THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Designing collaborative robot workstations for human-centred automation in final assembly - a task allocation approach

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ABSTRACT

With the rise of increasingly intricate products, human operators are stretched thin by greater physical and cognitive demands. A growing necessity has also arisen for automation to assist these operators supportively and productively while maintaining optimal efficiency. One solution to this problem is the integration of collaborative robots; specifically, the use of task allocation to correctly apply collaborative robots in the design process.

Thus, this thesis aims to enable task allocation in designing human-centred automation by using collaborative robot workstations in final assembly. This aim is achieved through theoretical and empirical research and a mixture of different research methods, such as qualitative, quantitative and mixed-methods research.

This thesis focuses on collaborative robots in manufacturing and final assembly. It analyses the current and intended use of these robots in final assembly and explores how task allocation can help develop collaborative robot workstations that support human-centred automation.

Through theoretical research, the thesis finds that collaborative robot applications are highly useful in manufacturing and final assembly and can easily be combined with other human-centred automation technologies. However, the thesis also highlights the fact that in complex assembly processes, there is negligible collaboration between humans and robots. The empirical research presented in this thesis finds that companies recognise the potential benefits of using these robots to tackle human operators' challenges. However, for human-robot collaboration to be successful, the collaboration must be based on the capabilities of humans and robots. This can be achieved using task allocation.

This thesis uses task allocation based on *levels of automation* (LoA). This thesis proposes a new LoA that can serve as a helpful tool for production designers to create collaborative robot workstations. This approach enables production designers to obtain valuable insights on effectively distributing tasks between robots and humans. By doing so, they can determine the level of collaboration required and the necessary skills from the human operators required to accomplish a particular task.

Keywords: human-robot collaboration, levels of automation, task allocation, collaborative robots, human-centred automation

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These five years of PhD studies have been a rollercoaster of ups and downs. As I prepare to pen down this final piece before sending my thesis to print, reflecting on my time as a PhD student, I feel privileged to be able to carry out this work. The knowledge and experiences of this journey are something that I will cherish for the rest of my life.

I want to start by expressing my utmost gratitude to Professor Johan Stahre for his invaluable guidance and unwavering support throughout my journey. Your mentorship has been instrumental not only in shaping the direction and quality of my research but also in helping me grow and develop as an independent researcher. Your commitment to achieving academic excellence, providing me with vital feedback, and offering constructive criticism have encouraged me to extend my academic and personal limits. Thank you for those impromptu and often long discussion sessions, they have been invaluable.

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During my time in the division of production systems, I had the pleasure of working alongside an exceptional group of researchers. I sincerely thank you for your support and invaluable feedback throughout this journey. I want to extend a special thanks to Clarissa, Hao, Greta, and Dan for all the moments of laughter and impromptu after-work gatherings. I feel incredibly fortunate to have had you by my side.

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Omkar Salunkhe
Gothenburg, November 2023

LIST OF APPENDED PAPERS

The five appended papers in this thesis are listed here, with the authors' contributions and the distribution of work.

Paper I Assembly 4.0: wheel hub nut assembly using a cobot.

Omkar Salunkhe, Olivia Stensöta, Magnus Åkerman, Åsa Fasth-Berglund and Per-Anders Alvefloo (2019).

Presented at the 9th IFAC/IFIP/IFORS/IISE/INFORMS Conference on Manufacturing Modelling, Management and Control, MIM 2019, Berlin, Germany. Published in IFAC PapersOnLine, vol. 52, no. 13, pp. 1632-1637.

Omkar Salunkhe devised and wrote the paper with contributions from Olivia Stensöta, Magnus Åkerman and Åsa Fasth-Berglund. Omkar Salunkhe planned the study. Olivia Stensöta and Omkar Salunkhe collected and analysed the data. Per-Anders Älveflo provided the industrial perspective. Omkar Salunkhe presented the paper.

Paper II Industry 4.0-enabling technologies for increasing operational flexibility in final assembly.

Omkar Salunkhe and Åsa Fasth-Berglund (2022).

Published in *International Journal of Industrial Engineering and Management*, volume 13, issue 1, pages 38-48.

Omkar Salunkhe devised and wrote the paper with contributions from Åsa Fasth-Berglund. Omkar Salunkhe collected and analysed the data. Åsa Fasth-Berglund guided data collection and analysis. Omkar Salunkhe presented the paper.

Paper III Framework for identifying gripper requirements for collaborative robot applications in manufacturing.

Omkar Salunkhe, Patrik Fager and Åsa Fasth-Berglund (2020).

Presented at the IFIP International Conference on Advances in Production Management Systems, APMS 2020, Novi Sad, Serbia.
Published in IFIP Advances in Information and Communication Technology, Vol 591.

Omkar Salunkhe devised and wrote the paper with contributions from Patrik Fager and Åsa Fasth-Berglund. Omkar Salunkhe collected and analysed the data. Patrik

Fager provided input regarding kitting operations. Åsa Fasth-Berglund guided data collection and analysis. Omkar Salunkhe presented the paper.

Paper IV Review of Current Status and Future Directions for Collaborative and Semi-Automated Automotive Wire Harnesses Assembly.

Omkar Salunkhe, Walter Quadrini, Hao Wang, Johan Stahre, David Romero, Luca Fumagalli and Dan Lämkull (2023).

Presented at 56th CIRP Conference on Manufacturing Systems, CMS '23, Cape Town, South Africa. Accepted for publication.

Omkar Salunkhe devised and wrote the paper with contributions from Walter Quadrini, Hao Wang, David Romero and Johan Stahre. Omkar Salunkhe, Walter Quadrini and Hao Wang collected and analysed the data. Johan Stahre and Luca Fumagalli provided data collection and analysis guidance and Dan Lämkull provided the industrial perspective.

Paper V Bridging the Hype Cycle of Collaborative Robot Applications.

Omkar Salunkhe, David Romero, Johan Stahre, Björn Johansson and Anna Syberfeldt (2023).

Presented at the IFIP International Conference on Advances in Production Management Systems, APMS 2023, Trondheim, Norway.
Published in IFIP Advances in Information and Communication Technology, Vol 689.

Omkar Salunkhe devised and wrote the paper with contributions from David Romero, Johan Stahre, Björn Johansson and Anna Syberfeldt. Omkar Salunkhe collected and analysed the data. Johan Stahre and Anna Syberfeldt guided the data analysis.

Paper VI Specifying Task Allocation in Automotive Wire Harness Assembly Stations for Human-Robot Collaboration.

Omkar Salunkhe, Johan Stahre, David Romero, Dan Li and Björn Johansson (2023).

Published in *Computers and Industrial Engineering* Journal, volume 184, article number 109572. ISSN 0360-8352.

Omkar Salunkhe devised and wrote the paper with contributions from David Romero, Johan Stahre, Dan Li and Björn Johansson. Omkar Salunkhe and Johan Stahre conceptualised the matrix with contributions from David Romero.

LIST OF ADDITIONAL PAPERS

This list of additional papers includes related work, important for the content of this thesis but beyond the scope of answering the research questions.

Paper 1 **Cyber-physical production testbed: literature review and concept development.**

Omkar Salunkhe, Maheshwaran Gopalakrishnan, Anders Skoogh and Åsa Fasth Berglund (2018).
Presented at the *8th Swedish Production Symposium*, Stockholm, 16th -18th May.
Published in *Procedia Manufacturing*, vol. 25, pp. 2-9.

Paper 2 **Effects of information content in work instructions for operator performance.**

Dan Li, Sandra Mattsson, **Omkar Salunkhe**, Åsa Fasth-Berglund, Anders Skoogh and Jesper Broberg (2018).
Presented at the *8th Swedish Production Symposium*, Stockholm, 16th -18th May.
Published in *Procedia Manufacturing*, vol. 25, pp. 628-635.

Paper 3 **Design concept towards a human-centred learning factory.**

Sandra Mattsson, **Omkar Salunkhe**, Åsa Fasth-Berglund, Dan Li and Anders Skoogh (2018).
Presented at the *8th Swedish Production Symposium*, Stockholm, 16th – 18th May.
Published in *Procedia Manufacturing*, vol. 25, pp. 526-534.

Paper 4 **Conceptualising Assembly 4.0 through the Drone Factory.**

Åsa Fasth-Berglund, Magnus Åkerman, Dan Li and **Omkar Salunkhe** (2019).
Presented at the *9th IFAC/IFIP/IFORS/IISE/INFORMS Conference on Manufacturing Modelling, Management and Control,* Berlin, 28th - 30th August.
Published in *IFAC PapersOnLine*, vol. 52, no. 13, pp. 1,525-1,530.

Paper 5 **Gripper types and components in robotic bin picking.**

Patrik Fager, Stefano Rossi, Robin Hanson, Lars Medbo, **Omkar Salunkhe**, Mats I. Johansson and Åsa Fasth-Berglund (2020).
Presented at the *IFIP International Conference on Advances in Production*

Management Systems, Novi Sad, 30th August - 3rd September.
Published in *IFAC Proceedings Volumes - IFIP Advances in Information and Communication Technology (IFAC-PapersOnline), vol 591.*

Paper 6 **Low-cost automation – changing the traditional view on automation strategies using collaborative applications.**

Åsa Fasth-Berglund, **Omkar Salunkhe,** Magnus Åkerman (2020).
Presented at the IFIP International Conference on Advances in Production Management Systems, Novi Sad, 30th August - 3rd September.
Published in IFAC Proceedings Volumes - IFIP Advances in Information and Communication Technology (IFAC-PapersOnline), vol 591.

Paper 7 **Overview of Computer Vision Techniques in Robotized Wire Harness Assembly: Current State and Future Opportunities.**

Hao Wang, **Omkar Salunkhe**, Walter Quadrini, Dan Lämkull, Fredrik Ore, Björn Johansson, Johan Stahre.
Accepted for publication at 56th CIRP Conference on Manufacturing Systems, CIRP CMS ’23, South Africa.

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1 INTRODUCTION

This chapter introduces the research area of automotive final assembly systems, otherwise known as "final assembly". It provides the background to automation in assembly systems and the role of task allocation. It also emphasises the need for human-centred automation, leading to the research aims and questions presented in this thesis.

1.1 Background

Robot applications in automotive final assembly are often static processes requiring safety cages so that the human operators remain safe and work unhindered. Generally, automation is also viewed as an obstacle to the free flow of human operators in final assembly (Sheridan, 2012). Even when automation is implemented, it is often a binary decision; a choice between a human and a machine for a particular task. Such an approach is not just suboptimal; this tendency to regard the choice as being between a human and automation is unhelpful in tasks requiring the collaboration of both. The inclination to allocate tasks left over by automation to humans started in the late 1980s (Bainbridge, 1983) and remains quite common today (Parker & Grote, 2022).

The introduction of any new technique or technology brings both benefits and drawbacks. The same goes for automation, especially in automotive final assembly, where introducing automation has often led to decreased systems performance and human-automation interaction issues (J. D. Lee & Seppelt, 2023). However, Thurman et al. argue that automation itself is not the problem here, so much as the improper design and inappropriate application of it (Thurman et al., 1997). An example of such automation is the role of robots in final assembly. Provided all safety measures are implemented, robots can work with human operators but there needs to be an understanding of how and where they should collaborate.

Henry Ford invented assembly lines to standardise the assembly process (Lazdowski, 2020). The Toyota Production System (TPS) optimised assembly lines with their "jidoka" and the "just-in-time" concepts to remove quality-related issues and reduce inventory costs. In 1989, Arai predicted the rate of automaton in final assembly would be between 35% and 75% of all final assembly operations (Arai, 1989). This forecast was based mainly on robots being a key technology around which the design of both products and production will evolve. Based on the present author's observations and collaborations in automotive final assembly, automation has yet to match the predicted levels.

Final assembly processes are often complex, with numerous steps and intricate parts that can be difficult to automate (Kiyokawa et al., 2023). Early approaches to human-centred automation were divided into "automating", whereby a process is automated and "information", whereby the information in the process is provided to the human (Badham, 1991). The classification and division of work between humans and machines relied on the notion that humans are creative yet slow and unreliable. By contrast, machines are non-creative yet fast and reliable. This approach followed the use of new technologies to aid skilled operators by providing the necessary information to make crucial judgements about a process; the assembly of a complex product, for example. Such an approach can be challenging in an environment of constantly changing products and a high turnover of operators. While discussing flexible assembly systems (FAS), (Mårtensson et al., 1993) highlighted the fact that modern manufacturing systems are too complicated for a fully automatic process and a proper division of tasks is required,. Sheridan (1996) suggested, "*downloading some of the rule-based and almost all of the skill-based commands (or programs) into the supporting computer while retaining the knowledge-based tasks for himself/herself.*" This supervisory control model assumes that certain semi-automatic and automatic processes and tasks can be supervised and controlled using sensors and actuators. Over the years, Sheridan's supervisory control model and levels of automation (Sheridan, 1997) have been used as the basis for a division of tasks and functions in different models. The situational awareness approach by Endsley (M. Endsley et al., 1996), adaptive task allocation by Parasuraman (Parasuraman et al., 1996) and levels of automation in manufacturing by Frohm (Frohm et al., 2008) bear a resemblance to Sheridan's work. These models were not limited to task allocation in assembly but were also applied to human-robot collaboration.

In modern assembly systems, collaborative robots are an essential tool for increasing human-centred automation. The division of tasks is vital to the successful implementation of human-robot collaboration. The division of tasks in human-robot collaboration has heavily relied on Fitts' "*Men are better at/machines are better at*" (MABA-MABA) list (Fitts, 1951). This model was developed based on technology available in the 1950s. The technological progress of the past half-century is not reciprocated with the task allocation models, especially in human-robot collaboration. Today's advanced sensors and vision systems can ensure safe, high-quality assembly, thus narrowing the gap in the MABA-MABA list. As robots become smarter, the allocation of tasks between humans and robots in this complex assembly process is becoming more critical than ever (Kiyokawa et al., 2023). Most successful automated applications in a final assembly are human-centred, whether it be the use of power tools, digital technologies such as digital instructions (Li et al., 2022) or xR technologies (Å. Fast-Berglund et al., 2018). These tools are designed based on a human-centric approach. A similar approach is needed for using robots in final assembly.

With unpredictable market demands and globalised supply chains, the need is greater than ever for more flexibility, better quality and ergonomic-friendly workstations in assembly, whilst keeping costs low. As of 2015, the number of assembly operations carried out by human operators stands at around 95% (A. Fast-Berglund et al., 2016). Reasons that limit the use of robots in assembly include complexity of assembly (where a task is too complex for a robot and requires human intervention, Heyer, 2010) or the safety of humans cannot be completely assured (Galin & Meshcheryakov, 2020).

Collaborative robots are an excellent technological solution that can be easily combined with currently availabe advanced sensors to ensure human safety. Nevertheless, according to the *International Federation of Robotics* (IFR, 2022), the use of collaborative robots is low, especially in automotive final assembly. Regarding the use of collaborative robots in manufacturing and automotive final assembly systems, it is crucial that the technology is secure and that the human operators understand how to work with it. Research has shown that the technology is mature and secure enough to be used alongside human operators (Simões et al., 2022). However, compared to industrial robots, the number of collaborative robots currently in use is still quite low (IFR, 2022). One reason for this could be the fact that there is a considerable mismatch between how researchers perceive the collaboration between humans and robots and how industry perceives it. There is a lack of understanding of attaining a sustainable collaboration between humans and robots. Task allocation, which is widely used in industry today, can help simplify such collaboration.

1.2 Vision and Aim

The author of this thesis envisions automotive factory floors in which collaborative robot workstations enable human-centred automation to achieve highly flexible and ergonomically friendly assembly.

With this thesis, the author aims to enable task allocation for designing human-centred automation using collaborative robot workstations in final assembly.

This thesis offers tools to simplify the process of creating collaborative robot workstations for human-centred automation in the final assembly of vehicles.

1.3 Research Questions

Two sequential research questions were formulated to support this aim:

RQ1: How do humans and robots collaborate in manufacturing and final assembly operations?

Human-robot collaboration has a long history but this growth has increased over the last decade with the emergence of collaborative robots. Collaborative robots possess the desired properties, such as being lightweight, flexible and easily programmable machines capable of working alongside human operators without fences. Collaborative robots can take over unergonomic and often tedious tasks from operators. The popularity of collaborative robot application research and development has grown exponentially, as evidenced in academic publications. And yet industrial acceptance has been thin. This research question aims to identify the status of human-robot collaboration involving collaborative robots, in terms of its advantages, use as a solution for human-centred automation and the challenges that hamper its acceptance in the automotive industry.

RQ2: How does human-centred task allocation support the design of collaborative robot workstations in final assembly?

Collaborative robots are designed to work alongside a human operator and are an ideal solution for implementing human-centred automation in final assembly. However, this implementation needs to be based on the cognitive and physical abilities of humans and robots rather than intuition. This research question examines the use of task allocation in simplifying human-robot collaboration in complex assembly processes, such as final assembly. The question also aids the design of human-robot collaborative workstations in final assembly.

