). Excepting the measurements already suggested (EDA, HRV, respiratory factors and BVP), physiological measurements such as eye-monitoring and/or pupil dilation could be investigated further. Real-time operator wellbeing and performance assessments should also be combined with assessments of job satisfaction and motivation.

RQ2 results

By assessing EDA combined with HRV or BVP in real-time, reliable data could be collected and several data types combined.

4.4 RQ3: How can result from RQ1-2 be used to design prototypes that support operators in complex assembly?

In Paper II, it was suggested that variable work and disturbances should be supported by better presentation of information (information may mean work instructions but can also be how components/materials are presented to the operator). The highest number of comments (the last statement in the questionnaire) dealt with better support tools (N= 7), station layout (N=6) or material handling (N=5, N_{total}=25). This indicates that there are opportunities for companies to facilitate efficient work for the operators, which could positively influence operator wellbeing and performance.

The results from CXI indicate a need for better presentation of information and support for cognition. This is not surprising since work instructions are limited at the assembly station (often just text and rarely used) (Fast-Berglund et al., 2014) and that operators are therefore less well-informed than before (Endsley, 2000). Cognitive processes should be considered as a means of supporting operator wellbeing and performance (Kahneman, 2003b), so that information can be presented more intuitively and effortlessly (as suggested in Figure 6). Several studies show that depictive work (instructions given as images and movies) tend to be much better than descriptive (text-based) instructions in terms of cycle-time, quality, flexibility in time and space and learning curve (Watson et al., 2010, Fast-Berglund and Blom, 2014, Blom, 2014, Thorvald et al., 2010, Fässberg et al., 2010).

In Paper V, a model of operator cognition was formed based on three assembly phases, see Figure 9.

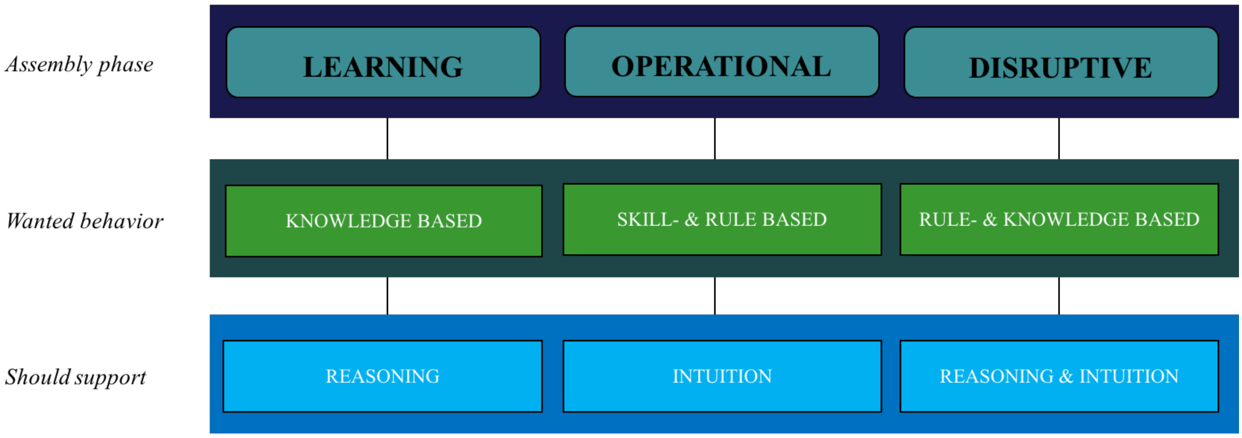


Figure 9: Learning, Operational and Disruptive (LOD) model for cognitive processes in assembly work.

The Learning, Operational and Disruptive (LOD) model for cognitive processes is based on a theory of operator work concerning learning, cognition and disruptive work. Whenever an operator needs to learn something new, he or she works in the *learning phase*. To support this type of behaviour, the operator needs to be actively aware and reasoning. These processes are often consuming of energy and time (not automatic) (Evans, 2003, Tsujii and Watanabe, 2009). In the *operative phase*, the operator instead needs to work based on his or her experience and skill (as described in Supporting operator cognition and Figure 6). For the *disruptive phase*, the operator needs to think consciously about a solution. This means using reasoning and intuition; in other words, both knowledge-based and rule-based behaviour is used.

Based on the LOD model design, principles were developed to better present information to operators. The prototype, Design principles For Information Presentation (DFIP), was developed based on experiments by Söderberg et al. (2014), a Bachelor's thesis supervised by the author and 13 design principles presented in Bohgard et al. (2009). The aim of these experiments (assembling gearboxes from LEGO) was to investigate the correlations between instructions, takt time and emotion. Interviews were held after each experiment and then coded, with the codes matched to assembly errors to highlight common errors. Codes from 50 participants were used as input to improve the assembly instructions and 10 additional experiments were conducted to study the effects. The results showed that satisfaction and performance increased (Söderberg et al., 2014, Li et al., 2014) and an example of the improved instructions appears in Figure 10 (further developed in the Bachelor thesis with by Dean et al. (2014)).

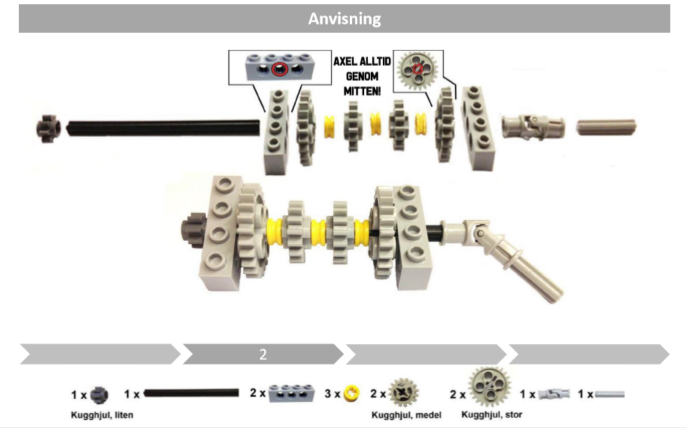


Figure 10: Example of DFIP use for LEGO assembly (Dean et al., 2014).

