Mälardalen University Licentiate Thesis 317

Supporting the implementation of industrial robots in collaborative assembly applications

Staffan Andersson

MÄLARDALEN UNIVERSITY
SWEDEN

Mälardalen University Press Licentiate Theses
No. 317

SUPPORTING THE IMPLEMENTATION OF INDUSTRIAL ROBOTS IN COLLABORATIVE ASSEMBLY APPLICATIONS

Staffan Andersson

2021

School of Innovation, Design and Engineering

ISBN 978-91-7485-535-7
ISSN 1651-9256
Printed by E-Print AB, Stockholm, Sweden

Abstract

The ongoing push for customized products and cost reduction are driving manufacturing companies to automate their assembly operations. Yet, automating assembly operations is challenging because many tasks in assembly require human abilities like problem-solving and flexibility. Therefore, manufacturing companies need assembly technologies that are easy to implement and where technology and humans can collaborate. Industrial robots in collaborative assembly applications enable such opportunities. Specifically, these collaborative assembly applications present an opportunity to, in a fenceless environment, combine the flexibility of the human with the accuracy, repeatability, and strengths of the robot.

Despite the potential benefits of industrial robots in collaborative assembly applications, it seems common that these collaborative assembly applications do not progress past a pilot (or pre-study) and rarely get implemented in assembly operations because manufacturing companies face many challenges when implementing them. Therefore, manufacturing companies need support when implementing industrial robots in collaborative assembly applications, and providing that support is the objective of this thesis. To fulfill this objective, this work included two empirical studies; first, an interview study maps how manufacturing companies use industrial robots in collaborative assembly applications. Second, a multiple-case study maps the challenges and enablers when implementing collaborative assembly applications. Finally, the studies were combined with literature reviews aiming to fill the theoretical and practical gaps.

The reported work proposes an implementation process with the proposed enablers for mitigating critical challenges that manufacturing companies face when implementing industrial robots in collaborative assembly applications. For example, two important enablers are that the manufacturing companies should conduct the application design and installation themselves – not relying solely on system integrators – and the importance of involving operators from the shop floor in the implementation process. Finally, this work contributes to filling the identified gaps in the literature and provides practitioners with enablers that can support managers when implementing industrial robots in collaborative assembly applications.

Samanfattning

Det pågående trycket för förändringabara produkter och kostnadsminskningar driver tillverkande företag att automatisera deras monteringsverksamhet. Emellertid är automatisering av monteringsverksamhet utmanande för att många uppgifter i monteringen kräver människans förmågor så som problemlösning och flexibilitet. Tillverkande företag behöver därför monteringstekniker som är enkla att implementera och möjliggör samarbete mellan teknik och människa. Industrirobotar i samarbetande monteringsapplikationer möjliggör detta. Specifikt så möjliggör dessa samarbetande monteringsapplikationer att, i en staketlös miljö, kombinera människans flexibilitet med robotens precision, repeterbarhet och styrka.

Trots de potentiella fördelarna med industrirobotar i samarbetande monteringsapplikationer verkar det vanligt att dessa samarbetande monteringsapplikationer inte framskrider förbi pilotstadiet (eller förstudie) och därmed sällan blir implementerade i monteringsverksamheten. Detta för att tillverkande företag står inför otaliga utmaningar när dem ska implementeras. Därför behöver tillverkande företag stöd med implementeringen av industrirobotar i samarbetande monteringsapplikationer. Att bidra med sådant stöd är syftet med detta arbete. Två empiriska studier genomfördes för att fylla detta syfte; först en intervjustudie som kartlägger hur tillverkande företag brukar Industrirobotar i samarbetande monteringsapplikationer. För det andra genomförs en flerfallstudie som kartlägger utmaningar och möjliggörare för implementeringen av dessa samarbetande monteringsapplikationer. Till sist kombineras dessa studier med en litteraturgenomgång med syftet att fylla de teoretiska och praktiska gapen.

Det rapporterade arbetet föreslår en implementeringsprocess med föreslagna möjliggörare som mildrar de kritiska utmaningar som tillverkande företag står inför när dem implementerar industrirobotar i samarbetande monteringsapplikationer. Till exempel är två viktiga möjliggörare att tillverkande företag själva bör genomföra applikationsdesign och installation – istället för att förlita sig på systemintegratörer – och att det är viktigt att involvera verkstadsoperatörer i implementeringsprocessen. Till sist bidrar arbetet till att fylla de identifierade gapen i litteratur och praktik och tillhandahåller praktiker med möjliggörare som kan stödja ledare under implementeringen av industrirobotar i samarbetande monteringsapplikationer

Acknowledgments

These first two and half years of my Ph.D. journey have finally been summarized into a licentiate thesis. This adventure has been shared by several influential people whom I like to thank. But first, it is vital to acknowledge that this work was carried out within the ARRAY research school financed by the KK-foundation and MITC.

I would like to thank my supervisors for showing patience during my learning curve in writing and research skills. I think you contribute with diverse and important skills that support my work. Anna Granlund, thanks for your focus on details; it has been imperative to clarify much of my, at times, general nature of writing. Jessica Bruch, for your ability to find the *good-enough* state of things when I become too invested in my work or on a specific topic. Thank you both for your contributions and hard work through this adventure so far.

I think it is important to mention the significant support given by MITC. Mikael Hedelind deserves my gratitude for his support and feedback on my work, especially regarding robot-related topics. Your experience has been very valuable. In addition, my thanks are extended to Vincent Adoue for your patient and support. I hope my research contributes to you and MITC and continuous to do so in the coming years.

Special thanks are needed to William and Josefine and others working at Robotdlaen. It has been a privilege working with you and contributing to Robotdalen and your consortium. I am truly grateful for your support and belief in my work. Both of you helped tremendously with your experiences and insights. I sincerely hope that my investigations have contributed to you as much as the opportunities you have given me contributed to the results in this thesis. In fact, much of my work would have been difficult without your enthusiasm.

I would also like to thank my colleagues at Mälardalen university for providing a supportive and engaging environment. No one mentioned, no one forgotten.

Special thanks to my beloved Viktorija Badasjane. For everything.

I'd like to finish this chapter with a quote from one of the greats. Seemingly accurately describing the feeling of completing this work: "*I feel thin—sort of stretched. Like butter, scraped over too much bread. I need a holiday. A very long holiday*." Bilbo Baggins in the motion picture The Fellowship of the Ring.

Staffan Andersson
Dingtuna, November 2021

Publications

Appended Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals. The author of this thesis was the main author and initiator of the append papers. In addition, the author carried out the data collection, data analysis and wrote the papers. The co-authors mainly contributed by reviewing the papers and increasing their quality.