1.4 Scope and Delimitations

The scope and findings of this thesis are limited to manufacturing, specifically automotive final assembly. Although results may be applicable to other sectors, most of the industrial research and fieldwork was conducted in collaboration with Swedish multinational automotive companies, plus their sub-contractors and suppliers located in Sweden and the European Union.

This research does not focus on developing new technologies. However, combining different technologies explored in this research shows potential in that collaborative robots could be augmented with research supplementing their application in final assembly. This research uses existing technologies that are either available off-the-shelf or easily ordered from manufacturers. This research does not cover human behaviour and ergonomics and relies on existing literature to cover those aspects. Robot control theory or systems engineering is also outside the scope of this thesis.

1.5 Outline of the Thesis

After this first chapter introducing the importance of the research, the thesis is structured into the following five chapters.

Chapter 2, Research Approach and Methods. This chapter explains the research methods used and the rationale behind the choice of methods. A mixed-methods research approach is used.

Chapter 3, Theoretical Framework. This chapter elaborates on the theoretical foundations of the research by introducing operational flexibility and its role in final assembly and Industry 4.0-enabling technologies.

Chapter 4, Results and Summary of Appended Papers. This chapter summarises the highlights of each appended paper. The summaries also include information on case studies and their contribution to the research questions.

Chapter 5, Discussion. This chapter combines the contributions of the appended papers and thereby answers the research questions. The academic and industrial contributions of this thesis are also presented, alongside proposed future research.

Chapter 6, Conclusion. This chapter summarises the thesis by providing final remarks on the research questions.

Note: the application of collaborative robots is mainly referred to as “collaborative robot applications” in the appended papers and, in some instances, in this thesis. This has been done to offer a better semantic presentation of the context in which it is used.

2
THEORETICAL FRAMEWORK

This chapter begins with an introduction to assembly systems and automation. The role of humans in automated systems is discussed through human-centred automation and human-robot collaboration.

2.1 Assembly

The International Academy for Production Engineering (CIRP) is widely regarded as the top organisation in production engineering research and defines production as "the pure act or the process (or connected series of acts or processes) of physically making a product from its material constituents and is distinct from designing the product, planning and controlling its production by assuring its quality" (CIRP, 2019). It may be said that production covers all activities required to produce a product, from the initial processing of raw material and on to finished product.

Assembly is part of this production process and is when different parts and components, either in the form of sub-assemblies or complete products, are brought together to create a finished product (Hu et al., 2011). In the automotive industry, a typical product flow structure is as follows: stamping and welding shops (often known as body-in-white), paint shops and final assembly (Tang, 2017). The final assembly, also known as the assembly line, is the final stage of the product realisation process (Hu et al., 2011; Michalos et al., 2010)

2.2 What is Automation?

The term automation is defined in several ways. The Oxford English Dictionary defines automation as "the use of machines and computers to do work previously done by humans." The International Society of Automation (ISA), a non-profit technical society geared towards promoting automation, defines automation as "*the creation and application of technology to monitor and control the production and delivery of products and services.*" Sheridan presents a complete definition of automation (Sheridan, 2002) as follows: (1) the mechanisation and integration of the sensing of environmental variables using smart AI-based sensors, (2) data processing and decision-making by computers, (3) mechanical action by motors and or devices exerting force on the environment, or information action by the communication of process information to people.

Initially, the term "automation" was used primarily in the context of manufacturing. Now, automation is used beyond manufacturing in the healthcare and service industries. The context in which it is used has also evolved. In the early days, when automation was mainly focused on manufacturing, it was in the context of machines replacing humans (Hitomi, 1994). With the advancement of automation-related technologies, especially with the Fourth Industrial Revolution, automation exists in terms of automated customer services, the use of intelligent bots in homes with smart-home solutions and smartphone applications which carry out different tasks in the background (Parker & Grote, 2022). As automation has expanded beyond our factories to our pockets, human interaction with automation has also evolved. Automation is not just seen as replacing humans but, in many cases, assisting them. Examples include smartphones or the medical robots used by doctors. These are a massive step towards seeing the coexistence of automation with humans (Wolf et al., 2023).

2.3 Automation in Final Assembly

From a moving assembly line to the introduction of robots in welding shops, paint shops and quality assurance, automation in automotive assembly systems has increased considerably in the past century (Krzywdzinski, 2020). Robots conduct most operations deemed harmful to humans; lifts, transport decks and AGVs move material around efficiently in assembly lines (Krzywdzinski, 2021; Pardi, 2019). However, final assembly has seen no drastic changes as compared to other parts of assembly lines. This is mainly due to the complexity of the assembly operations carried out in final assembly.

Physical Automation

Physical automation refers to the use of power tools and machines to accomplish a task (Fasth, 2012). Physical automation in the final assembly process often involves the use of smart reconfigurable power tools and AI-based vision systems to aid operators in their tasks (Romero et al., 2020). Collaborative robots are also used to eliminate harmful and unergonomic tasks for operators. However, human operators continue to play a crucial role in final assembly, just as they did in the early 20th century.

Cognitive Automation

According to (Thurman et al., 1997), "Cognitive automation is software intended to automate cognitive activities, such as situation assessment, monitoring and fault management, that are currently performed by human operators" Cognitive automation consists of technical solutions used in helping human operators with HOW and WHAT to assemble (Å. Fast-Berglund & Stahre, 2013). Such solutions include an automated screwdriver that provides haptic feedback on completing a nut-tightening operation or the use of tools with tolerance management to maintain quality. An excellent example of cognitive automation is using digital screens such as smartphones and tablets and augmented reality (AR) glasses to deliver assembly instructions to operators. Increased use of cognitive automation can improve operators' work conditions by decreasing their workload and retaining mechanical automation (Fasth-Berglund and Stahre, 2013).

2.4 Human-Centred Automation

Automation is a technological imperative; design engineers automate because they can, which is not always the best idea according to (Sheridan, 2002). Sheridan says that, even in the most relatively complex system, automation is far from able to do the whole job, especially when automation itself is failing. Often in these cases, human is seen as an essential element that monitors the automation and acts as a supervisor who can take over the failing automation (Frohm et al., 2008). The necessity of humans thus comes in conflict with the view of design engineers on automating all tasks that can be automated.

Table 2.1. MABA-MABA List by Fitts (1951).

Humans surpass machines in their:	**Machines surpass humans in their:**
Ability to detect small amounts of visual or acoustic energy	Ability to respond quickly to control signals and apply great force smoothly and precisely
Ability to perceive patterns of light or sound	Ability to perform repetitive, routine tasks
Ability to improvise and use flexible procedures	Ability to store information briefly and then erase it completely
Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time	Ability to reason deductively
Ability to reason inductively	Ability to handle highly complex operations; many different things at once
Ability to exercise judgment	

The most basic and vital part of human-centred automation is allocating tasks and functions between humans and machines. This task and functional allocation is based primarily on the Fitts list (Fitts, 1951) ("Men are better at/machines are better at") shown in Table 2.1. Even though this list has been criticised for its static nature, lack of organisational context, outdatedness and failure to acknowledge the complementarity of humans and machines (Jordan, 1963), it continues to be widely used in task and function allocation (De Winter & Dodou, 2014). In complementing the Fitts list, Price et al. (in Price, 1985) add that the final means of allocating tasks is based on expert judgement. Past experiences largely influence this expert judgement in the design phase. Price (1985) also highlights the necessity of context-dependent data for using the Fitts MABA-MABA list. However, such data is often unavailable. Price also emphasises the necessity of continuously evolving the task and function allocation rather than it being a one-off event. This rationale is based on the observation that operators are often clueless about what is happening when automation is in control. Due to their inability to keep their mental models of the system updated, operators are tempted to take over from the automatic control due to their lack of confidence in automation. To overcome such issues, Price proposed a decision matrix for task and function allocation, based on the performance of humans and machines (Price, 1985).

For an automated system to be human-centred, it should have features that allow humans and machines to work together in accomplishing tasks, argues Billings, (1991). He also states that automation, due to its superior quality of operation, should be able to conduct an entire sequence of operations with a human in a supervisory role. It can be difficult to implement this suggestion in dynamic systems where conditions are prone to change and human intervention may be required, as in final assembly systems. Billings argues that despite their imperfections, humans possess three valuable attributes. Firstly, they are skilled at detecting signals in noisy environments. Secondly, they can reason effectively, even in uncertain situations. Lastly, they are able to abstract and organise concepts (Billings, 1991). One might argue that this article, written in the context of aircraft operation thirty two years ago, does not apply in the age of advanced AI. However, the importance of humans in automated systems is emphasised by the three invaluable attributes mentioned above.

While discussing the effects of automation on human performance, Bainbridge (Bainbridge, 1983) highlights the potential complexities and challenges of fully automated tasks. The author discusses the impact of automation on human skills and complacency. She argues that relying too heavily on automated systems can lead to a decline in human efficiency and skills. Additionally, when automation controls most tasks, human operators may become overly reliant on it and become complacent in their supervisory role. This can result in reduced vigilance and a lack of preparedness to intervene when necessary. Bainbridge (1983) refers to these challenges as the "paradoxes of automation" and emphasises the importance of including human involvement in designing automation systems centred around humans.

Within the context of human-centred automation, Sheridan argues that using the Fitts list in the allocation of tasks and functions will do more harm than good since it divides tasks between humans and machines and overlooks the complementary nature of humans and machines working together. To overcome this issue, Sheridan proposed levels of automation inspired by human supervisory control (Sheridan, 1995).

Human Supervisory Control

Human supervisory control took off with the invention of computer-integrated manufacturing (CIM), with the role of human operators being limited to monitoring and supervising automated machines (Sharit, 1985). This monitoring and supervising approach of human supervisory control is also common in human-robot collaboration and interaction. Many of the existing assembly tasks now carried out by robots include such operations as pick and place, welding, painting and so on. These operations are generally called supervisory human-robot interactions since the involvement of humans is limited to planning, teaching, programming and monitoring processes (Sheridan, 2016). However, the increasing role of humans in the supervisory role also has its own set of challenges. Common among them is the operator's zeal to take over automated tasks due to a lack of transparency and information he or she receives from the automated system (Bennett et al., 2023). Such issues are also common in human-robot collaboration. Two critical problems identified by (Sheridan, 2016) concerning human-robot interaction envisioned here in the context of final assembly are: 1. The ability to observe the workstation at 360° 2. Response to or compensation for intermittent delays or drops in communication. With the emergence of advanced portable 3D cameras and infrared systems, 360° monitoring of physical activity at a workstation is now possible. Advancements in communication technology, such as the emergence of wireless 5G telecommunications technology and UPC UA industrial communication standards, have shown promise of near-elimination of communication delays in industrial devices (Mihai et al., 2022). The use of task allocation addresses the challenges of human supervisory control and keeps the operator engaged with automation.

2.5 Levels of Automation and Task Allocation in Manufacturing

Based on his work in human supervisory control, Sheridan proposed ten levels of automation. These are listed in table 2.2 and have been used as a foundation for developing task allocation methodologies in manufacturing, as reviewed by (Vagia, Transeth and Fjerdingen 2016).

Table 2.2. Levels of Automation by Sheridan & Verplank presented in (Vagia et al. 2016).

Level of Autonomy	Description	Explanation
1	Fully manual control.	The computer offers no assistance.
2	The computer offers a complete set of decision/action alternatives.	Several options are provided to the human, who then decides.
3	The computer narrows the selection down to a few items.	Human still has to decide.
4	The computer suggests one alternative.	Human chooses between suggestions.
5	The computer executes that suggestion, if the human approves.	Human approval needed for execution.
6	The computer allows the human a limited time to veto before automatic execution.	Limited time for veto given to the human.
7	The computer executes automatically and then informs the human.	No human interference, just information at the end.
8	The computer informs the human only if asked.	The human gets information only if requested.
9	The computer informs the human only if it decides to.	The computer decides whether to give information.
10	Fully autonomous control.	The computer decides everything and acts autonomously, ignoring the human.

These levels of automation were further refined by (Parasuraman et al., 2000) to add the independent functions of information acquisition, analysis, decision making and action implementation. This model is shown in Figure 2.1. Drawing on the LoA taxonomies proposed by (Billings, 1991; M. R. Endsley, 1997; Sheridan, 1997), (Frohm et al., 2008) proposed a new LoA taxonomy model better suited to reflect the needs of manufacturing and simplify the understanding of LoA in manufacturing. This model is shown in Table 2.3.

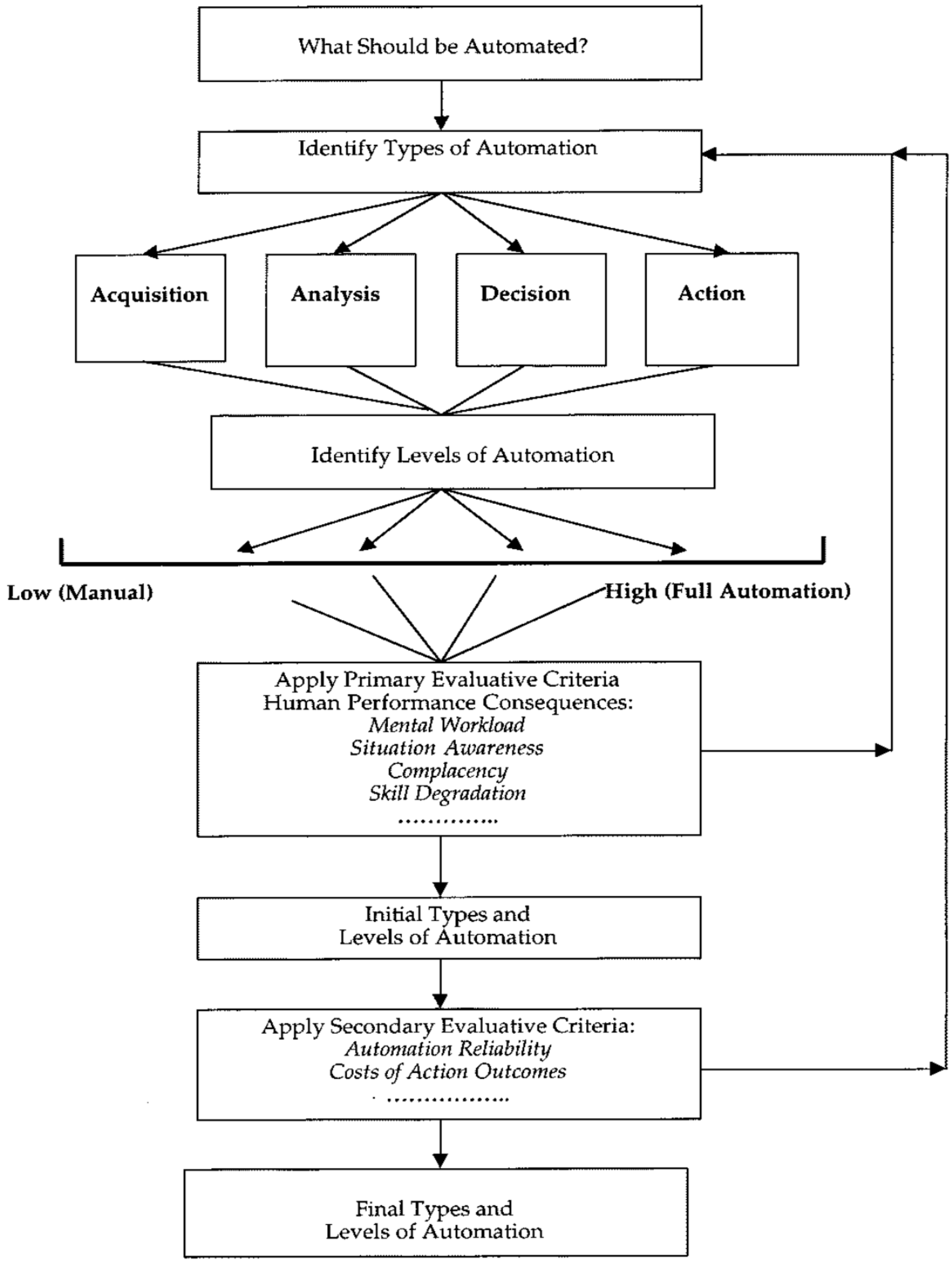

Figure 2.1. Flow chart of application of model types and levels of automation, as presented by Parasuraman et al., (2000).

Table 2.3. LoA Matrix for Physical and Cognitive Allocation of Tasks, proposed by Frohm et al. (2008).