DFIP was then used in education (for students and company representatives) and an evaluation of this DFIP was made (presented in Mattsson et al. (2016). This version of DFIP, *DFIP 1*, had five steps: 1) support active cognitive processes. 2) support mental models. 3) support abilities and limitations. 4) support individual preferences/differences and 5) support perception/placement. DFIP was then included in the course literature, entitled Smart Automation (Fast-Berglund and Mattsson, 2017). The DFIP 1 steps were then altered for use as is by practitioners and named DFIP 2. In *DFIP 2*, an additional step was added before the original steps and more information regarding the studied assembly station was included for consideration. For example, information on organisation and the correlation to other methods was explained. DFIP 2 has six steps (presented in full in Appendix B):

1) Choose a work task in the workplace where the presentation of information needs improvement, based on CXI findings for example.

2) Identify and support active cognitive processes in each sub-task (LOD-model).

3) Analyse tasks based on how the operator perceives their work environment (CXI can be used with other methods).

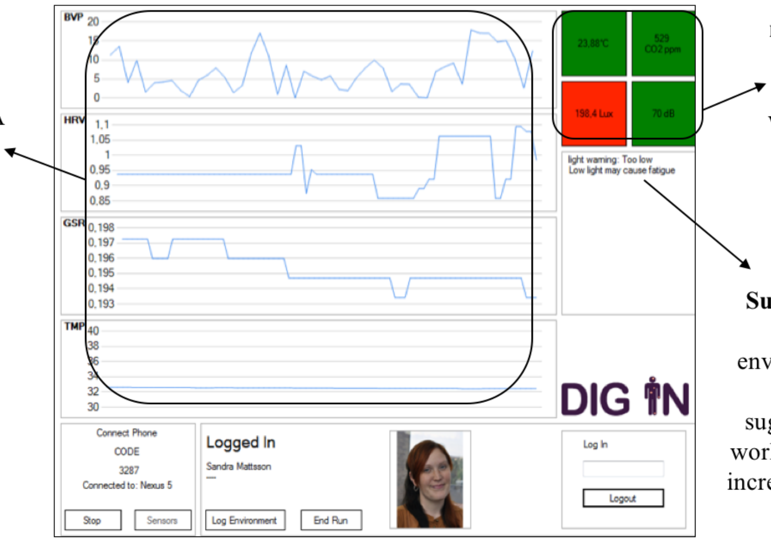
4) Analyse tasks which depend on cognitive limitations.

5) Analyse tasks which depend on individual differences and needs.

6) Analyse tasks which depend on the placement of information content and carrier.

DFIP has been used in education of over 150 students and company representatives to improve work instructions. Although DFIP has not been validated in a structured way (by comparing to other methods for example), it has been tested and evaluated. In the first evaluation of the guidelines (DFIP 1), the use of DFIP showed that students and company representatives mostly used step 3 (had a bulleted list of cognitive capabilities, step 4 in DFIP 2). One of the groups said that "it might be too difficult for them to use the guidelines as many of the results were based on their own experiences and feelings" (Mattsson et al., 2016). In education, DFIP was used in quizzes to assess the 102 students' knowledge of DFIP and suggested improvements (2016 and 2017). DFIP was also used in a case study to developed work instructions (on paper and video) for a complex product (Klinga et al., 2017)(supervised by the author). Both instructions were tested and evaluated by assembly operators, who were positive about the new instructions.

Paper III tested and evaluated DIG IN (DIGitalised well-beINg), a prototype which assesses operator wellbeing in real-time. The prototype is an interface in which physiological data and four measurements of the work environment (temperature, carbon dioxide, light and sound levels) are presented in real-time, see Figure 11.



23,88°C

529 CO2 ppm

198,4 Lux

70 dB

light warning: Too low
Low light may cause fatigue

Connect Phone
CODE
3287
Connected to: Nexus 5

Logged In
Sandra Mattsson

Physiological measurements: BVP, HRV, EDA (GSR) and Temperature (TMP) *Top to bottom.*