I Andersson, S. K. L., Granlund, A., Hedelind, M., & Bruch, J. (2020). Exploring the Capabilities of Industrial Collaborative Robot Applications. In *The 9^TH Swedish Production Symposium, 7-8 October 2020, Jönköping, Sweden.*

II Andersson, S. K. L., Granlund, A., Bruch, J., & Hedelind, M. (2021) Experienced Challenges when Implementing Collaborative Robot Applications in Assembly Operations. *International Journal of Automation Technologies,* Vol. 15 No.5, pp. 678-688

III Andersson S. K. L., Bruch, J., Hedelind, M., Granlund, A. (2021) Critical Factors Supporting the Implementation of Collaborative Robot Applications. In *2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (in press). IEEE

Additional publications by the author not included in the thesis

IV Eriksson, A., Music, A., Andersson, S. K. L., & Hedelind, M. (2021) Supporting Organizational Readiness when Implementing Robot in a Collaborative Environment. In *2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (in press). IEEE

V Andersson, S., Flores-Garcia, E., & Bruch, J. (2019). Enabling problem-based education in collaboration with manufacturing companies. In *26th EurOMA Conference: Operations Adding Value to Society, 17th-19th June 2019, Helsinki, Finland*

Table of Contents

1 Introduction

This chapter provides a background to this research focusing on industrial robots in collaborative assembly applications and their intended use in the manufacturing industry. This chapter also contains motivations for this works' problem statement, research objective, research questions, and scope.

1.1 Background

The increase in customizable products and high production costs point to a substantial need for manufacturing companies to automate their assembly. The need for automated assembly is further motivated by the fact that assembly is a costly part of manufacturing—up to 80% of the product cost—and automation can help reduce such costs (Siciliano and Khatib, 2016). One way manufacturing companies have reduced their costs in the past is by using traditional robot applications, i.e., industrial robots in a fenced application (Siciliano and Khatib, 2016). The term industrial robot is defined as an "automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications" (ISO, 2011, p. 2).

The use of traditional robot applications is, however, primarily reducing costs when manufacturing companies are producing at high volumes (Fryman and Matthias, 2012; Siciliano and Khatib, 2016). Moreover, traditional robot applications are commonly fenced, fixed in place, and inflexible in how many different products they can produce and are inflexible in their applications (inflexible robot cells) (Hentout et al., 2019), preventing their use in assembly as products become increasingly customizable. Nevertheless, the highly manual assembly applications (i.e., the assembly stations) are currently filled with tasks requiring human abilities like problem-solving and flexibility (Fasth et al., 2010; Nolan, 2021).

Increasingly customizable products and high assembly costs have been pushing manufacturing companies to use automation suitable for assembly applications. This situation was well-summarized by Nolan (2021, p. 25) "[…] new generations of miniaturised, complex products with short life cycles will require levels of adaptable assembly, precision and reliability that exceed human capabilities." Thus, one way for manufacturing companies to handle cost reduction and increasingly customizable products is to implement flexible assembly automation. For manufacturing companies, flexibility in assembly means that the automation is easy to implement, adaptable to different product mixes, quick in application layout changes, and portable between assembly applications (Nolan, 2021). Consequently, industrial robots in collaborative assembly applications are an enabling technology for reaching flexibility in assembly applications.

The term industrial robots in collaborative assembly applications is defined as a system that allows humans and robots to work together without a fence, thereby combining their strengths (also referred to as human–robot collaboration) (Hentout et al., 2019; Michalos et al., 2010; Siciliano and Khatib, 2016). Mainly, the goal of industrial robots in collaborative assembly applications is to combine the accuracy, endurance, and strength of the robots with humans' ability to be flexible and intelligent (Fast-berglund et al., 2016; Nolan, 2021). Furthermore, the term assembly applications refers to its scope of use in assembly stations in the manufacturing company's assembly line.

Industrial robots in collaborative assembly applications can involve operators collaborating with both larger industrial robots or the commonly smaller collaborative robot (or cobot), the latter being simpler to implement because of its inherent safety, ease of programming, utilization of limited floor space (because they are usually small and fenceless), quick set-up and adjustments, and portability (enabled by its lightweight design) (Hentout et al., 2019; Michalos et al., 2010; Nolan, 2021). However, there are limited assembly application scopes for which industrial robots in collaborative assembly applications are suitable (Fryman and Matthias, 2012). As seen in Figure 1, this scope lies between manual assembly and traditional robot applications. In Figure 1, the green line (across the figure) separates the purely manual scope (above the line) from the robotic applications (below the line), and the blue scope is where industrial robots in collaborative assembly applications are likely to be beneficial based on unit cost and production volume.

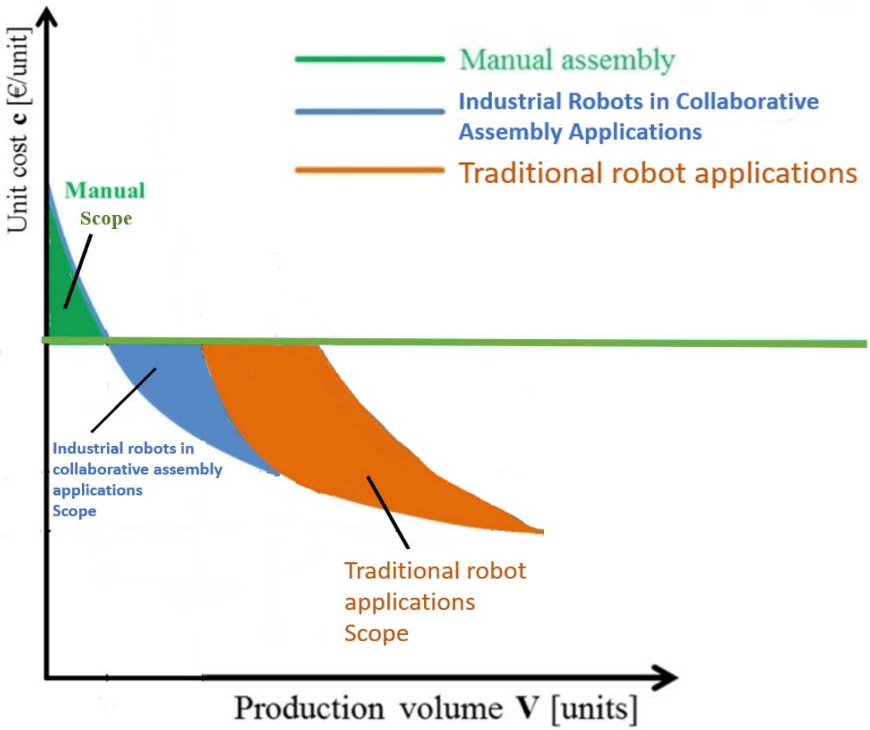

Figure 1 – The suitable scope for industrial robots in collaborative assembly applications, based on Matthias (2014).

Industrial robots in collaborative assembly applications are currently being implemented by manufacturing companies to increase their competitiveness (reduced cost and increased flexibility) (ElMaraghy and ElMaraghy, 2016). Nevertheless, implementing industrial robots in collaborative assembly applications shows significant challenges preventing their use. The term implementation refers to the act that manufacturing companies conduct to adopt technologies in their production processes. Manufacturing companies often conduct their implementation using an implementation process, which is a set of predefined phases (Bruch et al., 2015). The implementation process involves starting with a pre-study phase and ending with the operations phase when the technology is fully operational (Bruch et al., 2015; Kopp et al., 2020). By following a predefined implementation process, manufacturing companies can employ a structured approach instead of an ad-hoc approach, aiming to increase the likelihood of successfully implementing a technology (Baines, 2004).