LoA	Mechanical and Equipment	Information and Control
1	**Totally manual** - totally manual work; no tools are used, only the users' own muscle power.	**Totally manual** - the user creates his/her own understanding of the situation and develops his/her course of action based on prior experience and knowledge.
2	**Static hand tool** - manual work with the support of a static tool, e.g. a screwdriver.	**Decision giving** - the user gets information on what to do or a proposal on how the task can be achieved, e.g. a work order.
3	**Flexible hand tool** - manual work with the support of a flexible tool, e.g. an adjustable spanner	**Teaching** - the user gets instructions on how the task can be achieved, e.g. checklists, manuals.
4	**Automated hand tool** - manual work with the support of an automated tool, e.g. a hydraulic bolt driver.	**Questioning** - the technology questions the execution, if it deviates from what the technology considers suitable, e.g. verification before action.
5	**Static machine/workstation** - automatic work by a machine designed for a specific task, e.g. a lathe.	**Supervision** - the technology calls for the users' attention and directs it to the present task, e.g. alarms.
6	**Flexible machine/workstation** - automatic work by a machine that can be reconfigured for different tasks, e.g. a CNC machine.	**Intervene** - the technology takes over and corrects an action if its execution deviates from what the technology considers suitable, e.g. a thermostat.
7	**Totally automatic** - totally automatic work. The machine solves all deviations or problems by itself, e.g. autonomous systems.	**Totally automatic** - all information and control is handled by the technology. The user is never involved, e.g. autonomous systems.

Task analysis is widely regarded as the first step in human-system design (Sheridan, 2002). Task analysis usually consists of a breakdown of an overall task into its elements and the specification of how these different elements relate to each other in space, time and functionally. One task denotes a complete procedure (all activities), such as designing or building a product, assembling a product, part or component and monitoring or controlling a process, sub-process or even a machine. In manufacturing processes, tasks are both physical and cognitive (Williams & Li, 1999). Physical tasks entail supporting or replacing human muscle power, while cognitive ones entail carrying out information and control tasks. Furthermore, this approach is consistent with (Frohm et al., 2008), who state that the manufacturing process consists of physical and cognitive tasks and that task allocation must be separated into physical and cognitive tasks. Task allocation in manufacturing is further enhanced using the DYNAMO++ methodology for simplifying the distribution of tasks between humans and machines (Fasth et al., 2010).

Whenever a system is to be improved, automated, or changed, it is vital to reconsider the task analysis. This is due to changing roles, demands and responsibilities, which often have unintended and unanticipated impacts on the performance of a system. Task allocation is also used to increase the efficiency of a system (Heisler et al., 2020) and ensure the safety of the operators (Faccio et al., 2023). As technological advancement continues to grow, finding a proper balance between a task's complexity and the human operator's capability is becoming increasingly important. Task allocation helps in finding this proper balance.

2.6 Human-Robot Collaboration

Humans and robots have worked together in manufacturing for a few decades now. The early stages of human-robot work focused on humans loading parts into robot fixtures or assisting robots from outside the caged-off areas. This type of work is characterised as *human-robot interaction* (HRI) (Goodrich & Schultz, 2007). Here, the human operators and robots were clearly separated by cages and did not share the workspace or workpiece. The only interaction was either the human loading/unloading the workpiece for the robot to carry out its task, or vice-versa. In *human-robot collaboration* (HRC) using collaborative robots, humans and robots are expected to collaborate on a work task without fences (Villani et al., 2018). This type of work involves a more equal and independent relationship between humans and robots, focusing on collaborative exchanges of information towards accomplishing a given task. This is the primary principle of collaborative robots.

Collaborative Robots

Collaborative robots, commonly known as "cobots," are a type of industrial robot designed for direct interaction with humans in completing a task (Peshkin & Colgate, 1999). They are equipped with advanced sensors and actuators capable of detecting obstructions in the cobot's path. The ISO/TS 15066:2016 technical specification emphasises the external safety features required for a collaborative robot. Such safety measures are supported by infrared safety sensors, proximity sensors and other similar technologies that offer an extra layer of safety in human-robot collaboration. Traditional industrial robots face huge limitations, such as caged safety areas, less flexibility when moving between workstations and extended programming and verification processes for their applications in final assembly. Furthermore, a high degree of human operator involvement in assembly processes also limits the use of traditional caged-off robotic systems in final assembly. With their safety features, fast and comparatively easy programming and verification and their ability to work closely alongside human operators, collaborative robots can overcome the challenges faced by industrial robots (Ore et al., 2017). The most common use of collaborative robots in final assembly is in unergonomic and repetitive operations such as picking and placing, stacking and packaging. Collaborative robots are also used in quality assurance and assembly verification processes. The studies by (Faccio et al., 2019) and (Weckenborg & Spengler, 2019) show the cost-related benefits of collaborative robots vs traditional robot applications in assembly systems.

The most common basis for using collaborative robots is to help human operators perform tasks that are otherwise challenging to accomplish using conventional automation solutions. The different levels of collaboration are divided based on the actual collaboration between operator and collaborative robot in a collaborative workspace. The collaborative workspace is an area inside the robot's operating space, in which robot and human collaborate towards fulfilling a task, as shown in Figure 2.2.

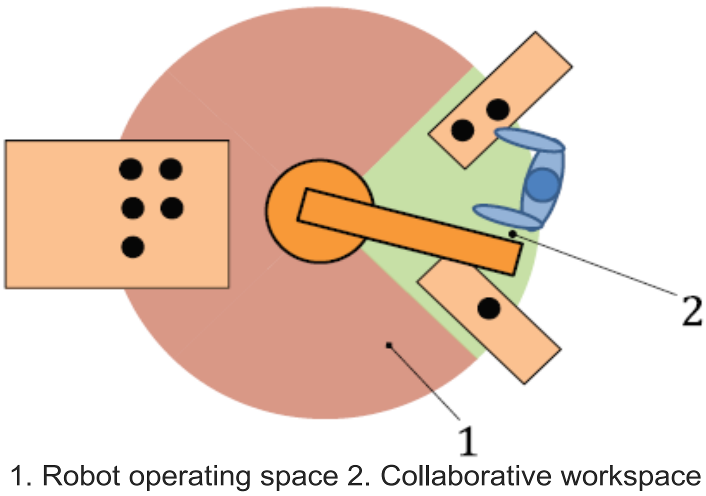

Figure 2.2. Collaborative workspace adapted from Bauer et. al (2016).

The different levels of collaboration are shown in Figure 2.3, with the levels explained further below.

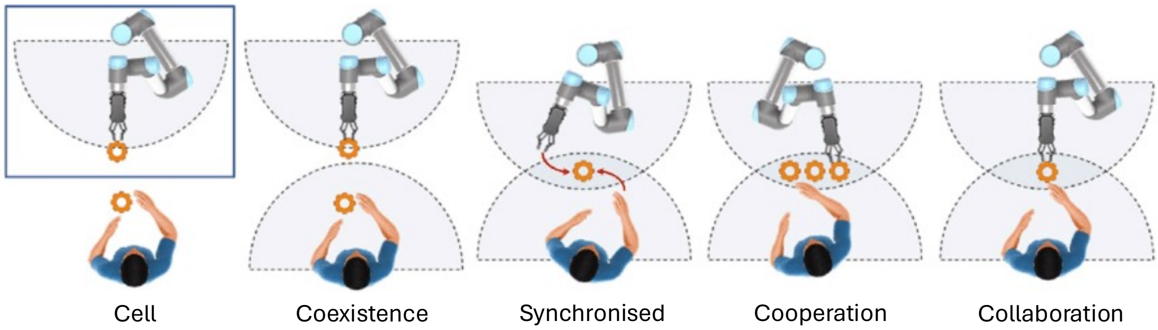

Figure 2.3. Levels of collaboration in collaborative robot application. Adapted from Bauer et. Al (2016).

- Cell: traditional cage scenario in which the robot is isolated in a cage.
- Coexistence: humans and robots work alongside each other without the presence of any cage, although the workspace is not shared.
- Synchronised: humans and robots share the workspace. Only one interaction partner (either human or robot) is actively working in the workspace.
- Cooperation: shared workspace, in which both humans and robots have tasks to perform. These tasks are not performed simultaneously in the exact location of a product or component.

- Collaboration: humans and robots work simultaneously on the same product or component.

Task Allocation in Human-Robot Collaboration

Task allocation is vital in human-robot collaboration. As the popularity of collaborative robots has grown over the last decade, the research into task allocation has gorwn exponentially. A hierarchical agent-based task allocation is proposed by (Johannsmeier & Haddadin, 2017), in which robots and humans are treated as skilled-based agents while planning the task allocation. As with skills, a capability-based task allocation is proposed by (Ranz et al., 2017). (Malik & Bilberg, 2019a) proposed a complexity-based task allocation. Their model is based on the distribution of tasks based on skills and the complexity of the task. The model classifies tasks into high and low levels of complexity.

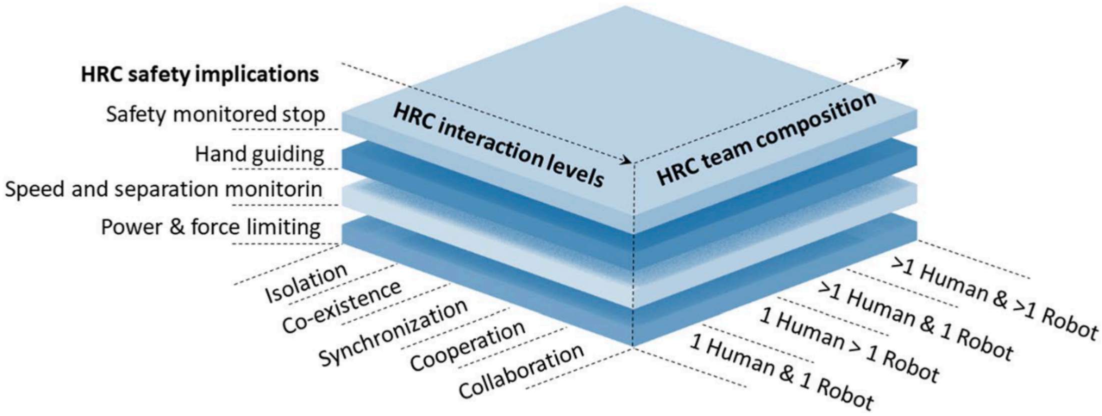

Figure 2.4. Architecture model for HRC by Mailk & Bilberg, (2019b).

Furthermore, an architecture for human-robot collaboration between multiple teams of humans and robots is also presented by (Malik & Bilberg, 2019b), highlighting the complex nature of task allocation in human-robot collaboration with respect to the safety, levels of collaboration and distribution of tasks shown in Figure 2.4. Other notable work includes a task allocation model aimed at improving ergonomics, by (Makrini et al., 2019). They argue that allocating and integrating ergonomic requirements into capability-based task allocation reduces musculoskeletal disorders (MSDs) among operators caused by heavy-duty tasks. Yet these methods have not fulfilled the needs and requirements for a better task allocation process, as highlighted by (Ranz et al., 2017).

3

RESEARCH APPROACH AND METHODS

This chapter presents the research approach and methods used in this thesis.

According to Creswell (2017), a research approach is based on three interconnected components that form a strategy for conducting research as shown in Figure 3.1. These are: 1. Philosophical worldview 2. Research design and 3. Research methods. The philosophical worldview of the researcher influences the understanding of the research problem, the research questions and the selection of the research methods.

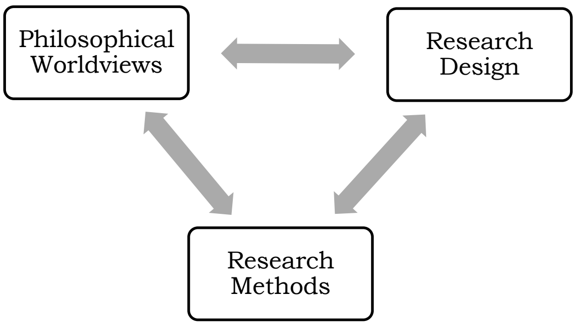

Figure 3.1. Research approach proposed by Creswell (2017).

3.1 Philosophy

The researcher's philosophical worldview refers to their fundamental beliefs about the nature of knowledge, reality and human behaviour (Hirschheim, 1985). These beliefs shape the researcher's approach in selecting the research process. They also influence the research questions, based on the researcher's assumptions about reality. The research presented in this thesis concerns the use of collaborative robots in assembly systems. It targets the manufacturing domain, a field in which the author has education and personal experience. The author's previous education in mechanical and production engineering and work experience in machining and manufacturing automation have influenced his philosophical worldview.

Researchers in various fields all have differing philosophical worldviews. This means they will select the most appropriate methods in answering their research questions. Creswell (J. W. Creswell & Creswell, 2017) presents the following four, widely-used worldviews or epistemologies: positivist, constructivist, transformative and pragmatic. Epistemology refers to our theory of knowledge and the assumptions regarding what creates valid, legitimate and acceptable knowledge and how we acquire it (Hirschheim, n.d.). Positivistic research is used in explaining reality and strives to reduce uncertainty. Constructivist research is a subjective process exploring how people interpret and rely upon the participant's views of the research being undertaken. Research based on a transformative worldview links research to political change and tends to change the researcher's and participants' lives. A pragmatic worldview does not commit to any one philosophical doctrine but emphasises the problem defined in research and uses all approaches available to understand it (J. W. Creswell & Creswell, 2017).

The author of this thesis is a pragmatic researcher. The research in this thesis follows a pragmatic approach to applied research. This pragmatism is influenced by the author's philosophical worldview and the nature of the topics studied in this research. While basic research focuses on theory-building and hypothesis-testing (with a focus on advancing scientific knowledge and understanding), applied research is conducted to solve practical problems in specific situations (Williamson, 2002). Basic research aims to generate knowledge about the underlying principles of a particular topic or phenomenon. Applied research seeks to apply this knowledge to solve problems or improve existing systems or processes (Bell et al., 2019; Hair et al., 2019). Considering the nature of the topics being studied (essentially how collaborative robots and human operators can work together in final assemblies, which are real-world problems involving collaboration with industry), this thesis follows a pragmatic approach to applied research, which is more suitable in this context. Pragmatic research emphasises an understanding of user needs, preferences and behaviours, which is crucial for developing a human-robot collaboration application. The pragmatic approach followed in this research has helped identify and address practical challenges related to human-robot collaboration in manufacturing and final assembly. A pragmatic approach to applied research was also used in the iterative process of design, execution, testing and refinement of HRC applications in the various stages of this research. This technique is well-suited to human-robot collaboration as it allows constant enhancement of human-robot collaboration based on feedback and data analysis from both academic and industrial partners.

Inductive, deductive and abductive reasoning are the most-used strategies in a systematic scientific investigation (Bell et al., 2019). Inductive reasoning is based on analysing empirical data to build a theory, while deductive reasoning uses a hypothesis to confirm or reject a theory (Bell et al., 2019). Abductive reasoning focuses on possibility and plausibility rather than outright confirmation or rejection (Knowles, 2006). Based on pragmatism, the research presented in this thesis is guided by abductive reasoning in its process of scientific investigation.

3.2 Research Activity

The research presented in this thesis and the appended papers is based on various research activities conducted between 2017 and 2023 in five research projects funded by *Vinnova* (the *Swedish Governmental Agency for Innovation Systems*), the *Sten A Olsson Foundation for Research and Culture,* the *Stena Foundation* and the *European Commission* through *EIT Manufacturing*.

- 2017–2020: Demonstrating and testing smart digitalisation for sustainable human-centred automation in production. Funded by Vinnova.
- 2018-2020: Stena Industry Innovation Lab at Chalmers (SII-Lab). Funded by the Stena Foundation.
- 2019-2022: A Pan-European Network of Robotics DIHs for Agile Production (DIH2). Funded by the European Commission.
- 2020–2023: DIH World – Accelerating deployment and matureness of DIHs for the benefit of digitisation of European SMEs. Funded by the European Commission.
- 2021-2022: Sustainable human-robot co-production for cargo bicycles (Robofiets). Funded by the European Commission through EIT Manufacturing.
- 2022-2025: Empowering Human Workers for Assembly of Wire Harnesses (EWASS). By Vinnova.

The alignment of the appended papers with the research questions is shown in Table 3.1

Table 3.1. Alignment of appended papers with research activities.