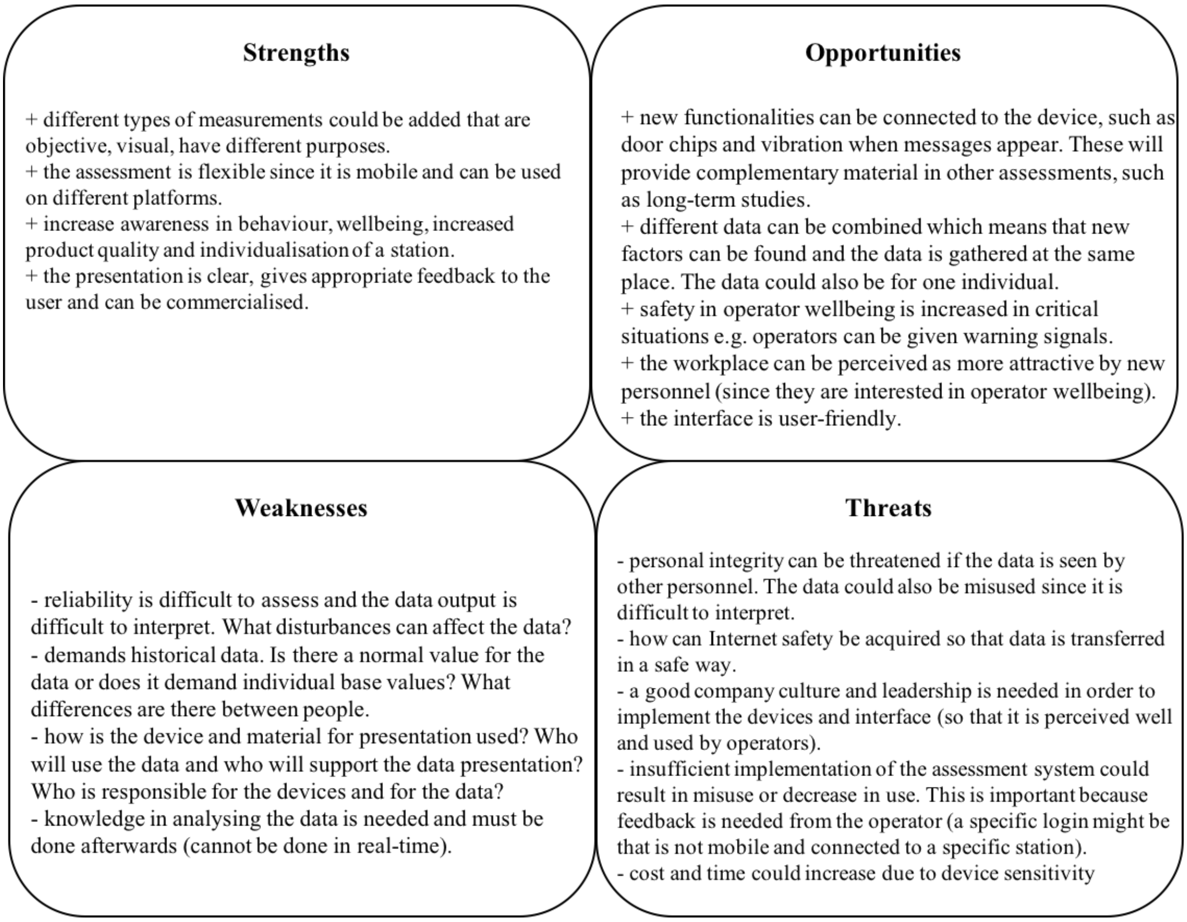
Environmental measurements: Room temperature, carbon dioxide level, workplace lighting and decibel level, *Left to right, top to bottom.*

Suggestion to operators: If physiological or environmental data exceeds its limits a change is suggested (in this case the workplace lighting should be increased since it might cause fatigue).

Figure 11: DIG IN prototype.

The DIG IN prototype was developed in cooperation with CGM (part of ABB AB) as part of a research project. 12 experiments were performed to test different devices that could be used to assess physiological measurements. Based on discussions with the company regarding physical ergonomics, the DIG IN prototype also included the four environmental measurements. Below the work environment indicators is a comment field where suggestions are given to the operator, should threshold limits be exceeded. For example, if the temperature is above 23 degrees, a message appears with a suggested change.

The opportunities offered by DIG IN were that it is flexible, mobile-based and could be connected to many types of data. Moreover, wearables could improve health and safety as well as the attractiveness of the company (Brown and Ryan, 2003), a fact also supported in the workshop findings. A SWOT analysis of wearables gave similar findings in terms of opportunities, such as improved health and increased awareness (Casselman et al., 2017). The workshop results are presented in full in Figure 12.



Strengths

+ different types of measurements could be added that are objective, visual, have different purposes.
+ the assessment is flexible since it is mobile and can be used on different platforms.
+ increase awareness in behaviour, wellbeing, increased product quality and individualisation of a station.
+ the presentation is clear, gives appropriate feedback to the user and can be commercialised.

Opportunities

+ new functionalities can be connected to the device, such as door chips and vibration when messages appear. These will provide complementary material in other assessments, such as long-term studies.
+ different data can be combined which means that new factors can be found and the data is gathered at the same place. The data could also be for one individual.
+ safety in operator wellbeing is increased in critical situations e.g. operators can be given warning signals.
+ the workplace can be perceived as more attractive by new personnel (since they are interested in operator wellbeing).
+ the interface is user-friendly.

Weaknesses

- reliability is difficult to assess and the data output is difficult to interpret. What disturbances can affect the data?
- demands historical data. Is there a normal value for the data or does it demand individual base values? What differences are there between people.
- how is the device and material for presentation used? Who will use the data and who will support the data presentation? Who is responsible for the devices and for the data?
- knowledge in analysing the data is needed and must be done afterwards (cannot be done in real-time).

Threats

- personal integrity can be threatened if the data is seen by other personnel. The data could also be misused since it is difficult to interpret.
- how can Internet safety be acquired so that data is transferred in a safe way.
- a good company culture and leadership is needed in order to implement the devices and interface (so that it is perceived well and used by operators).
- insufficient implementation of the assessment system could result in misuse or decrease in use. This is important because feedback is needed from the operator (a specific login might be that is not mobile and connected to a specific station).
- cost and time could increase due to device sensitivity

Figure 12: Results of the SWOT analysis.

Interpreting the data was identified as a risk in the SWOT analysis. This was also seen in the laboratory test. The EDA data is complex to interpret since the physiological measures are connected to several activities (cognitive and physical) (Figner and Murphy, 2011, Mendes, 2009). EDA does not measure any precise emotion but instead serves as a general indicator of arousal, attention, habituation, preferences and cognitive effort (Figner and Murphy, 2011, Mendes, 2009). However, although EDA is perceived as difficult to understand by participants, the measurement is relevant. EDA can show otherwise hidden processes, such as how people make decisions (Figner and Murphy, 2011) and provide information about an emotion before the participant becomes conscious of it (thereby preceding a reaction) (Picard, 2003, Smith and Kirby, 2004). Another risk was connected to personal integrity and data presentation. Personal integrity was identified as threat in a similar SWOT analysis. For example, the use of smart wearables was connected to personal integrity, and support or maintenance of the devices (Casselman et al., 2017). Regarding personal integrity, the technological solution in an industrial application would also need to be integrated with current systems and these need interoperability with industry standards (Åkerman et al., 2016). An Internet-centric solution, described by Li et al. (2015), could be used for these types of measurements. Furthermore, the next generation of cellular networks, 5G, promises several advantages and should help solve many issues of mobility and security.