1.2 Problem statement

Despite their benefits, few industrial robots in collaborative assembly applications have been implemented in the manufacturing industry, and there is a significant gap in the literature regarding such implementations (Bauer et al., 2016; Hashemi-Petroodi et al., 2020; Hentout et al., 2019; Nolan, 2021; Villani et al., 2018). Furthermore, the lack of implemented industrial robots in collaborative assembly applications emanates from significant uncertainties that prevent them from progressing past the pre-study phase (Bauer et al., 2016; Hentout et al., 2019). Specifically, significant uncertainties about attributes, safety, and knowledge prevent manufacturing companies from implementing industrial robots in collaborative assembly applications.

Research has yet to identify the attributes (the ascribed qualities or capabilities) of industrial robots in collaborative assembly applications (Bauer et al., 2016). Focusing on attributes is important because there is no clear understanding of what attributes can be used in a collaborative assembly application (Hentout et al., 2019; Villani et al., 2018) and what sets that apart from traditional robot applications.

Previous research has stated that manufacturing companies face substantial uncertainties about safety with industrial robots in collaborative assembly applications, including safety in collaborative assembly application design (Djuric et al., 2016; Gualtieri et al., 2021; Malik and Bilberg, 2017) and adhering to harmonized standards (for instance the machine directive) in collaborative assembly applications (Bauer et al., 2016; Villani et al., 2018). Consequently, these safety uncertainties hinder manufacturing companies from implementing industrial robots in collaborative assembly applications.

Regarding knowledge, previous research has pointed out uncertainties concerning the involvement of system integrators (also known as technology suppliers), namely, to what extent system integrators should be involved when manufacturing companies implement industrial robots in collaborative assembly applications (Bauer et al., 2016). Moreover, previous research has shown that industrial robots in collaborative assembly applications can reduce costs and increase flexibility; yet, there are knowledge uncertainties at manufacturing companies about the benefits of implementing industrial robots in collaborative assembly applications (Kopp et al., 2020). Finally, there are knowledge uncertainties in the design of industrial robots in collaborative assembly applications, specifically encompassing their layout and collaborative assembly equipment (grippers, fixture, and feeding systems) (Djuric et al., 2016; Wojtynek et al., 2020).

There are many uncertainties when implementing industrial robots in collaborative assembly applications, and there are few descriptions of the challenges faced by manufacturing companies and which enablers could support them in their implementation efforts. Moreover, it is unclear what attributes of industrial robots in collaborative assembly applications are useful for the manufacturing companies in a real assembly environment.

1.3 Research objective and research questions

Based on the problem statement above, the objective of this thesis is to support the implementation of industrial robots in collaborative assembly applications. To fulfill this objective, the following research questions have been formulated:

RQ1: What are the predominant attributes of industrial robots in collaborative assembly applications compared to traditional robot applications?

This research question aims to identify and provide a context for the use of attributes of industrial robots in assembly applications. The attributes and theoretical areas should be mapped to answer this question, providing the scope for the coming research questions.

RQ2: What are the challenges when implementing industrial robots in collaborative assembly applications?

The second research question focuses on identifying the critical challenges that manufacturing companies face, thus creating a broader understanding of those challenges. Thereby, this question aims to map the critical challenges in the manufacturing industry to significant areas in research.

RQ3: What are the enablers when implementing industrial robots in collaborative assembly applications?

Finally, research question three is important because little support has been given to defining the enablers that support the implementation of industrial robots in collaborative assembly applications. This question aims to fill this gap by mapping these enablers. Significantly, the findings of this question should aim to mitigate the critical challenges, consequently contributing to both theory and practice.

1.4 Scope

The focus of this work is on the implementation of industrial robots in collaborative assembly applications. The implementation of any technology typically involves manufacturers using a predefined implementation process. Hence, the focal point of this research is to study the manufacturing companies' use of these implementation processes when implementing industrial robots in collaborative assembly applications. Thus, this work can support the implementation of industrial robots in collaborative assembly applications by exploring the implementation processes.

The work herein is scoped to manufacturing companies with smaller-sized products, in the sense that the industrial robots investigated, whether Cobots or collaborative robots, had sufficient load capacity to manipulate the products. This work does not encompass *large* industrial robots in collaborative assembly applications, which some researchers have focused on previously (Gopinath et al., 2018). Another focus is that the manufacturing companies currently have highly manual assembly applications with sufficient opportunities for industrial robots in collaborative assembly applications, as shown in Figure 1.

1.5 Outline of the thesis

The remainder of this thesis is structured as follows: Method and study design are presented in chapter 2. Applied literature within the frame of reference is presented in chapter 3. Chapter 4 contains a summary of the appended papers. Then, Chapter 5 presents the proposed support when implementing industrial robots in collaborative assembly applications. Finally, in Chapter 6, the author discusses the thesis results and generalization of the findings, its conclusions, and future research.

2 Method

This chapter firstly describes the overall method, research process, and design for the carried work. It also describes the method in the respective studies (A and B). Data analysis and quality aspects are also presented.

2.1 Research method

This thesis positions itself in the operations management (OM) field. OM is a research field that focuses on interdisciplinarity real-world cases within the act of producing, e.g., goods or services, to contribute to both research and practitioners with novel ways to manage such operations. In OM research, case studies are an increasingly popular way to conduct studies (Barratt et al., 2011).

Case studies are appropriate when processes or phenomena need inquiries into their context because few explanations exist (Williamson and Bow, 2002). Therefore, this work included multiple-case studies (Study B), as few explanations existed regarding the implementation of industrial robots in collaborative assembly applications (Bauer et al., 2016; Hashemi-Petroodi et al., 2020; Villani et al., 2018). Moreover, a case study is proper when the process or phenomenon has multiple and uncontrollable variables in contrast to, for instance, experiments when a variable can be controlled in its setting (Yin, 2018). Case studies are often categorized into single- or multiple-case studies. The former provides a more in-depth inquiry into a process or phenomenon in a specific context, whereas the latter provides generalizability over multiple contexts.

This work also included an interview study (Study A) that aimed to investigate the attributes of industrial robots in collaborative assembly applications. Study A consists of interviews with the personnel involved with that technology daily. The interview study allowed flexible data collection and access to key persons having experience with industrial robots in collaborative assembly applications. According to Karlsson (2009), data collection flexibility and increased access to significant interviewees are the significant strengths of interview studies. Moreover, because the interview studies were retrospective, the author could select relevant manufacturing companies based on whether they had used industrial robots in collaborative assembly applications, another major benefit of this method (Karlsson, 2009).

A definition of research based on case study methods (interviews, documents etc.) was defined by Maxwell (2013), who wrote that this method aims to understand better: "(1) the meanings and perspective of the people you study – seeing the world from their point of view, rather than simply your own; (2) how these perspectives are shaped by, and shape, their physical social and cultural contexts; and (3) the specific processes that are involved in maintaining or altering these phenomena and relationships." (Maxwell, 2013, p. viii).