<table>
<tr><th></th><th>Paper I</th><th>Paper II</th><th>Paper III</th><th>Paper IV</th><th>Paper V</th><th>Paper VI</th></tr>
<tr><td>RQ1</td><td>Major contribution</td><td>Major contribution</td><td rowspan="2">Minor contribution</td><td rowspan="2">Major contribution</td><td>Minor contribution</td><td>Minor contribution</td></tr>
<tr><td>RQ2</td><td>Minor contribution</td><td>Minor contribution</td><td>Major contribution</td><td>Major contribution</td></tr>
<tr><td>Research activities timeline</td><td>2017-2019</td><td>2018-2021</td><td>2019-2020</td><td>2021-2022</td><td>2022-2023</td><td>2022-2023</td></tr>
</table>

3.3 Research Design and Data Collection

As defined by (Bell et al., 2019), research design "represents the structure that guides the execution of a research method and the analysis of the subsequent data". Various research methodologies were applied while conducting this research, based on the pragmatic approach to applied research and abductive reasoning. The enquiry presented in this research is diverse and requires different research methods to understand individual enquiries and their collective impact. The research presented in this thesis uses quantitative, qualitative and mixed-methods approaches. Quantitative research focuses on data collection and analysis of numbers with the aim of generalising facts, while qualitative research focuses on data collection and analysis of words to gather detailed analysis. Simply put, quantitative research gives breadth to research, while qualitative research provides depth (Johnson & Onwuegbuzie, 2004). A mixed-methods approach helps in a different type of data collection that provides a complete understanding of the research problem than quantitative or qualitative data. In this approach, the quantitative and qualitative data is collected roughly simultaneously and the final results are based on the information derived from interpreting the overall results (J. W. Creswell & Creswell, 2017; Moseholm & Fetters, 2017). Mixed-methods research involves integrating or combining quantitative and qualitative research methods (J. W. Creswell & Creswell, 2017). A convergent mixed-methods research is a research approach in which the quantitative and qualitative data is merged to analyse a research problem comprehensively (J. W. Creswell & Creswell, 2017).

Table 3.2. Research design, data collection and validation of appended papers.

Paper	Classification	Research design	Data collection and analysis	Research validation techniques
I	Empirical	Mixed-methods research Design research-based case study	Participant observation in the industry Quantitative analysis in laboratory experiments	Expert review Peer debriefing Demonstrations
II	Theoretical	Quantitative research Literature study	Systematic literature review using keyword searches Coding using a pre-defined coding scheme	Intercoding reliability Negotiated agreement Peer debriefing
III	Empirical	Qualitative research Conceptual framework	Thematic analysis Open coding scheme	Intercoding reliability Peer debriefing
IV	Theoretical	Quantitative research Literature study	Systematic Literature review using keyword searches. Coding using a pre-defined coding scheme	Intercoding reliability Negotiated agreement Peer debriefing
V	Empirical	Quantitative research Survey	Questionnaire for industrial participants Statistical analysis	Pilot testing Reliability analysis Peer debriefing
VI	Empirical	Mixed-methods research Conceptual framework	Participant observation in the industry Thematic analysis	Expert review Peer debriefing

The research presented in this thesis uses a mix of research methods to comprehensively understand how collaborative robots are perceived in industry as shown in Table 3.2. Quantitative studies, such as literature reviews, are used to understand where and how collaborative robots are used in industry. They are also used to study how complex assemblies use automation techniques to solve ergonomic issues. Such an approach is used to afford academic rigour to this research. Quantitative approaches, such as surveys, are used to gain in-depth knowledge of how industrial practitioners use collaborative robots and the challenges they face while implementing human-robot collaboration. In this research, a qualitative method such as participant observation is used to capture the experiences, opinions and concerns of the industrial partners involved in developing human-centred automation. This is crucial to understanding the needs and requirements of the industry. Using convergent mixed-methods research, this information is combined in an iterative process to conceptualise a framework for simplifying the application of collaborative robots and enabling human-centred automation. Using both qualitative and quantitative research methods and a mixed-methods research approach at different stages of this research has afforded a robust understanding of human-robot collaboration and collaborative robots.

Papers II and IV are theoretical research papers, while Papers I, III, V and VI are empirical research. Papers I and VI used mixed-methods research combining qualitative and quantitative methods in different orders (J. W. Creswell & Creswell, 2017). Papers II, IV and V used a quantitative research approach, while Paper III used a qualitative one. This approach has also helped in using different papers to present rich contextual information based on scientific evidence to different stakeholders (such as academia and industry).

Paper I follows a qualitative research approach. It presents an exploratory case study based on design research to test whether a manual assembly station can be automated using a collaborative robot. The design research approach defines, develops and refines theories (Edelson, 2002). The activities in design research are iterated more often between the construction of an artefact, evaluation of an artefact and feedback to improve that artefact (Hevner, 2007). Since this case study required the design and refinement of a collaborative workstation based on initial theories, design research was selected as the method. Initial data collection was done by studying the relevant station on-site. The participant observation technique was used to gather information about the station's operation. Quantitative analysis was used as the research method in laboratory experiments.

A systematic literature review, as defined by (Grant & Booth, 2009), seeks to draw together all known knowledge on a topic area by adhering to the guidelines on conducting a review. It aims to answer a particular research question, test hypotheses and build theories. Paper II used a systematic literature review in which 93 articles were identified and used in the study. This paper followed a systematic literature process proposed by (Mertens, 2018) using a pre-defined coding scheme for data collection and analysis. Scopus and Web of Science repositories were used in the data collection.

Paper III uses a qualitative research approach based on thematic analysis in developing a gripper selection framework. Thematic analysis is a research method used in analysing and interpreting written text, audio, video and images and identifying and analysing patterns in the data (Nowell et al., 2017; Vaismoradi et al., 2013). Thematic analysis based on open coding was used to collect and analyse data related to grippers. It used different sources such as scientific literature, informal interviews and online discussions.

Paper IV follows a systematic literature review with a research process similar to that of Paper II. Based on pre-defined coding, an initial 77 articles were identified using a keyword search in the Scopus repository. This was followed by an appraisal, in which 61 articles were excluded and 16 were used for complete analysis and then synthesised.

Paper V follows a quantitative research approach based on surveys. These are widely used as an effective method of collecting data and then using statistical analysis to aid the analysis of patterns and trends (Bell et al., 2019); in this case, how companies use or intend to use collaborative robots. This paper followed a surveying methodology (Blair et al., 2013). Seventy-eight survey results were collected, analysed and summarised using descriptive statistical analysis.

Paper VI follows a mixed-methods research approach. Preliminary studies were conducted using the participant observation technique on-site. There was also thematic analysis in developing a design tool for task allocation in the human-robot wire-harness assembly process.

3.4 Research Quality

Two essential criteria that ensure the quality of scientific research are validity and reliability (Bell et al., 2019). Validity relates to whether the research methods that were applied have investigated the intended questions (Yin, 2018). Concerning the reliability aspect, (J. Creswell, 2014) proposes strategies such as crosschecking transcripts of records. This assures the reliability of research and further supports its validity. Based on this recommendation, the details of the research procedures, transcripts of informal interviews and discussions, images, videos and experimentation records are prepared and documented in detail, in an appropriate structure. Table 3.2 shows the summary of research validation and reliability.

Expert review is a research validation method whereby individuals who are experts in their research fields are asked to give feedback on the research topic (Tracey, 2009). Experts may be from academia and industry and can provide feedback on research design, data collection and analysis methods and the interpretation of findings. They may also help identify any weaknesses and biases in research and help ensure that the research is based on solid theoretical and empirical foundations. Peer debriefing is similar to expert review but involves colleagues and other researchers familiar with the research topic giving feedback on it (Janesick, 2015). Peer debriefing also helps by offering fresh perspectives and is useful in ensuring the research is ethically sound.

Papers I and VI used expert reviews as their research validation method. The research outcome was shown to the industrial partners from whom the original data was obtained. Furthermore, the research presented in Paper I was also presented to the relevant industrial and academic experts to strengthen the research validity. All papers appended in this thesis used peer review as a research validation method. A peer debriefing was conducted for colleagues, industrial partners and external reviewers. Papers I, III, IV and V were subjected to the single-blind review process, while Papers II and VI were subjected to double-blind review.

Reliability as an appropriate quality assessment criterion for qualitative data collection methods is debated by researchers (Bryman et al., 2018). To ensure reliability (Yin, 2018) recommends documenting the detailed procedures in research studies. Various such documentation steps have been taken to ensure the reliability of this research. In Papers, I and VI, images, videos and transcripts of informal discussions on-site were kept to ensure on-site data collection quality. The reliability and validity of thematic analysis used in these papers were checked using expert review and peer debriefing, as suggested by (Neuendorf, 2018). A detailed process of keyword selection and data collection, including the dates and review process, was kept for Papers II and IV. In content and thematic analysis research, coding is vital to ensure its reliability; intercoding reliability is a commonly used method in such analysis, to ensure the reliability of data analysis (Nili et al., 2020). Unreliable data analysis, such as untrustworthy coding, also negatively impacts the validity of research (Pedersen et al., 2000). In this research, (specifically in Papers II, III and IV) intercoding reliability was used to ensure the trustworthiness of the research given the open, pre-defined coding that was used. In Paper V, pilot testing followed by reliability analysis was used to test the reliability and validity of the survey, as recommended by (Blair et al., 2013).

4 SUMMARY OF APPENDED PAPERS

This chapter summarises the results of the thesis by summarising the six appended papers. There is also a summary of the contribution of the appended papers to the research questions.

4.1 Contribution of the Appended Papers

This thesis focuses on using collaborative robots as a source for implementing human-centred automation in final assembly.

Paper I begins by assessing the usability of collaborative robots in final assembly operations. Paper II looks at what other technologies can work in conjunction with collaborative robots. These two papers provided an initial basis for formulating RQ1; they made a major contribution to RQ1 as well as a minor one to RQ2. Paper III provides a supplementary contribution to both RQ 1 and RQ2. Papers VI and V provide the basis for RQ2 by assessing the different obstacles to implementing collaborative robots in final assembly. Paper VI is built on the theoretical and empirical findings of Papers IV and V and makes a major contribution to answering RQ2. A summary of the purpose of each appended paper and its contribution to the research questions is presented in Table 4.1 and visualised in Figure 4.1

Table 4.1. Summary of the main contributions of the appended papers

Paper	Purpose	Main contribution to RQ1	Main contribution to RQ2
I	To evaluate the usability of collaborative robots in final assembly.	Demonstrates collaborative robot characteristics such as flexibility, agility, ease of use and how they offer major benefits to final assembly systems.	Highlights the need for simplifying task allocation, to exploit the full potential of collaborative robots in final assembly.
II	To identify different technologies that aid human-centred automation in final assembly.	Other technologies can aid human-centred automation in final assembly; collaborative robots being among the best.	Human-centred automation needs can also be aided by other technologies which supplement collaborative robots.
III	To provide insights into selecting a gripper for human-robot collaboration.	To be used safely and efficiently, collaborative robots need to be supported by appropriate grippers.	Successful use of task allocation depends largely on the functionality afforded by grippers.
IV	To compare and evaluate solutions for human-robot collaboration in complex assembly processes.	Shows how the use of collaborative robots in complex final assembly processes can help overcome problems related to ergonomics and help improve the quality of operation.	Highlights how in complex final assembles, there is negligible collaboration between humans and robots.
V	To identify the needs of industry and give insights into the status of collaborative robots.	Shows there is great enthusiasm for using collaborative robots in final assembly and manufacturing in general.	Highlights the fact that the industry needs simpler methods and gives examples of best practices when using collaborative robots.
VI	To develop a prescriptive task allocation method for implementing collaborative robots.	Exemplifies task allocation between humans and robots by using a task allocation method.	Evaluates different task-allocation-based methods and presents such a method for simplifying human-robot collaboration (using a newly developed LoA matrix for collaborative robot applications).

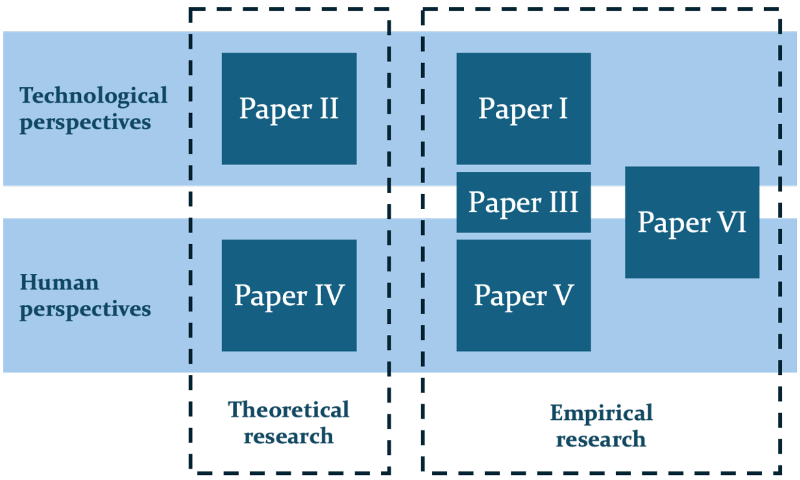

Figure 4.1. Diagram presenting contribution of appended papers.

4.2 Paper I

Title:Assembly 4.0: Wheel Hub Nut Assembly Using a Cobot

This paper aimed to explore the use of a collaborative robot application in final assembly. The paper and its application are based on an actual industrial assembly task at Volvo Group Truck Operations. The workstation (using a human operator) fitted nuts onto a truck wheel hub. Based on the industrial study, a collaborative robot from Rethink Robotics (called "Sawyer") was used to fit nuts onto the hub. The results were documented using the Thingworx IIoT platform. The challenges and advantages of using a collaborative robot application in final assembly systems are also discussed.

Summary of Paper I

An industrial study was conducted to evaluate the current state analysis. This included studying the manual workstation and its potential problems. Two significant issues identified were quality problems due to mismatched threads and unergonomic work postures. The requirements for a collaborative robot application were determined based on the industrial study visit and analysis of the manual assembly task. These included: ease of programming; higher degrees of freedom; inbuilt vision systems; good accuracy in measuring force control; and the highest possible reach of the TCP (tool centre point). Based on these requirements, Sawyer was chosen for the experiments. A wheel hub was borrowed from the factory for lab tests. A lab setup was prepared which imitated an actual assembly operation and is shown in Figure 4.2. The factory assembles, on average, 250 wheels per shift. Thus, 250 iterations of each test were run in the lab. The Thingworx IIoT platform from PTC was used to log and analyse the results. Three different lab setups were tested, each followed by an evaluation in which problems were solved in the subsequent setup. The first setup was designed to test the feasibility of introducing a collaborative robot application into the assembly task. A significant issue with the factory's original setup was the mismatching of threads, leading to quality issues. This was overcome by introducing a 240° tool rotation in Lab Setup 1. As the mismatching of threads continued in the first setup, the rotation was increased to 300° in the second one. The third setup resulted in the removal of initial tool rotation and the introduction of torque-based thread matching. The results of these tests are presented in Table 4.2.

Table 4.2. Lab testing results.

Parameters	**Current State (Factory)**	**Lab Setup 1**	**Lab Setup 2**	**Lab Setup 3**
Quality %	70%	97.90%	98.78%	99.1%
Av. cycle time	145 seconds	127.5 seconds	120 seconds	107 seconds
Rotation	NA	240°	300°	NA
Torque	NA	NA	NA	Yes

Quality was tested based on the number of attempts it took to assemble a nut. To test the vision system, the wheel hub was rotated by 90° and moved 500mm left of its original position. The connection between the cobot and IIoT platform was made using open-source protocols, such as UPC UA and NODE Red.

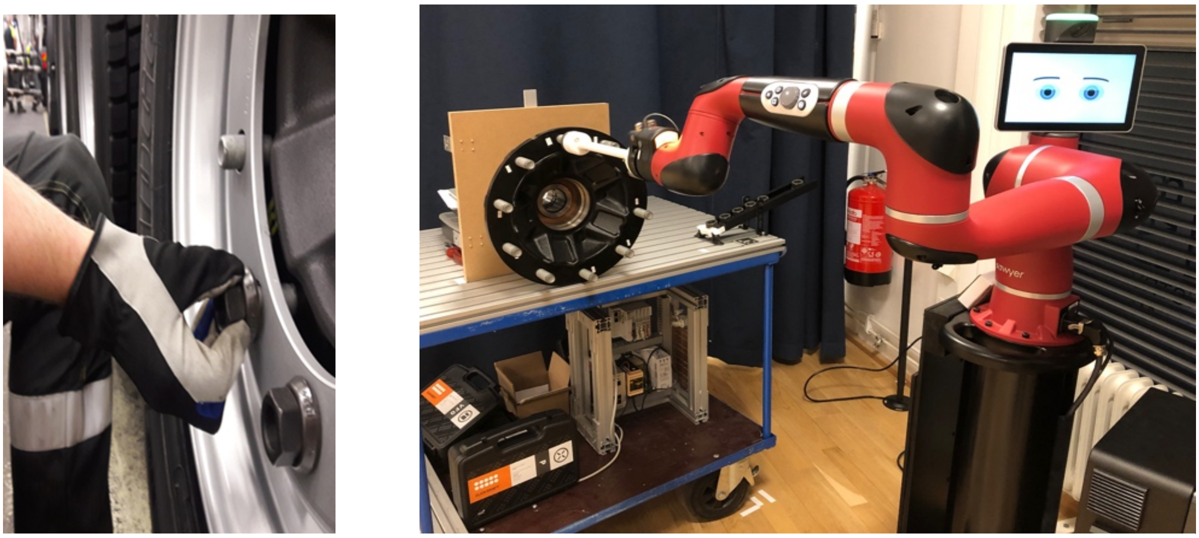

Figure 4.2. Manual station (left) Prototype testing in lab (right).