Although the sample size of the case studies was small, the feedback from operators is important. To design a system based on what the operators think can improve interaction and operator performance (Rasmussen, 1983) and usability (Endsley, 2016, Ropohl, 1999, Trist, 1981, Hendrick and Kleiner, 2001, Trist and Bamforth, 1951, Maguire, 2001).

RQ3 results

Two prototypes were developed. The DFIP prototype supports information presentation and the DIG IN prototype supports the assessment of operator wellbeing in real-time. DFIP was used in education and tested in industry for designing work instructions (with positive results). The DIG IN prototype was evaluated in a workshop (opportunities as well as risks were seen).

4.5 Research and industrial contribution

The research and industrial contribution of the appended papers are presented in Table 7.

Table 7: Appended papers I-V; connection to research questions, industrial relevance and research contribution.

Appended paper	Industrial relevance	Research contribution
I	HAI trends were identified and a **conceptual model** for system elements presented.	Complex system elements were categorised and research gaps and HAI trends identified and discussed.
II	Two causes of complex assembly were identified and case study results from the **method CXI** were summarised.	Causal elements for perceived production complexity were found. Questionnaire results were summarised.
III	Four physiological parameters used to assess operator emotion were identified and tested. Industrial implementation was the focus. The **DIG IN prototype** was presented.	The assessment of operator wellbeing was tested and evaluated using a mixed method research approach.
IV	Operator performance was connected to a decrease in **arousal**.	A weak correlation between EDA and operator performance was found. No other significant correlations were found.
V	A **model** for assembly work and operator cognition was formed.	A **model** based on cognitive psychology and cognitive ergonomics was formed.

5 DISCUSSION

This chapter combines and discusses the results from the appended papers. Research quality, reflections and limitations, and future work are then presented.

5.1 Two actions: supporting cognition and emotion

The aim of this thesis was to investigate and suggest actions that can increase operator wellbeing and performance in complex assembly. Based on the results, two actions are suggested: 1) supporting cognition through improved information presentation (DFIP prototype) and 2) supporting emotion by giving feedback to the operator based on real-time physiological measurements and environmental data (DIG IN prototype). This is visualised in Figure 13, where system elements are used to present the summarised results (from Chapter 4).

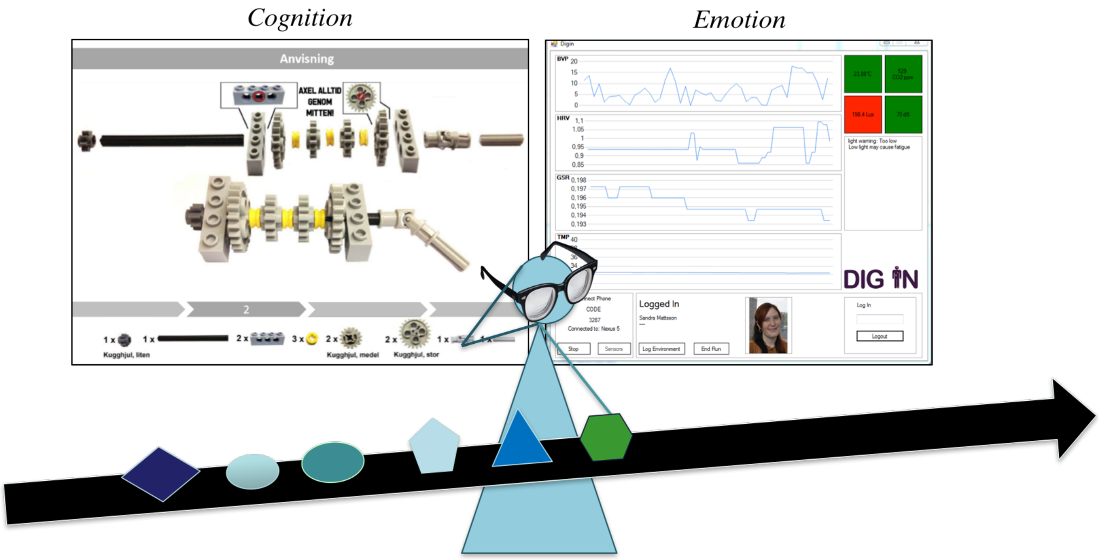
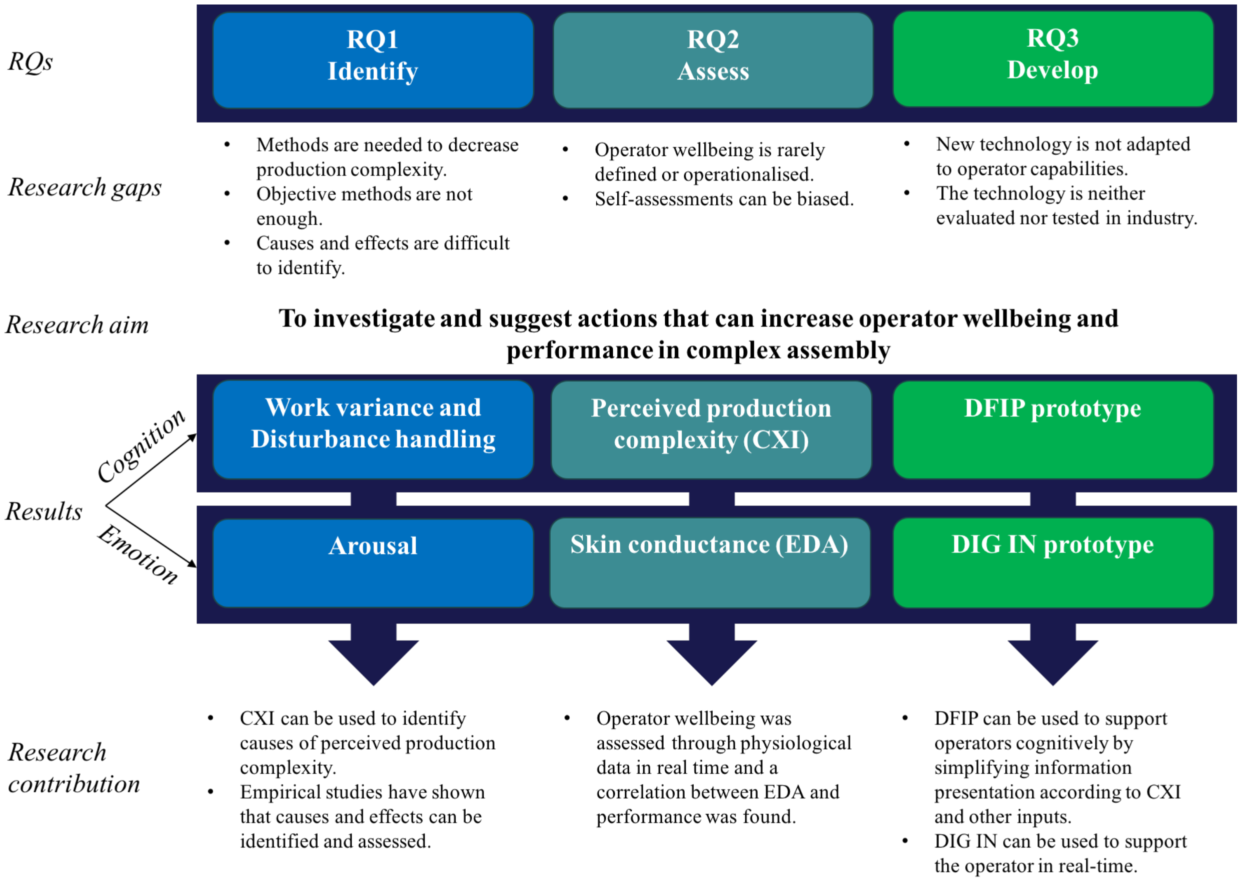