This definition has guided the research towards a process theory, as the studied phenomenon (the implementation of industrial robots in collaborative assembly applications) connects and influences the people and processes at manufacturers. Indeed, these aspects are essential to include when having a process view conducting a flexible approach. In contrast, variance theory serves to answer more numerically stratified (e.g., survey) types of inquiries (Maxwell, 2013). Additionally, the research questions are asked in a *what*-manner and include the studied phenomenon, the affected people (or things), and their context. Moreover, "what" questions are commonly asked when conducting exploratory research (Yin, 2018), as is done in this work. The explorative research is motivated by the infancy state of the implementation of industrial robots in collaborative assembly applications (Kopp et al., 2020; Villani et al., 2018).

The initial research questions were formulated based on an identified gap in extant research. These questions have been reworked and slightly adjusted through the work alongside data collection and data analysis. However, there have been only minor changes to the initial objective to remain within its scope. Hence, this work had a somewhat flexible approach. A flexible research design has been deemed a suitable tactic in a qualitative case-study approach (Säfsten and Gustavsson, 2019). Figure 2 shows the research process applied in this work.

2.2 Research process

This research was founded on studies with multiple manufacturing companies producing various products. These cases are essential for empirical evidence for practical problems. Nevertheless, scientific methods and literature correlations are needed (Säfsten and Gustavsson, 2019). However, the research process can be pretty messy and non-linear (Williamson and Bow, 2002), indicating that researchers should try and structure their way of working to at least have a clear scope and focus through the work. Therefore, this research used a helpful, flexible, and simple research process, as presented in Figure 2, to ensure that the inquiry was somewhat structured.

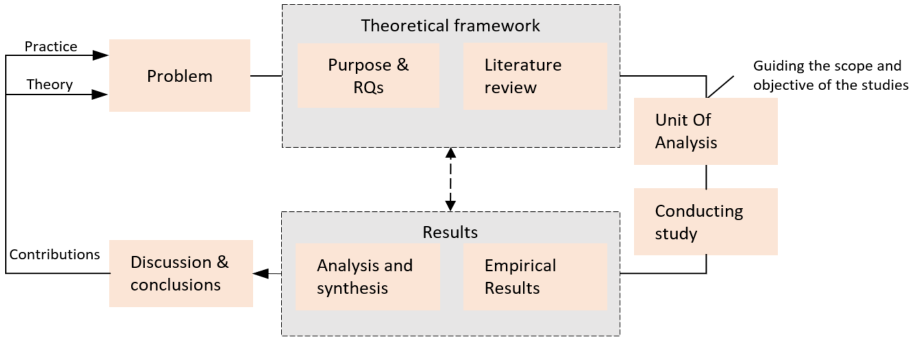

Figure 2 – Flexible research process based on Säfsten and Gustavsson (2019, p. 3).

Figure 2 shows that the research began with a theoretical gap and relevance to practice. The continuation of the process was an iterative approach where the theoretical framework was reevaluated by scrutinizing the studies' results and vice versa. Nonetheless, the unit of analysis and the studies stayed set towards the problem through the process. Finally, the conclusions and discussion stemming from the flexible process brought new insights into the problem as the research progressed. Hence, some minor modifications were made to the details of the problem as knowledge about the area increased.

2.3 Research design

In this work, two studies were carried out, Studies A and B. Study B and its design were guided by a unit of analysis. The unit of analysis is important because it guides the research and its design throughout the process. Significantly, using a precise unit of analysis helps the researcher avoid losing focus on the case study's overall objective (Yin, 2018). Moreover, in multiple-case studies (used in this work) the unit of analysis defines the contextual link between the cases. Thus, the unit of analysis serves to define the case, what to study (e.g., organization, process, or individual, and what to analyze), and the study's purpose (Säfsten and Gustavsson, 2019).

Table 1 summarizes the conducted studies and how they contribute to the respective research question (RQ). In addition, Table 1 also shows an overview of the studies' data collection and the method employed in the respective studies.

Table 1 – Overview of the studies' contribution to the RQs

Study	Study Objective	Method	Data Collection	Publication	RQ
A	Investigate attributes of industrial robots in collaborative assembly applications	Retrospective interview study	- Interviews	Paper I	1
B	Investigate the implementation of industrial robots in collaborative assembly applications	Multiple-case study	- Interviews - Internal Documents	Papers II & III	2, 3

Figure 3 shows a timeline of this research's conducted studies. It also shows when the respective papers were published. The paper's writing process began towards the end of the studies, which is not shown explicitly in Figure 3. The studies contain case selection, developing an interview guide, data collection, and data analysis. The remainder of this section presents the research design for the respective studies.

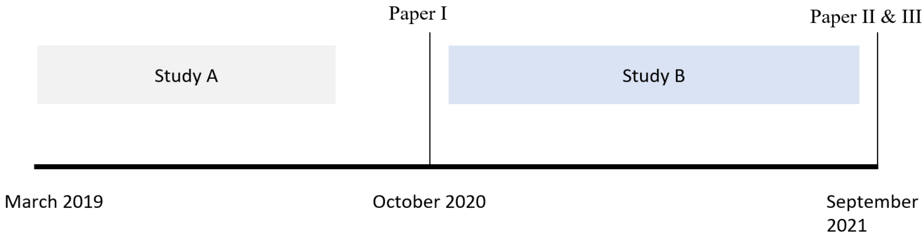

Figure 3 - Timeline of the studies and when their papers were published

2.3.1 Study A – Attributes of industrial robots in collaborative assembly applications

This study required real-world interviews with personnel at case companies that had used industrial robots in collaborative assembly applications. The interviewees were selected based on two main criteria: First, they had project or management positions where they worked closely with the industrial robots in collaborative assembly applications. Second, they knew the case companies' assembly. The interviews were carried out between March 2019 and September 2019.

Study A included four manufacturers, where the interviews encompassed project leader, production engineer, and production manager roles. Two manufacturers had implemented an industrial robot in a collaborative assembly application in full production, whereas the other two had pilot applications in or before the pre-study phase. Moreover, three manufacturers were in the automotive industry, manufacturing components and conducting final assembly operations. Additionally, one manufacturer was within high volume, high variety production. Table 2 shows the data collection for Study A.

Table 2 - Data collection in Study A

Type of Industry	Duration	Interview Method	Participants
Automotive	1h	Interview	Industrial Doctoral student
Automotive	1h	Interview	Industrial Doctoral student
High Volume, High Variety	1h	Interview	Production Project Leader
Component Supplier	1h30min	Group Interview	Three Process Engineering Managers, Process Engineer

One of the interviews was a group interview with four interviewees who were all involved in the implementation and daily work of their industrial robot in a collaborative assembly application. During the group interview, the author used the same interview guide as with the other interviewees. This type of interview was beneficial for several reasons: First, several interviewees could be interviewed at once, saving time and resources for both the author and interviewees. Second, during the group interview, the author allowed everyone to answer each question, resulting in the emergence of differing viewpoints and discussions. Third, in retrospective studies, there is an integral risk that some events might be recalled inaccurately by the interviewee (Karlsson, 2009). Hence, using a group interview somewhat prevented such discrepancies because the interviewees could openly discuss and supplement each other's statements when needed.