Based on the lab test results, the feasibility of using a collaborative robot application for fitting nuts onto a wheel hub was tested and proved. A total of over 750 iterations were tested and logged using the IIoT platform. This testing also showed the elimination of quality and ergonomic issues identified in the factory setup. The results also showed reduced cycle times for fitting the nuts and increased quality in the operation. The connection between the IIoT platform and cobot was easy and reliable. All data was easily logged and used to improve the subsequent test setups.

Furthermore, quality problems with the nuts and bolts were identified using the IIoT platform. To conclude, the use of cobots improves the quality and efficiency of a workstation. By eliminating operators from the assembly task, operators may refill the nut rack and carry out other tasks. The IIoT platform may be used to bring the operator back to the workstation in case of any problems or emergencies.

Contribution Towards Research Questions

Paper I contributed to both RQ1 and RQ2. The paper demonstrates the use of a collaborative robot application in a final assembly operation to improve the quality and flexibility of a workstation. The paper also explains the use of an IIoT platform for data logging and quality assurance purposes. The major contribution of Paper I is to RQ1, which demonstrates the robot's characteristics of flexibility, agility and applicability in final assembly. To a lesser extent, the paper contributes to RQ2 by showing the need for proper task allocations to enable the active collaboration of humans and robots in final assembly.

4.3 Paper II

Title: Operational Flexibility in Final Assembly

The paper uses a systematic literature review to:

- Analyse different Industry 4.0-enabling technologies.
- Identify technologies that can help increase operational flexibility in final assembly.

The Scopus and Web of Science databases were used for data collection. A total of 448 papers were identified in the initial search, based on the keywords:

- "Flexibility + Industry 4.0"
- "Assembly + Industry 4.0"

After abstract analysis, 139 articles were selected for further screening. Following the removal of overlapping and repeated articles, 93 articles were selected for final review.

Summary of Paper II

Based on the literature review, this article presents different sources of operational flexibility in final assembly (Figure 4.3) and Industry 4.0-enabling technologies (Figure 4.4), to increase operational flexibility in final assembly. A description of the various sources of operational flexibility is presented in the table below. The Industry 4.0-enabling technologies aim to influence these sources to increase the operational flexibility of final assembly systems. The sources of operational flexibility are listed in Table 4.3.

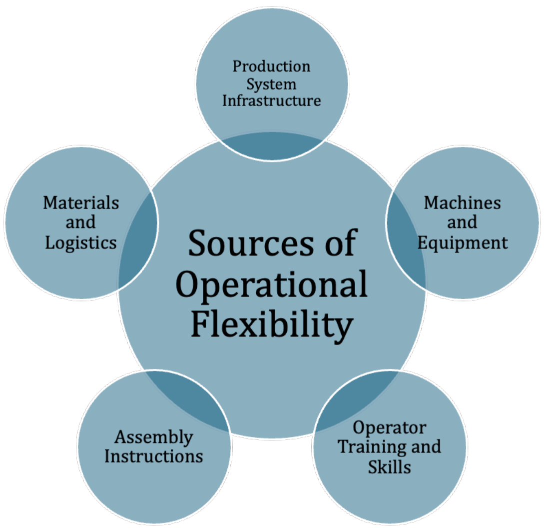

Figure 4.3. Sources of operational flexibility in final assembly.

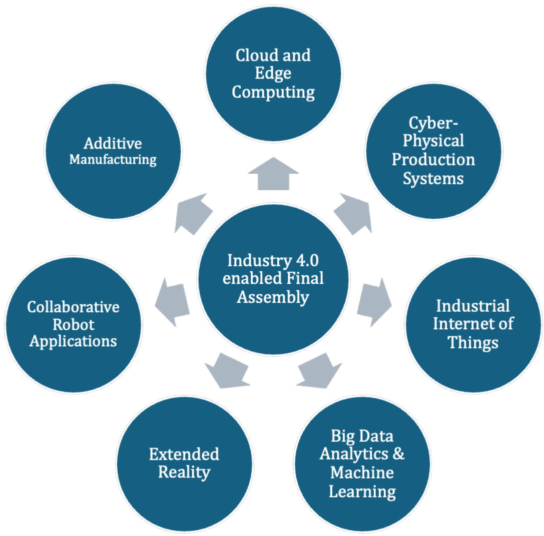

Figure 4.4. Industry 4.0-enabling technologies for final assembly.

Table 4.3. Description of operational flexibility sources.

Source of operational flexibility	Description
Production system infrastructure	Ease of changing/modifying the system layout, ease of integrating new machines and technologies into an existing system.
Machines and equipment	Different types of machines available; the capability of machines to produce different products; setup and changeover time for machines; availability and reusability of other equipment, such as fixtures.
Operator training and skills	The ability of operators to assemble a wide range of products without defects; operator skills and capability to quickly change stations; and their ability to use new technologies and techniques.
Assembly instructions	Different types of assembly instructions and their method of delivery.
Logistics and material handling	The ability of the system to deliver material to workstations in the shortest time and safest possible way.

To enhance the sources of operational flexibility, seven industry 4.0-enabling technologies have been identified and are listed below

1. Additive manufacturing.
2. Cloud and edge computing.
3. Cyber-physical production systems (CPPS).
4. Industrial internet of things (IIoT).
5. Big data and machine learning.
6. Extended reality (xR).
7. Collaborative robot applications.

Two examples of combining these technologies are presented in the article.

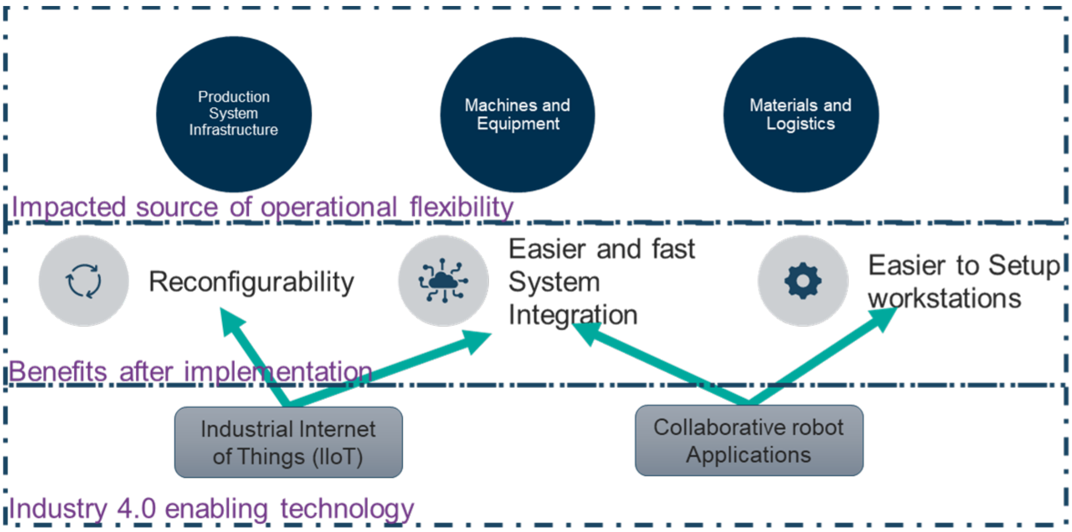

Figure 4.5. Combining IIoT and collaborative robot applications.

Case I: Combining IIoT and collaborative robot application.

In this case, the IIoT platform is shown as the backbone of the system. By using an IIoT platform one can achieve reconfigurability, as instructions can be developed and deployed directly from that platform. Easier and faster system integration is achieved by using CPPS-enabled plug-n-play workstations or collaborative robots, which are portable, easy to program and work safely around human operators. This case is illustrated in Figure 4.5

Case II: Combining IIoT and xR technologies.

This case exemplifies the enhancement of operators' capabilities by using an IIoT platform and xR technologies. This provides operators with training and skill enhancement using xR technologies and then supports them through an IIoT platform during the assembly operations. This case is shown in Figure 4.6

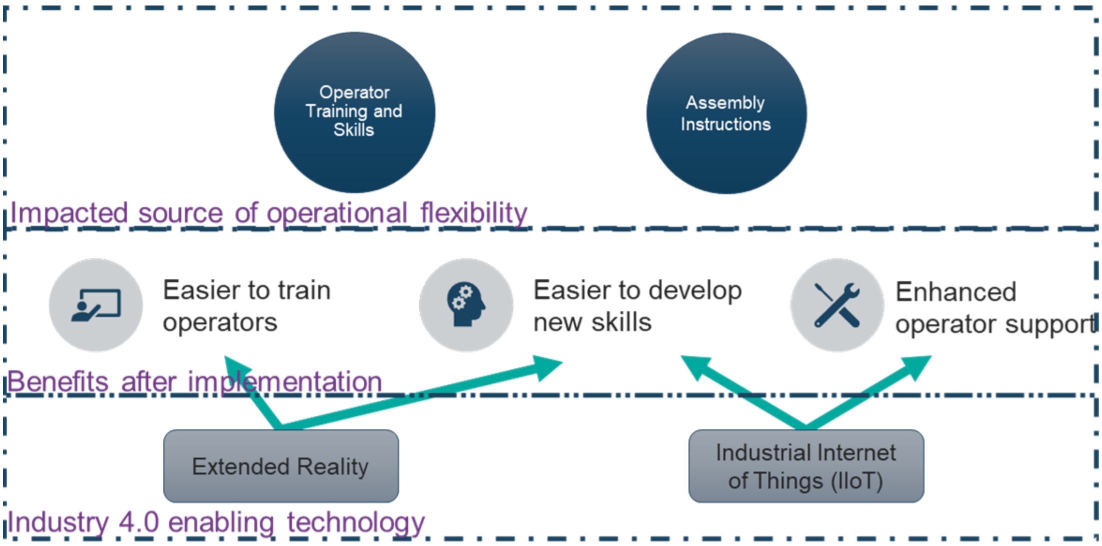

Figure 4.6. Combining IIoT and xR technologies.

The article identified different sources of operational flexibility. These sources are then matched with a corresponding Industry 4.0-enabling technology. A detailed description of these enabling technologies and their impact on operational flexibility is given in this article and exemplified by two cases. The article also underlines the requirement for a holistic approach, to increase operational flexibility in final assembly. Highlighting interconnectivity between different sources of operational flexibility, the paper also underlines that Industry 4.0-enabling technologies mentioned within it will have a domino effect on other sources and parameters of operational flexibility. A system-wide approach is required if the operational flexibility of the system is to be increased.

Contribution Towards Research Questions

This paper's major contribution is towards RQ1. It identified practical, proven applications of Industry 4.0-enabling technologies in assembly systems. These applications were specifically used to influence operational flexibility in assembly environments. A collaborative robot application was identified as an important technology for human-centred automation. Towards RQ2, the paper highlights the fact that to enhance human operator abilities and capabilities, human-centred automation needs a combination of different technologies. Industry 4.0-enabling technologies present some examples of this.

4.4 Paper III

Title: Framework for Identifying Gripper Requirements for Collaborative Robot Applications in Manufacturing

The aim of this paper was to propose a framework for identifying gripper requirements for collaborative robot applications. Collaborative robots are flexible machines which can be used for a wide range of operations in a manufacturing environment. Although a robotic arm is a vital part of a collaborative robot application, the end effector, most commonly known as the gripper, plays a vital role in a robot's function. Considering the importance of the gripper in handling the workpiece, this part is pivotal in increasing or limiting the operational flexibility of both the collaborative robot application and the workstation. This paper presented a framework for identifying gripper requirements based on different levels of human-robot interactions, task allocation and collaborative operations in assembly and kitting environments.

Summary of Paper III

To identify gripper requirements, it was essential to study the possible applications and different parameters involved in the operation of the gripper as well as the collaborative robot itself. The paper began with a design for automated assembly (DFAA) analysis and presented task allocation and different levels of interaction. The emphasis was on the five levels of interaction: cell, co-existence, synchronised, co-operation and collaboration. These levels were further studied and presented in terms of assembly and kitting environments. Grippers are highly influenced by part geometry, which was highlighted in terms of the graspability of a part. Comparisons with other gripper selection frameworks were also made. An important finding from these comparisons was the lack of consideration given to human involvement. Considering collaborative robot applications are orientated towards human-centred manufacturing environments (such as final assemblies), it was vital to consider the human role in a given operation while identifying gripper requirements. The framework presented in this

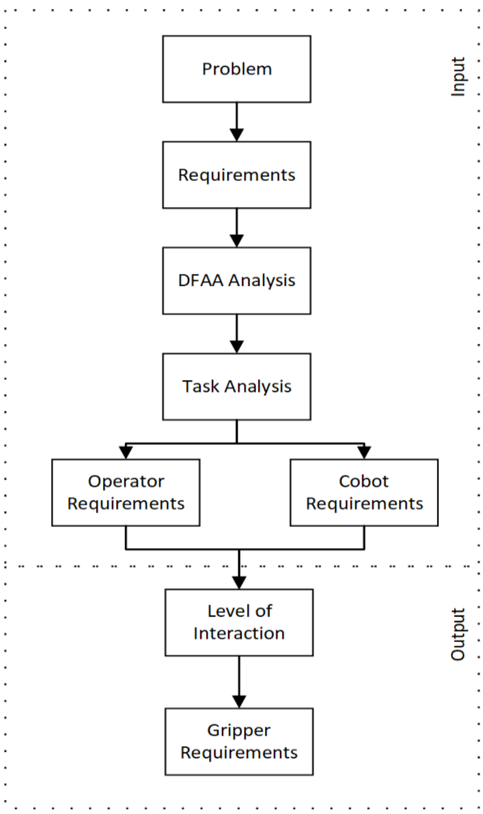

Figure 4.7. Framework for identifying gripper requirements.

paper and shown in Figure 4.7 did precisely that. In identifying gripper requirements for collaborative robot applications, the cobot (machine) requirements were considered alongside the operator (human) requirements.

Identifying and choosing a gripper should be based on exact requirements, to avoid unnecessary cost and compatibility issues and to make the collaborative robot application safe. This choice should also be based on systematically generated requirements. The method presented in this paper provides such a framework, focusing on the combined requirements of humans and cobots in a collaborative application. Furthermore, the proposed DFAA and task allocation steps provide feedback on changing and improving product design, generating assembly instructions and methodically distributing tasks by matching skills with competence. It is crucial to find the right task distribution balance and thus achieve an optimal rate of productivity and quality. Having these steps in place well in advance helps avoid the unnecessary time and money that may be expended due to changes and modifications to products and operations in later stages.

Contribution to Research Questions

This paper made minor contributions to both RQ1 and RQ2. For RQ1, the paper highlights how grippers are equally important as robots and play a vital role, not just in the efficiency of the collaborative operation but also in defining the safety of the operators. Since this is part of the robot, the operator will most likely come into contact with it. The contribution of this paper to RQ2 hinges on the need for task allocation in gripper selections and how successful task allocation depends on the functionalities offered by the grippers.

4.5 Paper IV

Title: Review of Current Status and Future Directions for Collaborative and Semi-Automated Automotive Wire Harnesses Assembly

The paper uses a systematic literature review to:

- Assess the status of a collaborative wire harness assembly process.
- Identify any lack of implementation of collaborative robots for assembling wire harnesses in automotive vehicles.

The Scopus database was used for data collection. An initial search identified 959 papers, based on queries with the formatted string:

- "(wir* OR cabl*) AND (harness* OR bundl*) AND assembl*"

An abstract analysis of 695 articles was conducted using the exclusion criteria:

- About manufacturing of wire harness (product).
- About physical properties of wires.
- Conference proceedings.

This screening narrowed down the number of articles to 77. A further exclusion criterion was applied to the previous criteria:

- About computer vision application.

Following these exclusions, the number of articles was narrowed down to 16. These articles were then reviewed in full.

Based on the analysis, these 16 articles may be separated into two areas.

- Area 1: General automation (6 articles).
- Area 2: Robotics (10 articles).

Summary of Paper IV

The grouping and corresponding synopsis of these articles identified in the literature review can be found in the Appended Papers section.

Using robots in the wire harness assembly process for automotive vehicles can improve efficiency and accuracy whilst also promoting better working conditions for assembly line workers. By automating repetitive and physically demanding tasks, robots can help reduce the risk of injuries. However, it is important to ensure safe and effective collaboration between humans and robots. This requires designing workspaces that minimise the risk of accidents and maximise the efficiency of human-robot collaboration. Additionally, ergonomics plays a key role in developing assembly processes and workstations. This involves considering such factors as reach, posture and force required to perform tasks, as well as providing proper equipment and tools to improve comfort, reduce the risk of injury and enhance overall productivity.