Figure 13: Two actions: supporting cognition and emotion, that can increase operator wellbeing and performance in complex assembly.

The two actions are further presented in Figure 14 with research gaps, objectives and contributions. “Job satisfaction, motivation and operator emotion” was changed to just “arousal” in the concluding figure since results showed EDA to be correlated to performance.



- Methods are needed to decrease production complexity.
- Objective methods are not enough.
- Causes and effects are difficult to identify.

- Operator wellbeing is rarely defined or operationalised.
- Self-assessments can be biased.

- New technology is not adapted to operator capabilities.
- The technology is neither evaluated nor tested in industry.

To investigate and suggest actions that can increase operator wellbeing and performance in complex assembly

- CXI can be used to identify causes of perceived production complexity.
- Empirical studies have shown that causes and effects can be identified and assessed.

- Operator wellbeing was assessed through physiological data in real time and a correlation between EDA and performance was found.

- DFIP can be used to support operators cognitively by simplifying information presentation according to CXI and other inputs.
- DIG IN can be used to support the operator in real-time.

Figure 14: Research gaps, aim, results and contribution connected to research questions.

For RQ1, research gaps were seen when it came to finding methods which do not rely solely on subjective data but which could decrease production complexity. There was also a need to structure system elements. A conceptual model was formed that structured causes, system elements and effects; two causes of perceived production complexity were found using the CXI method. The research gaps for RQ2 were: that operator wellbeing is rarely defined and that wellbeing assessments often involve self-assessments, which can be connected with bias. Operator wellbeing was then assessed in real time using physiological data. The research gap for RQ3 was that new technology exists but does not support operator cognition and was untested in industrial applications. Two prototypes were developed and tested by practitioners, with positive results.

The actions are discussed below in connection with operator wellbeing and performance.

Supporting cognition

Work variance and disturbance handling were identified as influencing factors for operator wellbeing and performance. The effect of work variance is crucial since it is connected to product variance as well as work content (from perceived production complexity definition and empirical results). Both of these aspects can be connected to the suggestions by the Swedish Work Environment Authorities to improve the work environment (due to work-related stress): participation on all levels, routines, allocation of tasks and sufficient knowledge (2016). This is similar to reaching a flow state, as described by Csikzentmihalyi; who advocated clearly stating rules, setting goals, providing feedback and control and receiving personal training (1990). *Flow* is a state that is achieved when an operator matches a goal with their own skill level (Csikszentmihalyi and LeFevre, 1989). Therefore, if operator cognition is supported in complex assembly, not only do they need improved information presentation, they need organisational support in terms of established routines and competence. This is also supported by the socio-technical perspective (Ropohl, 1999) and others such as Frederick Taylor who stated that in order for a person to carry out their work in the most efficient way (suited to that person's natural abilities) he/she should receive training or be educated (Taylor, 2005). This is especially relevant if operator work will become increasingly complex and include a lot of new work tasks. Disturbance handling is also connected to routines and competence, since it is important to be able to manage unknown events (Mårtensson and Stahre, 2003). Handling unknown events places heavy demands on the operator, who needs to be able to control his/her environment and receive appropriate information so that performance can be increased (Sheridan, 2002, Bäckstrand et al., 2010, Fjällström et al., 2007). As an example, a study of CXI in complex production (including also supervision of machine tools and medical equipment) indicated that empowerment was one way to manage complexity at a station (Mattsson et al., 2014b).