In this study, a semi-structured interview guide was used to allow informal talks, yet it focused on attributes of industrial robots in collaborative assembly applications. Moreover, the interview guide contained sub-questions to move the interview toward the intended focus if an interviewee strayed from the relevant subject. In this way, the author remained unbiased while focusing the interviews on the intended subject area. The interview guide consisted of questions like, “What were the biggest challenges with an industrial robot in collaborative assembly applications compared to a traditional robot?”, “What goals were you aiming to achieve with the industrial robot in collaborative assembly applications?”, and “Did you achieve your goals with the industrial robots in collaborative assembly applications? If no, why not?” These questions, and others alike, served to map the attributes.

2.3.2 Study B - The implementation of industrial robots in collaborative assembly applications

This multiple-case study investigated the enablers and challenges when implementing industrial robots in collaborative assembly applications. This study was explorative, because when a phenomenon is novel—as is the implementation of industrial robots in collaborative assembly applications—the study aims to clarify the phenomenon and gain insights into its existence (Karlsson, 2009). Thus, this study sought to clarify this implementation (the phenomenon) and map it, finally suggesting potential questions for future research avenues.

In addition to eight case companies, this study included a research center specializing in pre-studies for such collaborative applications. Several experienced robot programmers and application designers at the research center carried out 20 pre-studies from 2017 onward. The case companies used the conceptual designs created in the pre-study to determine if the industrial robots in collaborative assembly applications would benefit their assembly. From this pool of samples, eight case companies were selected for this work. The following case selection criteria were used to select the most relevant cases: (1) the case companies needed to have discrete parts production, which limited the sample to 13 cases; (2) the case companies were confined to industrial robots in collaborative assembly applications users, thereby excluding five system integrators.

In Study B, the unit of analysis was challenges and enablers when implementing industrial robots in collaborative applications, as shown in Figure 4. The study's context was set to the case companies' assembly. Thus, the unit of analysis provided a guiding reference during Study B, ensuring that data was purposefully collected.

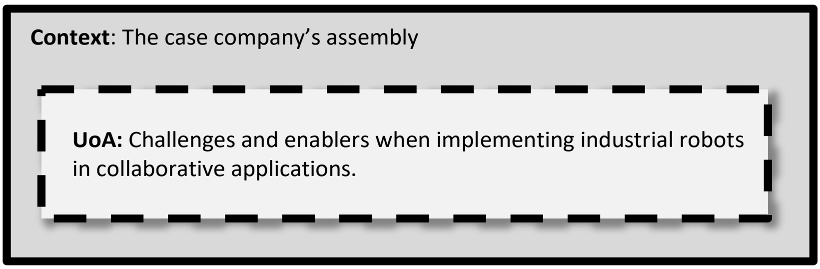

Figure 4 – Study B's unit of analysis

The data collected for Study B consisted of both interviews and documents. Table 3 summarizes information about the case companies and the data collection in Study B. The study's document collection included management presentations and technical reports. The technical reports were compiled by the research center for the respective case company. The reports contributed to the study with the technical specifications and pictures of the conceptual design of the industrial robots in collaborative assembly applications. The author scanned these reports before the interviews, clarifying the conceptual design and ensuring the author understood the case company context. Additionally, three of the case companies showed management presentations during the interviews explaining how they worked with their implementation project internally.

At the time of this study, the case companies were at different stages of implementation (see Table 3). Thus, they provided various insights from their implementation projects. The case companies in Study B resided within various industries (see Table 3), aiming for increasingly generalizable results. Study B contributes to RQ 2 and 3 with its two resulting papers. Paper II contributes with the challenges, and Paper III contributes with the enablers.

Table 3 - Data collection in Study B

Role of interviewees	Product at the case company	Implementation phase	Documents
Manager Production Engineering	Batteries	Pre-study	Technical Report
Project Facilitator	Circuit Boards	Start-up	Technical Report
Project Manager Production Engineer	Garden Tools	Factory Installation	Technical Report Management Presentations
Project Manager Associate Project Manager	Heat Exchangers	Pre-study	Technical Report Management Presentation
Project Manager Development Engineer	Metal Cutting Tools	Factory Installation	Technical Report
Project Manager Technical Operator	Mining equipment	Factory Installation	Technical Report Management Presentation
Two Production Engineers	Office Equipment	Pre-study	Technical Report
Project Manager Technical Operator	Water Pipes and Pumps	Start-up	Technical Report
Project Manager Research Center	Various	Pre-study	Technical Reports

The study contained interviewees involved in the implementation projects, including managers, production engineers, project managers, and operators. The interviews were between 40 min to 1h 30 min, but the majority were about 50 min to 1h. The selection criteria for interviewees were, first, interviewees involved in the implementation project from the start (pre-study). Second, if the first criteria were not met (some had switched employers or were otherwise unreachable), interviewees currently working on the implementation project or involved in the project to some extent were selected. Finally, the study aimed to interview people at several levels at each case company, yet some interviewees were not accessible during this study, resulting in two case companies with one interviewee each.

The interviews started with the author showing a standardized implementation process that served as a basis for further discussions in Study B. The interview contained questions like, “Tell me what the pre-study looked like,” “Tell me about your experiences implementing industrial robots in collaborative assembly applications,” and “How is the industrial robot in assembly application used today?” Furthermore, the interview guide included sub-questions used to gain a deeper understanding of specific topics. Such sub-questions were, for instance, “What was the purpose of the implementation?”, “What is your experience with robot applications?” and “What were the challenges/enablers in the implementation phases?” Figure 5 shows the implementation process presented to the interviewees.

Figure 5 – A standardized implementation process, based on Bruch et al. (2015)

2.4 Data analysis

Yin (2018) pointed out that in case study research, one important strategy for analyzing data from case studies is to base it on theoretical propositions. In essence, this means that the analysis, preferably, should be planned at the start of the case study based on the gap in literature resulting in the study’s objective and research questions. In this work, the theoretical propositions were defined first, therefore guiding the studies and the data analysis. Nonetheless, the objective and research questions were derived from gaps in the literature, simultaneously considering the challenges faced by practitioners. Then, the author worked continuously through the data analysis, consulting the research questions and objectives to shape how data was analyzed and evaluated. Thus, this work followed the analysis strategy to rely on theoretical propositions.

In Study A, a thematic analysis served to identify significant findings in the interviews. The analysis in Study A followed the checklist presented by Braun and Clarke (2008); as such, the analysis started with coding themes within the texts (attributes and its subthemes of safety, flexibility, and assembly application), analyzing them, and re-checking the original transcripts for consistency, aiming to ensure accuracy across the data sets. Furthermore, the findings were matched with the literature to show the subthemes’ relevancy.

Study B based the analysis on the thorough data analysis approach presented by Miles et al. (2020). Specifically, the steps in Study B were first coding (capturing parts of a text, either paragraphs or sentences) the critical challenges and the enablers when implementing industrial robots in collaborative assembly applications. The coding was conducted in the software NVivo. Second, a literature review identified significant areas related to challenges (safety, knowledge, and attributes) and enablers (7M dimensions). Finally, the coded areas of challenges and enablers were matched to the findings in the literature review, resulting in the lists in Papers II and III.