This article mainly discusses the wire harnesses used in automobile manufacturing, but automated wire harness assembly is also crucial in industries such as aerospace, home appliance assembly and other products needing electronic and electrical components. The aerospace industry has many similarities to the automobile industry but has more flexibility in terms of manoeuvrability and target surface, especially for flat wings. Currently, humans still assemble most of these products and the wire harness assembly station in automobiles is still manually operated. Therefore, the production design of any automated wire harness assembly solution must incorporate human characteristics. Collaborative robots (cobots) are ideal for human-robot collaboration and have unique features that make them suitable for automating wire harness construction.

When designing a collaborative wire harness assembly station that involves both humans and robots, it is important to consider certain characteristics of the assembly process. A review of the latest research has revealed several examples that should be incorporated in an assembly station. In particular, research into deformable liner objects (DLO) has provided valuable information on how to pick and position wire harnesses. For instance, the modulation of cables is an effective technique that only works on flat surfaces; it can be integrated with a human-robot application for creating wire harnesses on the vehicle's flooring. These findings from DLO research can be used, provided they meet the necessary time restrictions.

Considerable research has been dedicated to identifying and mapping wire harnesses. While this topic is explored in detail elsewhere, it is crucial to pair computer vision systems with robots for effective collaboration on wire harness assembly. The vision system plays a major role in identifying wire harnesses and clamps, as well as guiding the robot to its destination. Equally important in collaborative wire harness construction is the allocation of tasks between humans and robots. This must be based on their strengths and capabilities, rather than intuition.

This article reviews the use of wire harness installation in automobiles, as discussed in the scientific literature. It also explores the different automation methods available and their limitations during the wire harness assembly process. While various promising techniques are available for wire harness construction, they are often discussed separately from one another.

In the future, it is recommended that tests be conducted on the methods, tools and technologies that have been identified. The aim is to improve the efficiency of wire harness assembly operations by prioritising human-robot collaboration. Additionally, it is important to study human behaviour around robots in enclosed spaces (such as vehicle bodies) to develop effective assembly solutions.

Contribution to research questions

Paper IV provides a major contribution to both research questions. For RQ1, this paper highlights the fact that complex assembly processes can be automated using collaborative robots. Using collaborative robots can solve ergonomic problems related to MSD among operators. For RQ2, this paper highlights the fact that there is negligible human-robot collaboration in final assembly. This paper also points out that proper task allocation is necessary, if safe and efficient human-robot collaboration is to be achieved.

4.6 Paper V

Title: Bridging the Hype Cycle of Collaborative Robots.

This paper aims to investigate the current and planned use of collaborative robots by manufacturing companies, plus possible reasons for the slow growth in implementing Collaborative Robot Applications (CRAs) in the industry. The paper also discusses what connections may be drawn, based on the Gartner Hype Cycle for technology adoption. Survey findings presented in this paper suggest an increasingly positive attitude towards using CRAs as a tool and support mechanism to aid human operators in manufacturing and final assembly operations. Nevertheless, better methodologies and best practices are urgently needed for successful CRA implementations and efficient human-robot collaboration design.

Summary of Paper V

The quantity of papers on CRAs demonstrates their prominence in academic circles. From 2007 to 2021, the average increase in CRA publications was 19%. At the same time, the industry's reluctance is reflected in the percentage of cobots used over the previous five years. This has consistently averaged only 6% of total robot installations, according to IFR statistics. Because IFR data for 2022 was not available at the time of the enquiry, scholarly papers from that year have been excluded.

The technology for using CRAs safely and securely has matured. There is sufficient evidence of this in the scientific literature on proofs-of-concept and real-world use of CRAs in manufacturing. Nonetheless, the IFR figures do not reflect the predicted rapid growth. The Gartner Hype Cycle, depicted in Fig. 4.8, is commonly used to gauge the maturity of technology. The Gartner Hype Cycle assesses the relative maturity of technology in various fields (Linden & Fenn, 2003). It establishes the expectation that most technologies would eventually go through stages characterised by a peak, then disappointment (disillusionment) and then a recovery of expectations (Dedehayir & Steinert, 2016; Linden & Fenn, 2003). Gartner Hype Cycles were used to assess the technological maturity of Artificial Intelligence (AI), the Internet of Things (IoT), blockchain and other popular (Industry 4.0) technologies. They are also used to select innovation applications (Shi & Herniman, 2023; Sodhi et al., 2022).

This paper investigates manufacturing organisations' current and future use of cobots, plus possible reasons for the industry's slow growth in deploying CRAs and what links may be formed based on the Gartner Hype Cycle.

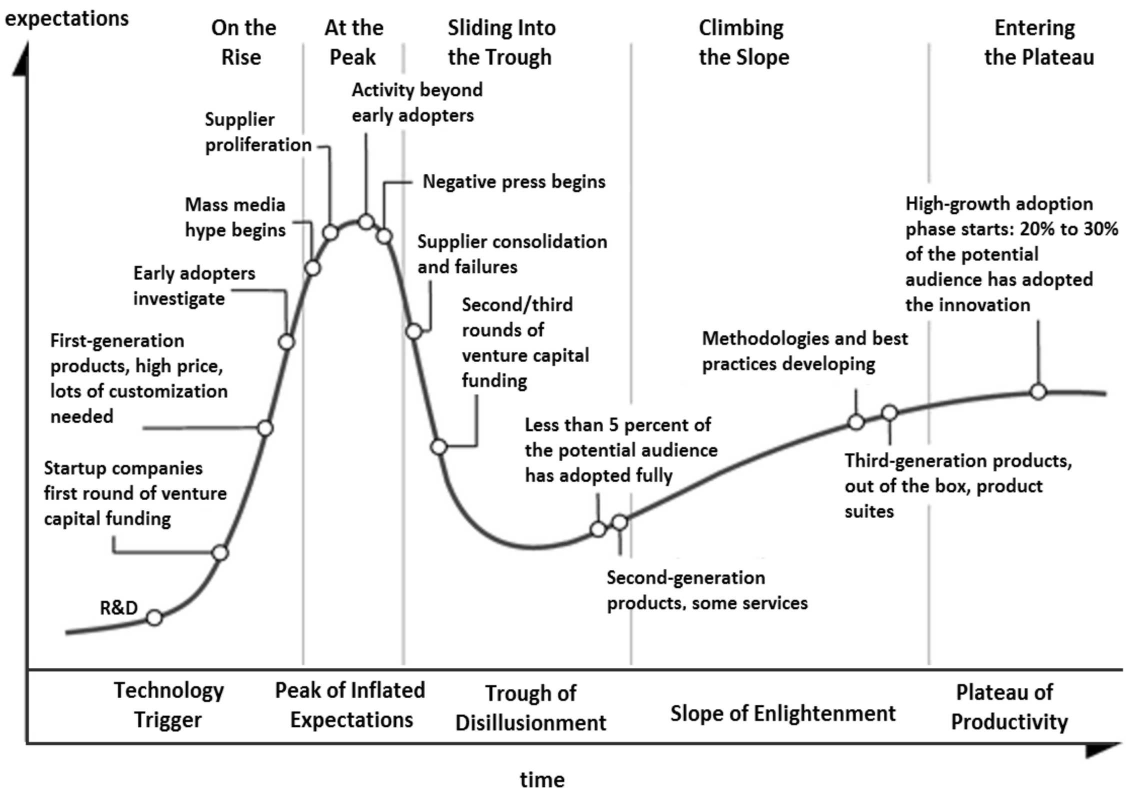

Figure 4.8. Gartner Hype Cycle (Linden & Fenn, 2003).

This survey included 15 organisations from Sweden and Denmark, ranging from SMEs to OEMs. The poll was carried out during guest demonstrations at SII-Lab - https://www.sii-lab.se/. It was designed for respondents with solely manufacturing and final assembly backgrounds and at least two years of experience in the field. Personal responses were obtained from 78 people. Of the 78 responses, 19 participants (or 24 per cent of all participants) had already implemented at least one CRA, while 59 (or 76 per cent of all participants) claimed they had not yet implemented a CRA but were researching/looking at options. The results are shown below. Questions with multiple choice answers have been labelled with "select all applicable."

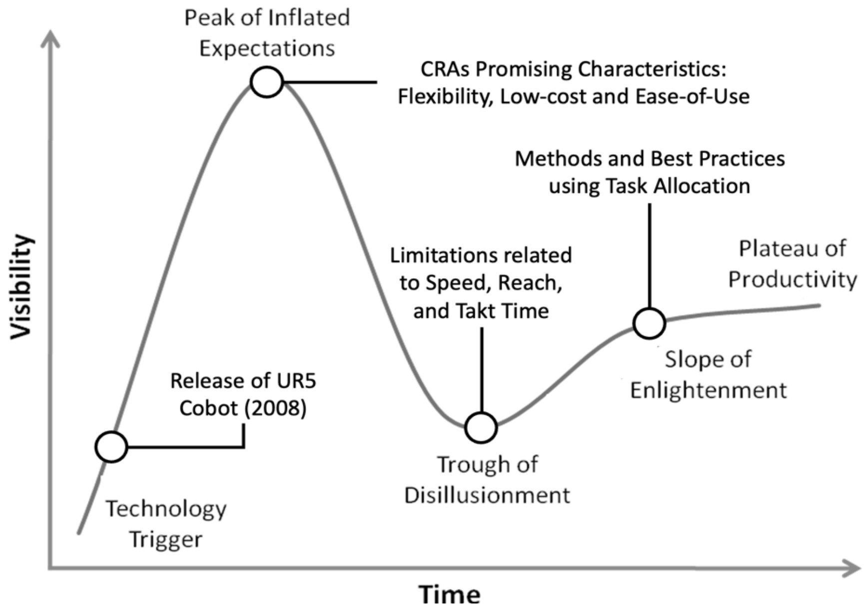

Figure 4.9. Collaborative robot applications hype cycle based on survey findings (Adapted from Gartner's Hype Cycle by (Linden & Fenn, 2003).

According to the study, CRAs are gaining acceptance in manufacturing and final assembly. Respondents support CRAs for flexibility, quality and productivity. These key performance indicators (KPIs) are linked to human operator qualities. Businesses seek automated solutions that can collaborate with humans, minimise effort and reduce workplace interruptions. Despite the availability of multiple *proofs of concept (PoCs),* only one quarter of participants have deployed at least one CRA. This raises the question of transparency regarding task and function allocation in human-robot collaborations.

According to survey findings, those who have deployed at least one CRA did not meet their expectations in terms of speed, reach and operator acceptance. Furthermore, for those intending to adopt a CRA in the future, the absence of safety techniques, competency, knowledge of human-robot collaboration and product compatibility are major problems. The fundamental causes of these safety concerns can be traced back to a lack of information about human-robot collaboration (HRC). A lack of appropriate expertise also implies that HRC knowledge is insufficient and there is a need for simple, easy-to-use procedures. Many of the previously identified issues will be automatically addressed if one conducts a thoroughly thought-out task allocation between people and robots (Malik & Bilberg, 2019a; Tsarouchi et al., 2017).

From a collaboration standpoint, firms choose a low level of HRC to allow some human-machine collaboration but without starting at the highest level. This approach is linked to economic or quality risk assessments. The survey indicates a strong desire to create in-house expertise among those implementing or who have implemented at least one CRA.

According to survey responses and comments, the Gartner Hype Cycle can be divided into four key blocks, as shown in Figure 4.9. The technological turning point for cobots was the launch of the UR5 cobot by Universal Robotics in 2008. The peak of inflated expectations occurred in 2017. Participants, either heading to the peak or who have peaked, are betting on the advantages of the new technology, such as flexibility, ease of use, ability to work alongside the human operator and low-cost automation. Participants nearing disillusionment have implemented some preliminary studies. Among those challenges is the cobots' inability to match the speeds required for a process. Other reasons for disillusionment include limitations to the ease of programming and the fact that CRAs are not a plug-and-play type of technology application. Participants in the group on the slope of enlightenment have passed the trough of disillusionment and are acting on what they have learned.

Conclusion

Companies now consider CRAs to be a supportive tool for human operators in their production processes. Although survey respondents believe cobots are promising, they focus too much on technological factors and ignore the human-centric methods necessary for successful CRA deployment.

Further investigation is needed for the successful implementation of CRAs and efficient HRC design. Manufacturing companies lack the knowledge and competence to program collaborative robots, something which can be addressed through universally applicable methods and best practices. One such method is task allocation, which can simplify collaboration between humans and robots in a CRA. Future work should focus on simplifying task allocation for HRC.

Contribution to Research Questions

In a minor contribution to RQ1, the paper highlights industrial enthusiasm for deploying collaborative robots in final assembly operations. It demonstrates how the industry has used this technology to create human-centred automation solutions. The paper makes a significant contribution to RQ2 by highlighting the urgent need for simpler and easier-to-understand methodologies and for examples of best practices aimed at developing human-robot collaborations and deploying collaborative robots in final assembly.

4.7 Paper VI

Title: Specifying Task Allocation in Automotive Wire Harness Assembly Stations for Human-Robot Collaboration

Wire harness assembly is a laborious and inefficient operation. Production engineers

strongly desire automation of this assembly process due to its unergonomic character. Moreover, with the advancement of robot technology and human-robot collaboration possibilities, some wire-harness-process activities can be automated. A successful automation programme must be founded on the proper work allocation approach. This paper proposes a design and specification methodology for human-centred manufacturing systems and complicated production systems, with a focus on collaborative assembly processes. It provides a case study of human-robot collaboration, including an example from a wire-harness collaborative assembly method. The design process combines hierarchical task analysis with assessments of cognitive and physical levels of automation (LoAc and LoAp), followed by levels of human-robot collaboration (LoC) and operator skill needs (LoSr). A task allocation matrix helps identify various automation and collaboration solution combinations for a human-centred and collaborative wire-harness manufacturing process. System designers and integrators can use the design and specification process to determine the possibility and extent of human-robot collaboration in collaborative assembly and manufacturing operations.

Summary

Technologies such as collaborative robots (cobots) have been proposed as tools to empower the assembly worker (Cohen et al. 2021; Vicentini 2021). Cobots can aid with various existing wire harness (WH) assembly activities and help reduce work-related health issues such as musculoskeletal illnesses. Collaborative robots can work near operators but for fast, effective and productive collaborative assembly operations, it is critical to have an optimal division of tasks between human operators and cobots. The current approaches to analysing the need and potential for collaborative robot applications are mostly concerned with the physical interaction of robots and humans. However, extending the analysis through improved task allocation approaches would allow for more precise specifications of the sometimes dynamic distribution of cognitive and physical work between humans and automated systems (robots).

A wire harness is a bundle of cables used in vehicles for various purposes. The manual assembly process during final assembly is repetitive, strenuous, unergonomic and tedious (Nguyen, Kuhn and Franke 2021) and contributes to the high degree of musculoskeletal disorders among assembly operators (Trommnau et al. 2019; Nguyen, Kuhn and Franke 2021). However, given the complexity of WHA and the fact that space and speed limits often render even advanced and expensive automation solutions inferior to human assembly in terms of quality and productivity, collaborative robots may create an elegant and efficient opportunity for WHA. One major issue is that models and methods for assessing and planning collaborative robot applications are frequently descriptive and less helpful "after-the-fact studies." Thus, the main question and concern of this paper is how to structure a method for the prescriptive design of human-robot collaboration in an assembly process and provide efficient guidance to manufacturing systems and workstation designers while meeting the needs and requirements of operators.

Selection of Levels of Automation

Task allocation and LoC are also complementary to each other. To achieve an optimal LoC, one must thoroughly conduct a proper task allocation between human operator and robot. This allocation needs to be conducted on two levels: cognitive and physical. The LoA matrix presented is based on the original model proposed by (Frohm et al. 2008) and the ten levels scale of automation by (Sheridan, 1997). It has been modified to suit the aspects of a collaborative robot working in conjunction with a human operator.

Table 4.4. Levels of Automation (LoA) for Collaborative Robot Applications.

Levels of Cognitive Automation (LoAc)	Levels of Physical Automation (LoAp)
Totally manual (1) – the human creates his/her own understanding of the situation and task at hand and develops a course of action based on previous experience and knowledge. No automation is involved in decision-making. For example, operators use previous knowledge and experience.	**Totally manual (1)** – no use of a robot or any mechanical tool by humans to complete the physical task. For example, no tool is used.
Basic task (2) – the human gets overall information on what to do or a proposal on how the task can be completed. For example, checklists and manuals.	**Basic task (2)** – the human or robot uses a flexible tool to complete a task. For example, the use of a multiple-purpose tool like an adjustable spanner or a gripper capable of picking-&-placing different sizes and shapes.
Instructions (3) – the human gets detailed instructions on how the task should be done. For example, assembly instructions.	**Instructions (3)** – the human or the robot uses a fixed tool to complete a task. For example, the use of a specialised gripper.
Supervision (4) – the human observes the automation performing the task and decides on intervention. For example, an Andon alert is triggered calling for human repair/fix intervention.	**Supervision (4)** – a robot self-selects the best possible solution for a given task and guides the operator in solving any issue if this occurs. For example, the use of an adjusting tool.
Totally Automatic (5) – all information and control are handled by automation. The operator is not involved. For example, autonomous manufacturing cells and smart workstations.	**Totally Automatic (5)** – the system handles all information and control by itself. For example, autonomous manufacturing cells and smart workstations.