The LOD model is relevant to supporting work variance and disturbance handling, since presenting information appropriate to each work phase supports cognitive processes. Because instructions are often text, or text and picture-based, there is a potential improvement that can be used to support cognition; including pictures and movies (Watson et al., 2010, Fast-Berglund and Blom, 2014, Blom, 2014, Thorvald et al., 2010, Fässberg et al., 2010). If active cognitive processes are supported, the operator should not be overloaded with information (Holm et al., 2014, Posada et al., 2015, Maguire, 2001). In Paper V, it was also suggested that the automation level should also be chosen on this basis. For example, a virtual tool could be used for learning which could decrease learning time and reduce assembly errors for operators (Malmsköld et al., 2014, Langley et al., 2016). The DFIP could be used to design a first draft of the work instructions, then further usability tests could be performed, to find user errors among other things (as suggested by Nielsen (1993), Jordan (1998)).

CXI can be used to find bottlenecks and potential improvements. In the assessment of CXI, the different areas are colour coded and one part of the output is a colour carpet. Statements in the CXI survey can give insights into job satisfaction and motivation, such as being involved in work planning for the station (statement 8, version used in Paper II, "I am part of the planning for the changes on this station") and whether the work is connected to stress and/or frustration (current version of CXI, see Appendix A). It is important to further discuss what the colours mean from an operator wellbeing perspective. For instance, whether a complex station (in red) means that something is bad for the operator's wellbeing, or is unconnected to operator wellbeing. Studying the effect on cognition, the red values on those statements indicate (if red indicates work variance or disturbance handling) that the operators' cognitive capabilities may be threatened.

Moreover, although Station design (area A in CXI) was not found a cause for complex assembly, the physical environment still affects cognition. If something is difficult to reach or the station is poorly designed, this has an effect on the operator's cognitive capabilities. An action to increase operator wellbeing and performance can be to rotate between stations that are complex due to different problem areas. For example, changing between physically and cognitively demanding stations.

Supporting emotion

The second action relied on physiological data measurements in real time. Physiological data is interesting because it can reduce the systematic bias otherwise seen in self-reports (respondents relying on momentary affective states) (Posner et al., 2005, Diener and Seligman, 2004). By assessing arousal, it may be possible to distinguish between the occupational wellbeing aspects (workaholics, engaged, burned-out and satisfied) included in Russell's circumplex model of emotion, Figure 4. However, valence is also needed and physiological data should therefore be cross-validated with other types of measurements (such as interviews or self-reports). Moreover, the operator should always be included in the analysis since the assessments may be individual. As seen in the development of the DIG IN prototype, the reliability of the data was connected to how the person saw themselves from within. In other words, what is normal to one person might not be to another. An example of cross-validated, semi-structured interviews was used to assess perceived production complexity and determining stress (as suggested in an approach by Brinzer and Banerjee (2018)). Another example is CLAM; a method and tool for assessing cognitive load in assembly (Thorvald et al., 2017).

Many possibilities were seen with the DIG IN prototype. For example, trends could be found if physiological data was captured over a longer period of the day. It may be possible to use artificial intelligence, such as machine-learning, to assess if the operator has rested enough. *Machine learning* is when computers learn from past experiences and find patterns in complex datasets, with no explicit teaching from humans needed (Cruz and Wishart, 2006). For example, machine learning used electronic health records to predict heart failure six months before clinical diagnosis (Wu et al., 2017). The prototype also has potential in other applications, such as cobot collaboration (described in Paper IV). This enabled a new way of assessing stress and discomfort in a collaborative state. The combination of EDA and additional measures was also seen in an analysis of robot placement and behaviour (Papadopoulos et al., 2016).

5.2 Quality of research

The methods used in Papers I-V were validated according to construct, internal, external and contextual validity (Yin, 2009; Ihantola and Kihn, 2010). Paper II replicated studies to ensure external validity. Internal validity was increased by combining quantitative results with qualitative data. For instance, the system elements found in Paper I were further developed in Papers II and III. This was also carried out in Papers III and IV (where theoretical constructs were tested empirically). The data was captured and stored in a structured way, which increased the reliability of the empirical data (Eisenhardt, 1989). Furthermore, transferability was ensured because abductive research was carried out and prototypes developed which showed the practical usefulness of the results. The model in Paper V being used in the DFIP prototype, for example.

5.3 Reflections and limitations

Although it is difficult to get permission to assess physiological data in industry today, attitudes surrounding physiological measurements may be changing. In healthcare, there are examples of smart wearables used for health monitoring. For instance, remote monitoring is used for personalised health care management (Lymberis, 2003) and smart textiles which include activity sensors and electrocardiograms (to check heart rhythm) (Pantelopoulos and Bourbakis, 2009). There are also wearable tactile sensors which collect data on the mechanical properties of the body, integrate artificial intelligence with personalised health management and can help improve human quality of life (Yang et al., 2017). Data security and personal integrity is important to ensure that physiological data is used safely.

More examples, case studies and tests like the ones presented in this thesis are needed to bridge the gap between technology and humans. Examples which can show engineers and developers that human emotions and perceptions can be quantifiable as well as understood. Many smart technologies are now available which can increase operator wellbeing and performance. However, there are not many examples of implementation in industry (Weyer et al., 2015). Research trends point to a need for more knowledge in this field. In Paper I, for example, it was seen that human cause elements are often not included in HAI studies (2011-14). Human cause elements are connected to operators' individual factors, such as motivation and other performance-shaping factors; personality traits, competence, personal flexibility and so on. These need to occupy an important role when interacting with complex assembly systems. Moreover, although human-centred automation is connected to usability and usability studies, usability in industry is seldom considered when daily improvements and new technologies are introduced. The threshold for implementing good usability solutions may therefore be connected to that research gap. Social factors and increased awareness are needed to ensure the success of these smart technologies and increase competitiveness in industry (Soldatos et al., 2016). More research is therefore needed if we are to describe the interactions within a complex system and gain a holistic view. Because the chosen research approach was pragmatic, the number of factors had to be limited. Had this approach been combined with a qualitative analysis, a wider scope could have been achieved.