Paper II assigned the challenges to the three first implementation phases (pre-study, collaborative assembly application design, and factory installation) and mapped the challenges into the literature-based areas of safety, knowledge, and attributes. Paper III used a newness perspective identifying how new the industrial robots in collaborative assembly applications were to the case companies by mapping their newness level. Furthermore, in Paper III, the enablers were mapped into the 7M dimensions to show how these could mitigate challenges when implementing industrial robots in collaborative assembly applications. The 7M dimensions, although typically applicable to less extensive implementation efforts, can support the identification of enablers, reducing the time (and effort) to implement a technology (Bergman and Klefsjö, 2013).

This work's results (see chapter 5) stem from a specific matching of the findings in the conducted studies. Firstly, the attributes set the context of industrial robots in collaborative assembly applications, indicating their use. Secondly, the critical challenges were described and mapped to the enablers that can mitigate them. Consequently, the results of this work originate closely from the conducted studies and show how the predominant attributes, critical challenges, and main enablers are linked to support the implementation of industrial robots in collaborative assembly applications.

2.5 Quality aspects

Some criticisms have pointed out that case studies can lead to the researcher's bias significantly impacting data collection and analysis, a situation frowned upon in research (Maxwell, 2013; Williamson and Bow, 2002). Nevertheless, Maxwell (2013) argued that a researcher's predisposition can provide valuable insights and validity when the researcher is seen as a research instrument. To that end, this author's predispositions supported this research from both previous working experience within the manufacturing industry and university courses in relevant manufacturing and engineering areas. These experiences provided reliable knowledge with which to interpret the results and ask significant follow-up questions during the interviews. Moreover, the unit of analysis, objective, and research questions were set at the beginning of this work, allowing the author to focus clearly on the studies. In case study research, three significant quality aspects are used to ensure that the work was done scientifically satisfactory, namely, construct, external validity, and reliability (Yin, 2018).

2.5.1 Construct validity

In this work, essential steps were taken to satisfy the construct validity. In Study B, the data came from interviews, internal documents, and technical reports created by the research center for each of the case companies. These documents and interviews were scrutinized in the data analysis process to increase accuracy in the results. Moreover, the results from Study A were discussed with one of the study's participants to ensure that the results were accurate. In Study B, the results were discussed and analyzed together with experts from the research center. Using various data sources (triangulation) and confirmation of results are two critical ways of reaching construct validity, a significant quality measure in case study research (Yin, 2018).

2.5.2 External validity

Each of the studied case companies provided the work with a unique context, thereby supporting the external validity of the results. The external validity, or generalization, ensures that the studies' results are applicable in a broader context than, for instance, a specific manufacturing company or a project. According to Yin (2018), the findings from case studies must be generalizable but accurate enough to be usable for practitioners and create knowledge for the scientific community. Thus, Study A and Study B provided insight from several manufacturers that are contextually dispersed; hence, generalizable findings were attained in this scope. Arguably, to increase the generalization of results, this thesis could have added other methods, such as a broad survey, to confirm the findings further herein. Nonetheless, a total of 18 interviews, 12 manufacturing companies, and one research center across two studies serve as significant contributors to this work's findings, providing much data from various industries and application contexts.

2.5.3 Reliability

In case study research, reliability means that the same results should be attained if the same procedures are applied (Yin, 2018). In this works' studies, the researcher checked off the question in the semi-structured interview guide, confirming that each question was answered irrespective of if the interviewee talked more freely about the topic or just answered the questions directly. In

Study B, the interviews started with the researcher showing the interviewee a standardized implementation process (a five-step process stemming from (Bruch et al., 2015)) for two reasons: to confirm if the case company worked according to a similar implementation process, and this allowed the researcher or interviewee to relate to these phases through the interview to determine when an event took place. By taking the steps described above, the reliability of this work was secured.

3 Frame of reference

This chapter defines key terms, sets the work's context, and provides a foundation for the conducted research. The frame of reference provides and discusses relevant scientific areas that are used to fulfill this work's objective. The main areas presented in this chapter are assembly, implementing technologies, and the implementation of industrial robots in collaborative assembly applications with challenges and enablers.

3.1 Assembly and assembly applications

This thesis takes a process view on manufacturing and its subsumed processes. A process view means that each part cannot be viewed individually but rather as interconnected processes that are strongly affected by one another, forming a whole system of processes. Moreover, the process view envelops manufacturing processes (i.e., forming a product out of raw materials) and the organizational processes (i.e., how humans work and act in the system). For example, in assembly, the individual assembly applications are connected by the overall process for assembly, which, in turn, depends on the preceding parts' production processes. In addition, assembly is affected by organizational processes like working methods and assembly application improvements (Bellgran and Säfsten, 2009).

Assembly is the section of the manufacturing processes where parts are joined together into the intended product. Part joining involves tasks such as adhesive joining, screwing, and riveting, to name a few. The assembly applications, including the consecutive tasks to assemble the product, are often done by humans, as they are highly flexible and capable of assembling complex and fluctuating parts (Cohen et al., 2019; ElMaraghy, 2006). Nevertheless, assembly is a costly part of the manufacturing processes partly because the manual assembly application tasks are challenging to automate, which results in high labor costs (ElMaraghy and ElMaraghy, 2016; Siciliano and Khatib, 2016).

Assembly is highly affected by the continual increase of customizable products. In the last steps of the manufacturing processes, the manufacturing companies add product variants according to customer specifications. Therefore, the assembly applications need to be highly flexible in handling various products. It can, therefore, be increasingly challenging to automate assembly applications because traditional robot applications focus on high volumes of a few products rather than the required low volume of many different or customized products (Siciliano and Khatib, 2016).

Some assembly applications are, however, suitable for automation. For example, in their review of the robot assembly, Cho et al. (1987) identified that robots could assemble parts with various geometries provided sensors can sufficiently adjust for positioning errors. However, parts with complex geometries were problematic to assemble using these early versions of industrial robots, partly because of the slow processing capabilities of the robots. Hence, the industrial robots in collaborative assembly applications with higher processing capabilities can be increasingly suitable for more complex assembly applications (Michalos et al., 2010). Nonetheless, manufacturing companies commonly follow set procedures when implementing equipment in their assembly applications. In this work, manufacturing companies are the user of industrial robots in collaborative assembly applications.

3.2 Implementing technologies

When manufacturing companies implement technologies into their production processes, they often follow structured processes. However, these processes can be context-dependent, e.g., specific to a manufacturing company or a department, and researchers have defined different processes for this act. For example, Baines (2004) defined this effort as a process that included nine consecutive phases from problem identification to full production. Bruch, Rösiö, and Granlund, (2015), on the other hand, identified that manufacturing companies practice a five-phase process when implementing production equipment

Production technologies can be designed at the manufacturing company or as a joint venture with external actors. In addition, the manufacturing companies can buy off-the-shelf production technologies developed elsewhere. Regardless, the manufacturing company needs to install them into their production processes, and they can install the production technology themselves or collaborate with external actors, i.e., technology suppliers or system integrators (Bruch et al., 2015). Nevertheless, new technologies are often specifically challenging to implement (Bruch and Bellgran, 2014).