The cognitive and physical levels of automation are redefined to better reflect the technical development in the collaborative robotics area. This model is based on the concepts and methods of task and function allocation developed by (Sheridan 1997; Sheridan 2000) and (Kaber and Endsley 2004), as explained earlier. Figure 4.10 shows a simplified overview of the matrix proposed in Table 4.4. The physical LoA for collaborative robot applications are presented on the x-axis, while the cognitive LoA for collaborative robot applications are presented on the y-axis. The grey zone denotes the collaboration zone. The new matrix does not split the tasks between robots and machines but between their physical and cognitive abilities. In human-robot collaboration, the physical abilities of humans and robots are obviously different. Robots have the physical advantage of carrying more loads repeatedly and with greater accuracy than humans. Concerning cognitive abilities, a robot's cognition can be increased with the help of vision systems and sensors and enhanced with the aid of advanced technologies such as machine learning and artificial intelligence.

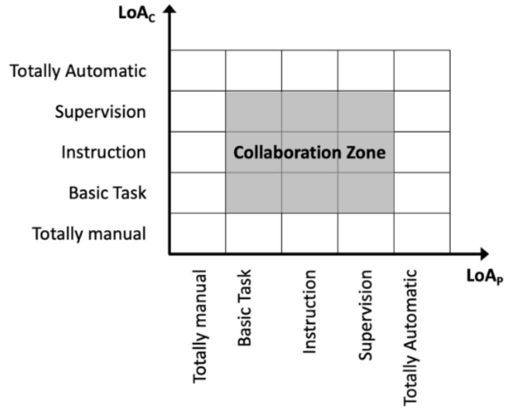

Figure 4.10. Levels of automation (LoA) matrix for collaborative robot applications.

Selection of Level of Collaboration

The current levels of collaboration are applied to the entire operation instead of individual tasks. By using the LoA matrix presented in Table 4.4 and shown in Figure 4.10, the levels of collaboration (LoC) for individual tasks can be determined, plus the corresponding skill requirements, as shown in Figure 4.11. This mapping helps in visualising the different levels of collaboration for each task and the corresponding skill level required. Tasks are allocated based on the abilities of both humans and machines, rather than complexity.

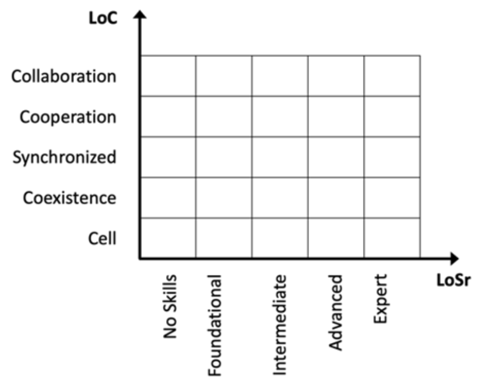

Figure 4.11. Levels of collaboration (LoC) & levels of skill requirements (LoSr) Matrix for collaborative robot applications.

Levels of Task Complexity and Skill Requirements

Based on results from (Mattsson 2018), there are three main areas of complexity in manufacturing assembly: station design, work variance and disturbance handling. These areas can be further divided into tools, layout design, product variants and work content. Reducing task complexity positively impacts assembly quality and cognitive automation can help reduce complexity. (Fast-Berglund et al. 2013). The *CompleXity Index (CXI)* is a tool for assessing perceived complexity by operators (Falck et al. 2017) and can be used to analyse the complexity of a task. The greater the complexity of a task, the greater the requirements placed on the operator. Therefore, the operator will either need more cognitive support or superior skills (Li et al. 2022). During the hierarchical task analysis

(HTA) and task allocation process, specific criteria for accomplishing a certain task are determined. The necessary abilities for accomplishing a task can be recognised based on the task's cognitive and physical requirements. The skill competence levels presented below are based on the European Qualification Framework (EQF). The competency levels for the following skills are identified in EIT Manufacturing's 2021 skills report:

Foundational: the operator possesses basic cognitive and practical skills. **Intermediate:** the operator possesses a range of physical and cognitive skills. **Advanced:** the operator has comprehensive and specialised knowledge. **Expert:** the operator possesses highly specialised knowledge. Based on these definitions and in the context of collaborative robots, different levels of skills are described below.

1. **No skills:** no skills are required of the operator.

2. **Foundational:** basic cognitive and practical skills are required, such as stopping the robot in an emergency.

3. **Intermediate:** normal cognitive and practical skills are required, such as understanding the basic functioning of the robot, understanding the safety parameters and so on.

4. **Advanced:** the operators should be able to read and understand data from sensors, such as the sensor's indication to initiate or stop an operation.

5. **Expert:** the operator should understand all parameters governing an HRC operation, such as the ability to read and understand data from the robotic system, PLC signals and so on.

Application of Levels of Automation (LoA) Matrix for Collaborative Robot Applications in Wire-Harness Assembly Processes

The levels of collaboration (LoC) are demonstrated through a wire-harness assembly process in a car, where the complexity of assembling wire harnesses using collaborative robots requires consideration of such factors as operator safety and the robot's tool central point (TCP). The task allocation method can reduce this complexity and efficiently divide tasks between humans and robots.

Table 4.5. WHA task breakdown and description.

Task	Sub-task	Task	Cognitive Task	Physical Task
1	1.1	Open the WH plastic package	Ensure that the WH is not damaged while opening	Open the plastic packages using a tool
	1.2	Load the WH package onto the metal pallet	Ensure the correct WH is completely loaded onto the pallet	Drag the WH onto the pallet using your own strength
2	2.1	Move the pallet inside the car	Decide how to move the pallet so that it does not hit the car's body	Use the power lift to take the pallet inside
	2.2	Unload the WH from the pallet	Observe that the placing area is clear	Rotate the pallet 90° using your own strength

Task	Sub-task	Task	Cognitive Task	Physical Task
2	2.3	Move the pallet out of the car	Decide how to move the pallet so that it does not hit the car's body	Use the power lift to take the pallet inside
3	3.1	Spread the WH	Decide which wire to pick up first and which direction to start from	Use your own strength to spread the wire harness for alignment
	3.2	Align the wire harness for assembly	Decide the best possible alignment positions	Ensure the location for placing the WH is correct
4	4	Plug in the wire harness sockets on the Y-axis	Verify that the assembly is successful	Insert the WH using your own strength at the required locations
	4.2	Plug in the wire harness sockets on the floor frame	Verify that the assembly is successful	Insert the WH using your own strength at the required locations
	4.3	Visual quality inspection of the assembly	Verify that the assembly is successful	Use of vision system to verify correct assembly

Selecting the Levels of Automation for Collaborative Assembly Processes

The goal is to automate WH assembly using collaborative robots. LoA is assigned based on maximising robot use based on Table 4.4, Table 4.5 shows the resulting LoA allocation. Figure 4.12 shows the LoA levels for wire-harness assembly, Figure 4.13 showed the levels of collaboration and skills requirement matrix.

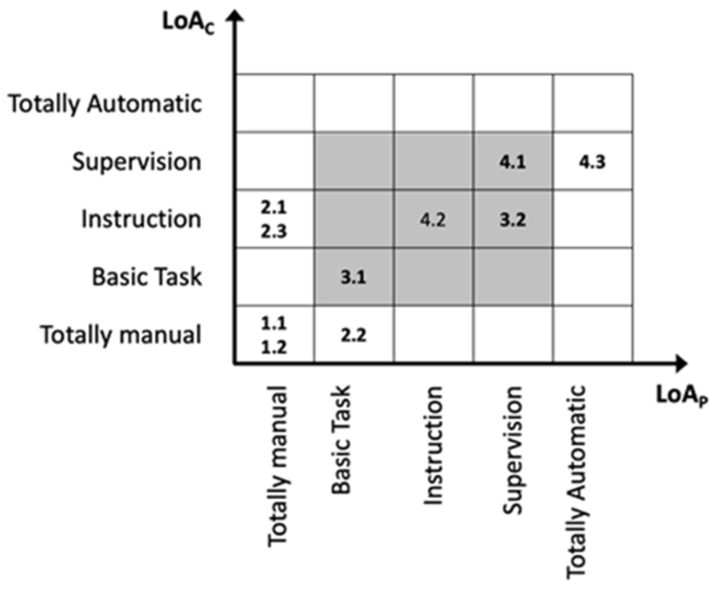

Figure 4.12. Diagram of LoA allocation in WHA.

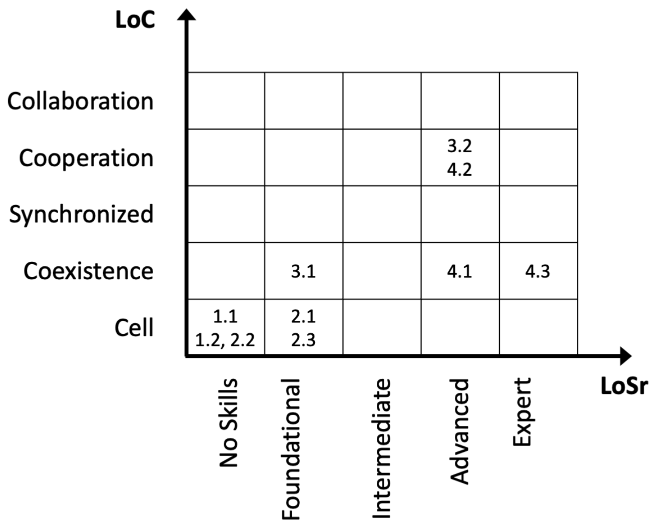

Figure 4.13. Diagram of LoC and LoSr allocation in WHA.

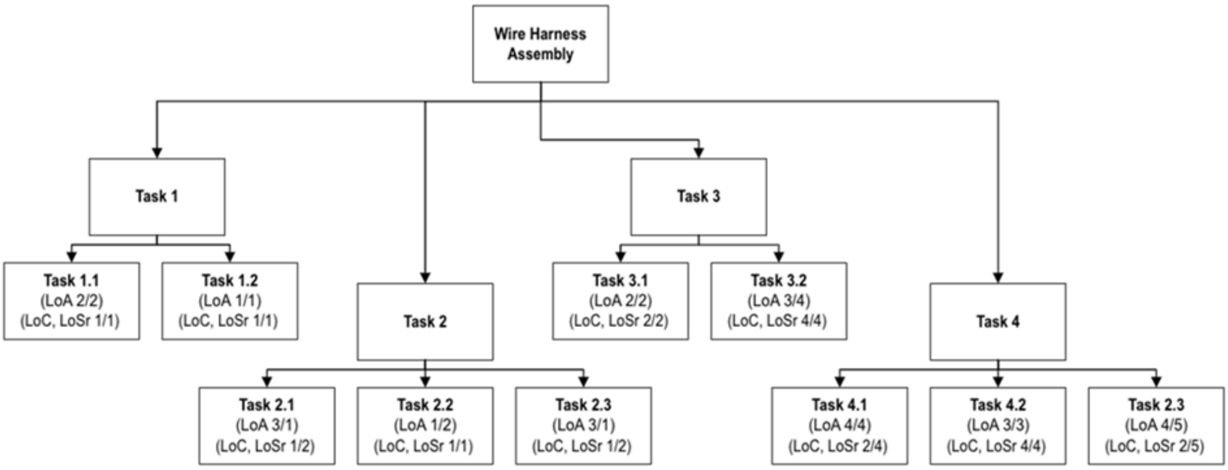

Figure 4.14. HTA wire harness assembly process overview.

We can see from the categorisation shown in Figure 4.14 that there is a lot of potential for human-robot collaboration. We know that robots can perform activities with greater cognitive and physical requirements, whereas humans can handle tasks that are less so. We need a robot that can reach all wire-harness assembly locations within the automobile, a sound vision system and correct instructions for the operators, according to the need specification.

The paper presents a methodology to generate specifications for workstations that facilitate human-robot collaboration. The tasks are divided based on levels of automation and collaboration. The selection of tools will be based on engineering choices, capabilities, costs and the like. The task complexity matrix identifies the task complexity and collaboration levels. Categorise risk factors using this information plus task breakdowns, to determine appropriate support tools, instructions for operators on how to complete complex tasks and enhanced safety zones for high collaboration tasks.

To allow for both human and robot involvement, collaboration levels should be allocated to tasks and not to entire operations. Complex tasks should be broken down into subtasks that can be handled at different levels of collaboration. This approach helps design collaborative workstations with appropriate levels of collaboration, based on task complexity and operational requirements.

Conclusion

This article presents a methodology for allocating tasks and levels of collaboration in a human-robot collaborative workstation. The article uses well-established methods, such as task allocation (TA), levels of automation (LoA) and levels of collaboration (LoC), to identify the appropriate balance of tasks and collaboration between the human and robot and provides visual matrices for LoA and LoC to offer an overview of the entire operation to the user.

This methodology aims to help designers develop human-robot collaborative workstations. While the article focuses on its use in wire harness assembly, the model can be applied to any design process. The article develops the model but does not analyse its impact on quality or performance (which is the next step).

Contribution to Research Questions

This paper's major contribution is to RQ2. This research compares and contrasts several task-allocation-based strategies for human-robot collaboration. It proposes a prescriptive job allocation strategy based on a newly built LoA matrix for cognitive and physical degrees of automation aimed at facilitating human-robot collaboration in a complicated manufacturing process. A matrix for levels of collaboration and skill needs is also offered, to help in work allocation and ease comprehension of human-robot cooperation. This study issue also emphasises the complications of final assembly human-robot collaboration. It demonstrates work allocation for collaborative robot applications of a wire-harness assembly process using an LoA matrix.

5 DISCUSSION

This chapter elaborates further on the results in the appended papers and provides a broad discussion of the results, followed by answers to the two research questions. The chapter also discusses the academic and practical implications of this thesis. The limitations of this research are also reflected upon and future work proposed.

5.1 Human-Centred Automation in Final Assembly Using Collaborative Robots.

Final assemblies, especially automotive final assemblies, are highly human-centric. Thus, any successful automation application in final assembly also needs to be human-centric. Collaborative robot applications are one such solution. Since collaborative robots are designed to work alongside humans, they can work safely alongside final assembly operators, provided the proper safety protocols are followed. Other human-centric technologies, such as *augmented and virtual reality* and the *Industrial Internet of Things* can also aid in human-centred automation. The selection of collaborative robots as a solution for the human-centric approach was based on the unique characteristics of these robots and their ability to synchronise with other technologies. The empirical results in Paper V show that the industry also sees collaborative robots as an excellent tool for helping operators. Collaborative robots can improve quality and efficiency, as seen from the results in Paper I. Moreover, their ability to work alongside operators is discussed in Papers I and II. The theoretical and empirical findings of Papers I and IV show that these robots can handle the repetitive and unergonomic tasks responsible for MSD.

The focus now needs to be on human-robot collaboration in complex tasks requiring a combination of cognitive and physical skills, as discussed in Paper VI. The results in Paper I also show that the quality of assembly operation is further improved when other techniques (such as a vision system) aid the robotic system. The efficiency, the quality of assembly operation and the safety of the human operator are highly dependent on the gripper or end-effector used by the collaborative robot application. Considering the importance of these grippers, a gripper selection framework was presented in Paper III to aid this research. The framework presents the user with requirement specifications based on information such as product design, plus component characteristics based on design for automated assembly (DFAA) and task allocation. It combines these requirements with operator skills and robot characteristics.

The current numbers from IFR show a steady growth in sales of collaborative robots, averaging 6% annually. Using Gartner's Hype Cycle curve, this places collaborative robots as a matured technology and yet the promises of higher flexibility and efficiency have not been fulfilled. The theoretical findings from Paper IV and empirical findings from Paper V show that higher costs, complexity of assembly operations and lack of proper understanding are some of the primary reasons for the lack of collaborative robots in final assembly operations.

Implementing automation in final assembly systems may require significant capital investment, including the cost of purchasing and installing the equipment and training employees to operate and maintain it. The total cost of implementing collaborative robots is usually less than that of traditional robots. With their intrinsic properties aimed at human safety (discussed in Chapter 2), the ability to be installed on workbenches or portable stands in final assembly and with no physical fences needed, the installation costs of collaborative robots are lower than for traditional robots. The programming costs can be kept low since many collaborative robot OEMs provide program templates and plug-ins. Focusing on developing in-house talent to program and operate collaborative robots (such as having the operators control robots) can further reduce the costs whilst adding the benefits of flexibility offered by in-house programming.