In the correlation studies, operator performance was not directly connected to perceived production complexity. Previous studies indicate correlations between complexity and performance but, because assembly error data has been difficult to retrieve, no correlations could be made. As seen in Johansson et al., assembly quality was rated by the production leader who said that some correlations could be seen (2016). In another study, assembly error logs were used to identify the most problematic station (Mattsson and Fast-Berglund, 2016). This did not correlate to CXI data but was used instead as an input to find problem stations in need of urgent change.

5.4 Future work

Interpreting and combining physiological data are important topics for future research. More studies are therefore needed to investigate how real-time assessments should be designed and how physiological data could be used in industry. Specifically, a social sustainability perspective that supports demographic changes is needed so that the smart technologies developed are efficient and support operators' cognitive and physical abilities (Romero et al., 2016b, Earthy et al., 2001). Health regulations and standards are needed to ensure that wearable devices are implemented successfully (Casselman et al., 2017).

More research in an industrial context is needed. Practitioners should therefore invest in testbeds or be open to case studies in which operator wellbeing is assessed in real time. Future work includes testing how physiological measurements can be combined with self-assessments to assess operator emotion in industry. Smart technologies should also be developed which can support cognition at all stages of assembly work.

6 CONCLUSIONS

This chapter presents the conclusions connected to the two suggested actions.

The aim of this thesis was to investigate and suggest actions that can increase operator wellbeing and performance in complex assembly. Two actions have been investigated and suggested: 1) supporting cognition through improved information presentation and 2) supporting emotion by giving feedback to the operator through real-time physiological measurements and environmental data. Although tests and evaluations of the prototypes show that operators' wellbeing and performance can be supported, more research is needed to understand the effect of work variance, disturbance handling and arousal.

Well-designed prototypes that do not disrupt the work flow can reduce complexity, increase performance, and create a more satisfying and attractive workplace. This could support production companies in meeting challenges of digitalisation connected to increased complexity, stress and information support.

The main conclusions are:

- Work variance and disturbance handling are the main causes of perceived production complexity.
- Operator emotion can be assessed in real-time through physiological data. Reliable data can be collected by real-time assessment of EDA combined with HRV or BVP.
- Arousal, assessed using EDA, is related to operator performance.
- Information should be presented according to the three phases of assembly work: learning, operative and disruptive.

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APPENDIX A – CXI

CSI LAB
CHALMERS SMART INDUSTRY LAB

Hello,

This questionnaire has been designed to find solutions that can simplify and improve your work. The survey is anonymous. It is important that you consider one chosen station as you fill in the questionnaire.

Chosen station: ___________

Number of years in assembly:________years

Number of years at actual station:________years

The questionnaire covers: product variants, work content, layout, tools and support tools and work instructions.

Thank you for participating!

Best regards

Sandra Mattsson, Malin Tarrar and Åsa Fast-Berglund
Chalmers University of Technology

Consider how well the following statements fit with the work you have carried out in the last month at the chosen station. The scale ranges 1-5, with 1 as “I agree completely” and 5 as “I don’t agree at all”.

A. Product variants

1. There are many different variants at this station.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

2. Many variants are similar to one another in function and/or external surface at this station.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

3. There are many variants that are seldom assembled at this station.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

4. The variants at this station require different strategies to assemble (for instance order, difficulty, different number of operations).

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

B. Work content

5. I have many other work tasks aside from the assembly work at this station (for instance material handling, 5S, documentation etc.).

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

6. The takt time at this station is generally enough for me to perform my work tasks.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

7. My work at this station is often affected by unplanned changes/uncertainties (for instance change of plans, new instructions/variants, or machine disturbances).

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

8. During unplanned changes/uncertainties, there is enough time for me to perform my work tasks.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

9. During unplanned changes/uncertainties (for instance change of plans, new instructions/variants, or machine disturbances), it is easy to find the information I need to perform the tasks at this station.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

10. I am part of the planning for the changes at this station.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

11. During my work at this station, I often feel stressed and/or frustrated.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all (never or more seldom)				Agree completely (every day)	Don’t know /not relevant

C. Layout

12. This station is well-designed regarding accessibility.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

13. This station is well-designed regarding heavy lifting in the assembly work.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

14. This station is well-designed regarding ergonomics in the assembly work (for instance stretching, bending down).

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

15. This station is well-designed regarding the material façade (for example type of packaging, placement, simplicity of picking and sequencing material).

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

16. The placement of tools, fixtures and components at this station is generally good.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

D. Tools and support tools

17. The tools/fixtures used at this station are well-adjusted for the tasks performed there.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

18. Which support tools are found at this station?

☐ Pick-by-light (lights are lit for a specific part)

☐ Barcodes and scanners

☐ RFID system

☐ Feedback from screens

☐ Feedback from tools (for example the correct force and correct bit)

☐ Checkpoints (feedback in the assembly work)

☐ Other ___________________

19. The above-mentioned support tools help me carry out my work at this station.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

E. Work Instructions

20. The work instructions are easy to understand.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

21. The work instructions at this station simplify my work.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don’t know /not relevant

F. General view

22. It takes a long time to learn the work at this station (compared to other stations in my team area) .

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don't know /not relevant

23. In general, I think this station is well-designed.

1	2	3	4	5	
☐	☐	☐	☐	☐	☐
Do not agree at all				Agree completely	Don't know /not relevant

24. Comments (for example a suggested improvement, changes to the station, work content, support or other things).

Thank you for taking time to answer this survey! Your answers are valuable to us.