3.2.1 New technologies

New technologies (such as industrial robots in collaborative assembly applications) have a high degree of newness to manufacturing companies. The degree of newness refers to what degree the technology is new to the manufacturing company. A high degree of newness indicates that the manufacturer must develop a never before tried technical solution. In contrast, the lowest degree of newness is carry-over solutions from known technologies by the manufacturing company (Bruch and Bellgran, 2014). Verworn (2009) showed that manufacturing companies could experience increasingly time-consuming problem-solving when implementing technologies with a high level of newness to the manufacturing company.

In the ’80s and ‘90s, manufacturing companies investigated advanced manufacturing technologies (AMT), which were then new to them. AMT was a significant shift from traditional, highly manual, and CNC-based production to an increasingly flexible, computerized, automated, and robotized production system to increase the manufacturing companies’ competitiveness (Sohal and Singh, 1992). Small and Yasin (1997) advocated that manufacturing companies that implemented new technology faced challenges with identifying the technology’s benefits, evaluating its performance, and adapting the organization to the technology. Moreover, the authors developed a framework for AMT implementation, emphasizing that manufacturing companies could adjust their processes towards the intended technology. These adjustments included adapting their performance evaluations, implementing technology systems on various levels from islands to integrated systems, and improving training, teamwork, and management commitment (Small and Yasin, 1997).

Maghazei and Netland (2017) reviewed the evolution of AMT research over several decades. Their results showed that when AMT was new to the market, the focus was on evaluating the technology, its benefits, and training the workforce. Later, when the technologies were somewhat demystified, the research focused on their implementation and resulting changes in organizations. Thus, organizational factors seem to play a predominant role. To that end, a manufacturing company might need to adapt its process to implement novel technologies, evaluate improvement potential, and introduce training programs for operators (Cardoso et al., 2012). Nevertheless, when a technology is new to a manufacturing company, they can mitigate their technology and implementation challenges via in-process testing (e.g., assembly applications) by focusing on trial and error (Trott and Simms, 2017).

Industrial robots in collaborative assembly applications are a piece of automated assembly equipment that is still new to manufacturers and the market (Villani et al., 2018), thus lacking research on implementing them beneficially. Compared to AMT, industrial robots in collaborative assembly applications are increasingly complex and involve human–robot collaboration (Hentout et al., 2019). However, following Maghazei and Netland's (2017) logic, this indicates that research is starting to investigate its implementation and organizational impact. Recent literature has introduced procedures for implementing industrial robots in collaborative assembly applications, showing that researchers have indeed initiated investigations toward this goal (Djuric et al., 2016; Kopp et al., 2020; Malik and Bilberg, 2017; Simões et al., 2020).

3.3 Implementing industrial robots in collaborative assembly applications

The purpose of this section is to define industrial robots in collaborative assembly applications and their implementation. Then, this section investigates the enablers and challenges when implementing this technology.

3.3.1 Defining industrial robots in collaborative assembly applications

The industrial robots in collaborative assembly applications are developed intentionally to work in a fenceless assembly application near humans (Akella et al., 1999). These robots commonly have a lightweight design, integrated force sensors, and pneumatically maneuvered grippers (Wang et al., 2019), and the robot is often designed to look friendly (Kock et al., 2011). In addition, its software aims to simplify programming (and thereby its implementation) and has various types of safe and slow operating modes to increase the capabilities for flexible and fenceless collaborative assembly applications (Hentout et al., 2019). Since the term cobot or collaborative robot includes a wide range of robots used for service applications, including healthcare robots, rehabilitation robots, and surveillance robots, to name a few (Garcia et al., 2007), it is necessary to limit the scope by adding *industrial* into the definition to clarify its use in the manufacturing industry and, more specifically, assembly applications.

One crucial aspect of industrial robots in collaborative assembly applications is the levels of collaboration, also known as human–robot collaboration. Researchers have presented different definitions of these levels (e.g., Aaltonen et al., 2018; Bauer et al., 2016; De Luca and Flacco, 2012; Wang et al., 2019; Yanco and Drury, 2004), which shows this work needs to define these levels. Thus, this work uses the levels of collaboration proposed by Bauer et al. (2016), namely, coexisting, synchronization, cooperation, and collaboration. Table 3 presents the human–robot collaboration within each level of collaboration, showing that the coexisting level is the least *collaborative,* ending with the collaboration level being the highest.

Table 4 - Levels of collaboration based on Bauer et al. (2016).

Allowed state (Y/N)	Coexisting	Synchronized	Cooperative	Collaboration
Fenceless	Y	Y	Y	Y
Shared workspace	N	Y	Y	Y
Simultaneous workspace presence	N	N	Y	Y
Simultaneous work on object	N	N	N	Y

An early appearance of industrial robots in collaborative assembly applications (then mainly called cobot) was a small weight-assisting robot supporting humans in assembly (Akella et al., 1999). In fact, the first appearance of human–robot collaboration in research is Miyake and Shimizy (1994); they proposed a responsive communication software allowing a virtual robot to mimic human movements. Since then, the research interest in industrial robots in collaborative assembly applications has grown (Hashemi-Petroodi et al., 2020; Hentout et al., 2019).

3.3.2 An implementation process for industrial robots in collaborative assembly applications

The literature has pointed out various ways that could support the definition of an implementation process for industrial robots in collaborative assembly applications. For example, Kopp et al. (2020) conducted a survey identifying significant success factors within a defined process containing the phases, decisions, implementations, and operations. On the other hand, Malik and Bilberg (2017) drew their implementation process from an engineering design perspective, resulting in a process focused on the early implementation phases. Nevertheless, manufacturing companies implementing any production technology commonly follow a standardized process (Baines, 2004; Bruch et al., 2015).

By combining the findings from industrial robots in collaborative assembly applications, implementation research and production equipment implementation research, this work suggests an implementation process (see Figure 6) containing the first three phases. The reasons for focusing on these three phases are that literature has suggested that many challenges exist in these phases (see section 3.3.3), and gaps exist in the literature on how to mitigate the challenges. This work's reviewed studies (see chapters 2 and 4) provided data for these three phases.

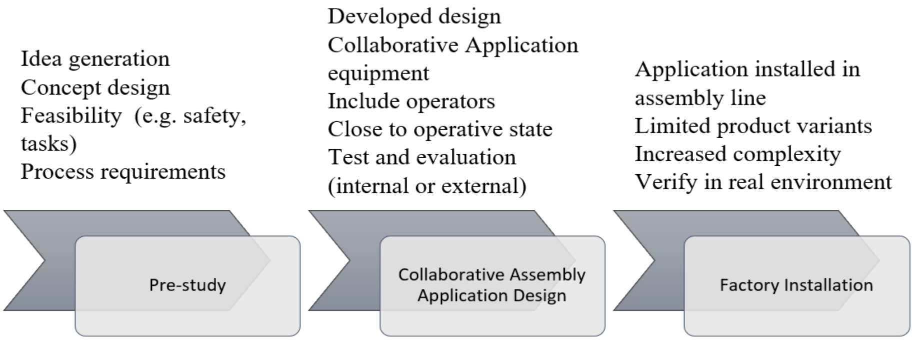

Figure 6 - Literature-based implementation process for industrial robots in collaborative assembly applications

The implementation process phases for industrial robots in collaborative assembly applications are: (1) pre-study, (2) collaborative assembly application design, and (3) factory installation. In the pre-study phase, manufacturing companies aim to identify significant application safety and task planning procedures (Malik and Bilberg, 2017). Correspondingly, they identify assembly application requirements and business needs, develop an application concept, and focus on idea generation (Bruch et al., 2015; Malik and Bilberg, 2017). Moreover, the manufacturing companies investigate the application's feasibility (Kopp et al., 2020).