The complexity of assembly operations was found to be the reason that collaborative robots are not implemented in final assembly. Paper IV's findings show negligible collaboration between humans and robots in complex assembly processes, such as the assembly of wire harnesses. Yet, these complex assembly operations, which are often highly unergonomic, require the help of tools like collaborative robots. Product and production design are two primary sources of complexity in final assembly. Well-established scientific methods like DFAA can help simplify the product design and make it better suited to assembly. The essence of this thesis is reducing complexity by simplifying the production design. That is, designing human-robot collaborative workstations and improving our understating of the collaboration between humans and robots. While there are many ways to solve this problem, this thesis addresses this issue using task allocation-based levels of automation, as discussed in the next section.

5.2 LoA-Based Task Allocation in Collaborative Robot Workstations for Final Assembly Operations

Task allocation is central to human-centred automation and the (Fitts, 1951) MABA-MABA list remains an established theory for allocating tasks in human-machine interaction, even in 21st-century reports (De Winter & Dodou, 2014). The complexity of allocating tasks between humans and automation was highlighted by (Billings, 1991; Sheridan, 1995) through their early works on human supervisory control for avionics systems. These supervisory control models have been refined through *levels of automation* by (Sheridan, 1995) and further refined by (Parasuraman et al., 2000). These levels of automation are central to improving the effectiveness of human-automation interaction and have been used as the basis for human-centred automation in manufacturing, such as the LoA matrix for manufacturing (Frohm et al., 2008), DYNAMO++ methodology for allocating tasks by (Fasth et al., 2010) and human-robot collaboration (Sheridan, 2016; Sheridan & Parasuraman, 2005). A further summary of different levels of automation presented over the years is available in (Vagia et al., 2016). The use of task allocation in achieving greater efficiency is presented by (Heisler et al., 2020) and in ensuring the operator's safety by (Faccio et al., 2023).

Human-robot workstations' design and operating process have been studied and developed in many ways. (Prati et al., 2021) propose using virtual reality to design HRC workstations, (Kim, 2022) proposes a framework based on adaptive body tracking in a safety-focused approach proposed by (Andronas et al., 2020). Its focus is on HRC workstation design based on operator-trusted safety layout. (Ore et al., 2017) propose a design method using a linear design process, incorporating task planning and different stages of workstation design, as a solution for planning and designing an HRC workstation. Though these models clarify collaborative robots' layout design and technological aspects, the fundamentals of collaboration between humans and robots - essentially, what tasks the human and the robot will carry out and how - are not clearly addressed. Papers IV and V highlight similar issues on the lack of clarity in collaborations between humans and machines. These issues are addressed in Paper VI by exemplifying a human-robot collaborative workstation in the wire-harness assembly process, with a clear explanation of human-robot collaboration. In determining the design of the workplace and allocation of tasks in collaborative automation, the assumption is that the greater the complexity, the greater the need for human integration in workstation performance. Thus, the tasks must be allocated to maintain and enhance appropriate human involvement and avoid the "paradoxes of automation" described by Bainbridge (Bainbridge, 1983). The arguments about the negative impact of over-automation on skills and complacency discussed in Chapter 2 are vital from the perspective of achieving safe and secure human-robot collaboration, where the role of the human is not just supervising the robot but also collaborating with it; a situation in which complacency may occasion severe injury. This highlights the necessity for thought-through task allocation (especially in human-robot collaborative workstations) and maintaining appropriate levels of human involvement in the collaboration.

Based on the findings of (Ranz et al., 2017), a gap in clarification on the allocation of tasks between humans and robots in human-robot collaboration was identified. (Johannsmeier & Haddadin, 2017) present a process-planning framework for the application of collaborative robots in assembly, based on hierarchical task allocation. Although the task allocation is based on skills and capabilities, there is no direct collaboration between humans and robots. (Ranz et al., 2017) propose a capability-based task allocation using assembly sequence and process times as criteria for task allocation. Task allocation in human-robot collaboration needs to be based on the physical and cognitive capabilities of humans and robots, argue (Parasuraman & Wickens, 2008).

(Malik & Bilberg, 2019a) addressed this issue by presenting task allocation based on the physical properties of products. And yet the knowledge gap simplifying human-robot collaboration remains, as seen in Paper V.

This gap is addressed in Paper VI by, firstly, developing a level-of-automation matrix for collaborative robot application (Table 4.4) and, secondly, by using this matrix in task allocation for a collaborative robot workstation. This matrix uses generic terms for defining five levels of automation in conjunction with the five levels of collaboration for specifying cognitive and physical task allocation in human-robot collaboration. The matrix is based on the level-of-automation concepts developed by (Kaber & Endsley, 2004; Sheridan, 1997). To better suit the requirements of a specific task, the cognitive and physical levels of automation are generically defined to accommodate the changing roles of humans and robots and the ability of robots to possess cognitive ability through artificial intelligence. These foundations and the broader acceptability of levels of automation ensure the robustness and applicability of this matrix in final assembly operations.

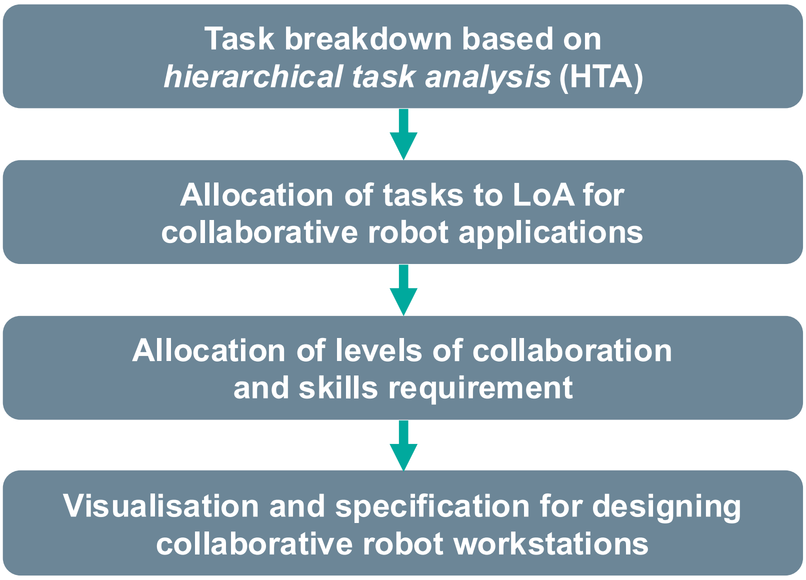

Figure 5.1. Design approach for an HRC workstation.

Every industrial application process starts with the development of its designs. A survey of designing human-robot collaborative workstations by (Simões et al., 2022) highlights collaborative workspace and task allocation as a vital component of the design process. This is addressed in Paper VI, in which task allocation in a collaborative wire-harness assembly station is exemplified using the levels of automation (LoA) matrix for collaborative robot workstations. (Mateus et al., 2019) highlight the need for multiple sub-methods supporting task allocation for designing and implementing human-robot collaborative workspaces. Such sub-methods include a tool to determine the level of collaboration (Aaltonen et al., 2018), the levels of skills required (Andronas et al., 2020) and an ergonomic analysis (Mateus et al., 2019).

The new matrix presented in Paper VI (Table 4.4) acts as a design tool for engineers developing a collaborative robot application workstation. The process of using the matrix is shown in Figure 5.1. According to (Lee et al., 2023), the levels of collaboration are directly related to the skill required from operators to complete a task. As the levels of collaboration between humans and robots increase, the skills required by the operator also increase. The findings of Paper V show less enthusiasm for higher levels of collaboration. This might be due to a lack of knowledge shown in the findings of Papers IV and V, or an overtly cautious approach by companies in selecting higher levels of collaboration (Villani et al., 2018). The levels of collaboration and skills required for a specific task are addressed in Paper VI. While these levels of collaboration have already been addressed in (Bauer et al., 2016), a complementary matrix has been developed in Paper VI, to assess the skills required for a specific task.

The process of implementing a collaborative robot application in final assembly starts with designing the process. Aided by the LoA matrix, the designer gets a complete picture of tasks carried out by humans and robots. Moreover, aided by a levels-of-collaboration and skills requirement matrix, the necessary collaboration and skill levels are readily generated during the system design process. Robots can be dangerous if not used properly and it is crucial to ensure that proper safety protocols and equipment are in place to protect workers from harm. This can include fencing, light curtains and other safety devices, plus worker training in how to interact safely with robots.

5.3 Answering the Research Questions

The research findings of the six appended papers have been used to answer two research questions in this thesis.

RQ1: How do humans and robots collaborate in manufacturing and final assembly operations?

Robots are slowly taking over repetitive and unergonomic tasks from humans in manufacturing and final assembly through the implementation of collaborative robots. Papers I and II show how, aided by other Industry 4.0-enabling technologies, this collaboration is further enhancing human operators' capabilities and helping to improve flexibility, quality and efficiency. However, as seen in Papers III and IV, humans and robots are not actively collaborating. Robots, mainly collaborative robots, have taken over reiterative operations such as pick-n-place operations, lifting and packing, with the human operators acting in a supervisory role. However, this level and extent of collaboration does not match the anticipated progress of the technological development as seen in Paper V. This is mainly due to the lack of simpler methods for achieving human-robot collaboration using collaborative robots. However, there is much willingness and potential for increasing this collaboration.

RQ2: How does human-centred task allocation support the design of collaborative robot workstations in final assembly?

Task allocation is commonly used in defining the sequence of product assembly in final assembly lines. Task allocations are also used in line balancing and optimising final assemblies. Using this familiarity with task allocation, challenges related to human-robot collaboration can be simplified, as discussed in Paper V. Using task allocation for final assembly tasks, the designers get a clear picture of the distribution of tasks between humans and machines, as seen in Paper VI. This helps avoid the technological imperative of automating the easier tasks and leaving the remaining tasks to humans, which is quite common in complex assemblies, as discovered in Paper IV. A prescriptive task allocation matrix guides the designers in assigning tasks between humans and robots, based on abilities and capabilities using generally defined and easily understandable levels of automation for collaborative robot workstations. It also provides suitable levels of collaboration and corresponding skill requirements. Using this matrix, designers can change and adapt their designs to better fit the requirements for human-robot collaboration before committing to implementing a solution. Such ability and capability-based solutions that engage operators in working with robots help improve human-centred automation in final assembly.

5.4 Research Contribution

As stated in the research methodology section, this thesis aims to contribute to research in academia and industry. This contribution is explained below.

Contribution to Academia

This thesis contributes to the theory on the practicalities of using collaborative robots in final assembly due to their unique characteristics. By using other Industry 4.0-enabling technologies with collaborative robots, one can enhance operators' capabilities. This approach helps clarify how and shows which technologies can be combined to aid operators in complex assemblies. Through theoretical and empirical research, not only does this thesis provide insights into the challenges faced by the industry in implementing human-robot collaboration (specifically complex assemblies), it also highlights the willingness of industry to use collaborative robots to solve ergonomic issues in final assembly. This willingness provides the motivation for researchers to continue their work on simplifying human-robot collaboration.

By highlighting the necessity of skills and capabilities-based task allocation, this thesis encourages researchers to adopt a human-centred perspective while developing solutions for human-robot collaborations. The new LoA matrix provides researchers with a starting point to refine and develop task allocation frameworks that actively engage humans to collaborate with robots while exploiting each other's cognitive and physical strengths. As AI takes over mundane tasks from humans, this thesis intends to draw the attention of researchers to a) the foundations of human-centred automation (in other words, human supervisory control) and b) levels of automation, proactively using and refining them and thus avoiding being trapped by the *paradoxes of automation.*

Contribution to Industry

For industrial practitioners, this thesis provides examples of using collaborative robots to increase flexibility and efficiency and combine different human-centred automation technologies to enhance human operators' capabilities, plus a framework for identifying gripper requirements.

Through theoretical and empirical research, this thesis bridges the knowledge gap highlighted by industry on human-robot collaboration. It presents a task allocation-based approach, using levels of automation to simplify human-robot collaboration in final assembly. The new LoA matrix is designed to integrate cognitive and physical skills and the capabilities of humans and robots in designing a collaborative robot workstation whilst visualising the collaboration and skill requirement levels. Using this approach as a tool to design human-robot collaborative workstations, industry can increase its adoption of collaborative robots in final assembly. Though this tool is designed with automotive final assembly in mind, the generic nature of the LoA matrix and other components enable its use in other sectors in which human-robot collaboration is being implemented.

5.5 Reflection on Research Approach and Methods

The discussion of and responses to the research questions are based on the research presented in the appended publications. The process of investigating aims and eliciting conclusions in academic papers very much depends on the methodology used. Each paper employs its unique approach, leading to varying investigations and findings. Of course, it is anticipated that slight errors may occur during the data-gathering process. However, the ultimate goal of research is to provide helpful tools rather than absolute truth. This aspect is evaluated in the appended papers.

The research paradigm used in this thesis was pragmatism, which is characterised by its emphasis on practical consequences and real-world implications. This approach was chosen to ensure that the research produced meaningful insights that could be applied to practical situations. The research used abductive reasoning to generate hypotheses that could explain observable events and encourage further investigation. This method combines induction, deduction and creative imagination to arrive at plausible explanations for phenomena that may not be immediately obvious. Through the use of abductive reasoning, this research was able to develop hypotheses grounded in empirical evidence whilst also being innovative and thought-provoking.

A mixed research methods approach was used to gain complete knowledge of human-robot collaboration in final assembly from multiple perspectives and help answer the research questions, based on qualitative and quantitative data collection and analysis. This research integrated quantitative data-gathering methods, such as surveys and literature reviews, with qualitative data-collection methods, such as participant observation and thematic analysis. The combination of quantitative and qualitative data increased the depth of comprehension, offering a more comprehensive perspective of human-robot collaboration. Each step in the research design, data collection, analysis and implementation was carefully undertaken to preserve the quality and reliability of the research. Relying solely on either qualitative or quantitative research methods conflicts with the author's pragmatic worldview and would have altered the outcome of this thesis. To ensure the usefulness and thoroughness of the research, reliability and validation were factored into its design. Data was systematically acquired and stored to ensure its reliability. The use of systematic literature reviews, surveys and multiple iterations of practical applications (carried out in the SII lab) ensured the validity and reliability of the research.

5.6 Limitations

Though the research findings can be utilised in various domains related to human-robot collaboration, it must be noted that the data used in this thesis relies heavily on the automobile manufacturing industry. The research presented in this thesis was conducted entirely in Sweden with visits to factories located in EU. The location and culture have played a huge role in the findings made and conclusions drawn in this thesis.

This thesis presents a task allocation matrix for implementing human-robot collaboration but does not include extensive testing of the matrix. The matrix is a tool used in developing human-robot collaborative workstations. However, a successful working solution is defined by other factors, such as the type of robot and work tasks, which were outside the scope of this thesis. This thesis focused on task allocation for safe human-robot collaboration; something which should, ideally, be carried out before investing in robots. Thus, applying this matrix to existing HRC workstations may be costly and further tests are required in this area.

5.7 Future Work

The author would suggest that future work be conducted on implementing the framework for designing collaborative robot workstations for final assembly. Although the design of the LoA matrix and exemplification is based on findings from manufacturing and final assembly, this tool should be applied in other domains of human-robot collaboration for the design of collaborative robot workstations. The impact of this matrix on different types of robots and support equipment, plus the skills of the operator collaborating with the robots need to be studied in detail.

For a successful HRC application, the role of humans needs to be further investigated and clarified. As technology evolves, so the role of humans in HRC applications will also evolve. Combining the proposed matrix with technologies such as AI and machine learning to study its impact on achieving active collaboration HRC application needs to be assessed as part of the continuing research in this field. Furthermore, this work encourages researchers to use the matrix to foster and ensure trust between humans and automation in assembly systems.

6 CONCLUSION

This thesis aimed to increase human-centred automation using collaborative robots in final assembly. Based on that aim, this thesis supports the implementation of collaborative robots aimed at increasing human-centred automation in the final assembly stages of manufacturing, by adopting a systematic, structured approach.

This thesis first analysed how humans and robots collaborate in the manufacturing and final assembly processes. It has demonstrated how the inherent characteristics of collaborative robots complement the requirements of human-robot collaboration in final assemblies. These collaborative robot applications can work safely alongside human operators, are easily reprogrammable and can be moved around. According to the thesis' empirical investigation, the reasons for the lack, or ineffective use, of collaborative robots include: the use of collaborative robots being based on intuition; the use of descriptive methods; and the necessity for suitable work allocations between people and robots. This thesis highlights the importance of prioritising the human element over technology when implementing human-centred automation through collaborative robots in the final assembly process.

An important aspect of this thesis was to look at how human-centred task allocation approaches could help in designing and implementing collaborative robots. The thesis proposed a prescriptive task allocation matrix based on theoretical and empirical research, which includes the physical and cognitive skills of humans and robots through specified levels of automation. Companies can use this matrix to optimise task allocation, allowing for full human-robot collaboration in final assembly.

The ongoing development of collaborative robots is generating fresh research and new concepts are being developed. Robots operating with people have the potential to revolutionise final assembly, but both the human and technological factors must be considered. This thesis serves as a starting point for moving in that direction.

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