For more information contact
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APPENDIX B – DFIP 2.1

Sandra Mattsson (Version 2.1 2017-05-02, based on Chapter in Smart Automation – Methods for final assembly)

To avoid errors and secure assembly quality, it is important to consider how information is presented. Information can be instructions (written and oral) such as assembly instructions or descriptions of where components or tools should be placed. Assembly instructions at a workstation are seldom designed with usability or cognitive ergonomics in mind and are often text-based with just a few pictures. To address these issues, design principles for information presentation (DFIP) have been developed. DFIP is built on information presentation theory and usability (in areas of design and Human-Automation Interaction). DFIP encompasses tasks that will be performed and aims to reduce the volume of information and thus support active cognitive processes. In other words, it enables the handling of more variants and differentiating between similar-looking components connected to those variants.

See the design principles in Chapter 9.5.1 of the course book to find out more.

6 steps of DFIP:

1. **Choose a work task in the workplace** where information presentation will be improved. Divide the work task into sub-tasks (using, say, Hierarchical Task Analysis, HTA). An example is the assembly of a cylinder where the first sub-tasks are to pick the component, then insert a spring and so on. Consider these aspects:

    a. **Relevancy.** Choose a work task that needs improvement; talk to the operators or do some sort of current state analysis. What improvements are needed? What is the purpose? Increased quality? Decreased time? Introduction of checkpoints, standard work sub-tasks or work instructions? Methods that can be used include DFA, DYNAMO++ and CompleXity Index (CXI).

    b. **Feasibility.** Choose a work task that can be improved; there should be funds available for you to actually implement and make the changes.

2. **Identify and support active cognitive processes in each sub-task.** Depending on whether the operator is meant to work quickly or actively solve a problem, he/she needs support based on what process is active at that time. It is therefore important to differentiate between: 1) intuitive processes (fast, automatic, unconscious), where the operator uses previous experience and 2) reasoning cognitive processes (slow, active, conscious, energy-consuming). Differentiate between the following categories of cognitive processes and support them as follows:

    a. **Intuitive processes** are used for routine assembly work. Intuitive processes are activated by signals (a traffic light for example). You can for therefore use lights, vibration or other types of signals that assist operator attention to support intuitive processes.

    b. **Reasoning processes** are used for active problem-solving. Reasoning is activated by a combination of inputs. For instance, when troubleshooting, a maintenance worker listens to the machine, looks at error logs, checks the oil, talks to personnel and so on. It is important to make relevant information available to the operator to support this process.

    c. Another type of process used for reasoning and intuition is **rule-based processes**. These processes are rules or patterns that you have learned previously and are activated by signs, such as an exit sign. When you see the sign, you know what lies beyond it and how to act in that type of situation. In other words, you have a memorised behaviour pattern for that. The same is true of a common variant or picture of a commonly used tool.

3. **Analyse tasks based on how the operator perceives the work environment.** Even though something may be objectively easy, it doesn't mean the operator feels that it is. It is therefore important to investigate what the operator perceives as complex or complicated, whether the operator has all available information or whether something is difficult to reach or feels stressful (supporting mental models). Methods that can be applied include CXI,

interviews or observation. This view is not limited to one operator; the organisational structure, company culture and routines may therefore be included. Depending on 1a and 1b, investigate some/all of these aspects:

   a. **Information flow.** What does the task and information flow look like to operators with different roles, such as machine supervision or logistical personnel? How is the material placed and how is the information presented?

   b. **Work environment.** What does the work environment look like? Are there things that can disrupt cognitive processes? Are the workspace levels of things like lighting, sound, temperature and CO^2 OK?

   c. **Standardised work.** Are standards used and are they observed?

   d. **Time management.** What does the work rota look like? Are there enough opportunities for recovery time after a stressful task?

4. **Analyse tasks depending on cognitive limitations.** There are many limitations to our cognition. For instance, it is difficult to keep many things in the working memory at the same time (especially if the situation is stressful or otherwise cognitively demanding). Consider the following aspects:

   a. **Reduce and simplify.** The working memory can handle 7 ± 2 chunks of information – reduce information.

   b. **Redundancy.** It is important to distinguish between similar components and to notify the operator when a new variant is about to be assembled. Use clear descriptions and presentations – it should not be possible to make mistakes. Use arrows, numbers and magnifications.

   c. **Clarity.** Focus on large, clear pictures with high contrast and no shadows. Only use text if pictures are not enough. Clarify differences between similar objects by using arrows or colours (consider colour-blindness).

5. **Analyse tasks based on individual differences and needs.** Due to demographic changes there will be individual needs regarding height, hearing and colour vision. However, there may also be other things to consider that are important if we wish to attract a diverse work force. Consider the following aspects:

    a. **Physical conditions** such as height, length, hearing and if the operator is left- or right handed.

    b. **Individual requests** such as colour, music or sound. For instance, one operator might like to listen to music (it relaxes the operator and makes them concentrate better). Another operator might really want to read up on instructions or guidelines well in advance.

    c. **Gamification.** Can elements of gamification such as walking competitions or number of times standing up (for office jobs) be used to increase motivation and to increase operator wellbeing?

6. **Analyse tasks depending on placement of information content and carrier.** Where the information is placed is crucial to whether it will be used or not. Assembly instructions are usually stored in a binder a few meters from the assembly line. When the operator needs help in terms of information, he or she might not have the time to walk over and check the binder and asks a colleague instead, or doesn’t ask anyone. Information should therefore be placed in the operator’s view (this also includes the content presented via an information carrier). Consider the following aspects:

    a. **Content placement.** Information content should be placed in the top-left-to-bottom-right diagonal. Place important information along this diagonal and less important information in the other diagonal (or in the lower left and upper right corners).

    b. **Additional information carriers.** Support memory by adding a picture that shows the complete product (supports the expert and does not need step-wise instructions). Remember to introduce as few carriers as possible, and that all information should be up to date.