Manufacturing companies design (or buy) specific industrial robots in collaborative assembly applications equipment in the collaborative assembly application design phase, such as grippers, feeding systems, and safety measures, and include operators in the design effort (Malik and Bilberg, 2017). Specifically, manufacturing companies design an industrial robot in a collaborative assembly application that more closely represents its use in daily operations (Kopp et al., 2020). In this phase, manufacturers commonly test the application either at a system integrator's facilities or in their facilities (Bruch et al., 2015). Testing the application is the last step of the collaborative application design phase, leading to the factory installation phase. The factory installation phase aims to validate the application in the manufacturing companies' assembly applications while continuously increasing complexity. However, they commonly use limitations in product variants and employ simplified tasks to finalize the installation (Bruch et al., 2015; Kopp et al., 2020).

The literature has identified some challenges and enablers when implementing industrial robots in collaborative assembly applications.

3.3.3 Challenges

Manufacturing companies implementing industrial robots in collaborative assembly applications need to follow harmonized standards, realize safety regulations such as the Machine Directive and specific robots (ISO, 2011), and collaborative robot specifications (ISO, 2016). Nonetheless, these standards seem to be challenging to apply to collaborative assembly applications because manufacturing companies need to learn to interpret and apply these standards to an area that is new to them (Bauer et al., 2016; Gualtieri et al., 2021; Hanna et al., 2020; Villani et al., 2018). Moreover, in industrial robot applications, manufacturing companies often employ a system integrator that delivers a robotic solution encompassing safety measures—naturally, the manufacturing companies themselves need to check and approve all safety aspects—universally known by the integrator and manufacturing company (Hentout et al., 2019; Kopp et al., 2020). Also, assessing safety could be essential in the early implementation phases (Malik and Bilberg, 2017) because industrial robots in collaborative assembly application equipment, such as sharp grippers, fixtures, feeding systems, or products, could harm the operator (Gualtieri et al., 2021). Besides adhering to significant harmonized safety standards, the operators working alongside industrial robots in collaborative assembly applications also need to feel safe (Charalambous et al., 2015; Kopp et al., 2020; Zanchettin et al., 2013); a feeling of safety is a new aspect specifically applicable to these collaborative assembly applications because of the fenceless environment.

Manufacturing companies commonly experience implementation challenges with industrial robots in collaborative assembly applications because their knowledge about technical and organizational aspects is limited, i.e., they often have limited domain knowledge (Danneels and Elko, 2001). Concerning organizational aspects, it can be challenging to understand the complexity of manual assembly tasks (Charalambous et al., 2015; Hirata and Yasuoka, 2018), identify ways of working, and for operators to accept working in fenceless collaborative assembly applications (Charalambous et al., 2015). Moreover, limited technical knowledge is a challenge in the early implementation phases (Tatikonda and Rosenthal, 2000), and the benefits of industrial robots in collaborative assembly applications are often unclear at this stage (Kopp et al., 2020).

The industrial robots in collaborative assembly applications have some predominant attributes that manufacturers need to be aware of when implementing them. First, their speed in safe, collaborative applications is often slow, which makes achieving a cost-effective and efficient collaborative assembly application a challenge (Bauer et al., 2016; Kopp et al., 2020; Simões et al., 2020). Second, it is challenging to design the industrial robots in collaborative assembly application equipment (e.g., grippers, feeders, and fixtures) in a way that ensures flexibility (Djuric et al., 2016; Malik and Bilberg, 2017). Finally, using the integrated vision systems can be challenging due to fluctuating part characteristics and the lack of processing power (Zahavi et al., 2020).

3.3.4 Enablers

In this section, three main areas emerged as predominant when implementing industrial robots in collaborative assembly applications: *safety*, *knowledge*, and *attributes*.

Manufacturing companies can mitigate *safety* challenges by implementing the simpler coexisting industrial robots in collaborative assembly applications, thus sidestepping some of the more complex safety issues (Bauer et al., 2016). The literature has suggested that safety should be a significant part of the early phases when implementing industrial robots in collaborative assembly applications (Kopp et al., 2020; Malik and Bilberg, 2017) and that manufacturing companies can collaborate with external actors to gain a more profound knowledge of its safety (Bauer et al., 2016).

In terms of *knowledge*, the literature has pointed out that when a technology is new to the manufacturing company, they can mitigate their challenges by increasing their domain knowledge (Danneels and Elko, 2001). Hence, manufacturing companies could increase their knowledge about industrial robots in collaborative assembly applications by joint training and close collaboration with a system integrator (Charalambous et al., 2015). Furthermore, such collaborations are becoming increasingly important with more complex automated assembly technologies, requiring manufacturing companies and their system integrators working in ecosystems to combine their knowledge (Benitez et al., 2020; Simões et al., 2020; Weyer et al., 2015). Additionally, increasing technical knowledge in collaborative assembly application design includes equipment and robot programming (Bauer et al., 2016; Kopp et al., 2020; Simões et al., 2020). Specifically, knowledge in industrial robot programming is considered an enabling factor when implementing industrial robots in collaborative assembly applications (Kopp et al., 2020). Increasing technology knowledge can also be an enabler for inflating the effectiveness of industrial robots in collaborative assembly applications (Quenehen et al., 2021). Moreover, division of tasks, a significant part of application design, affects its capacity (or productivity) and the level of collaboration, and it is therefore increasingly essential for manufacturing companies to have such knowledge (Shen et al., 2015; Zhang and Fang, 2017).

Increasing *knowledge* in work organizations concerning industrial robots in collaborative assembly applications (Charalambous et al., 2015) and explore their economic benefits are enablers (Charalambous et al., 2015; Kopp et al., 2020). Additionally, a long-term and automation-focused strategy could support the manufacturing companies in their implementation efforts focusing on long-term goals overshadowing the short-term gains and the challenges (Säfsten et al., 2007; Simões et al., 2020; Winroth et al., 2007). Charalambous et al. (2015) invoked a change management perspective identifying that involving operators through the industrial robots in collaborative assembly application implementation efforts can increase their understanding of manual assembly complexity. Furthermore, they found that operators can transfer such knowledge to system integrators and other operators, thus supporting the implementation. Furthermore, involving operators can mitigate the workforce's resistance to industrial robots in collaborative assembly applications (Bauer et al., 2016; Kopp et al., 2020; Simões et al., 2020) and encourage them to support the collaborative assembly application design (Charalambous et al., 2015; Malik and Bilberg, 2017). Therefore, involving operators in the early implementation phases seems significant because, with industrial robots in collaborative assembly applications, the operators need to work in a fenceless environment and feel safe doing so.

Regarding *attributes*, some brands of industrial robots in collaborative assembly applications have the attributes of lightweight design, ease of programming, and portability (Hentout et al., 2019), ensuring that they are safe and flexible. In addition, some brands have integrated vision systems that can support flexibility (Zahavi et al., 2020). Another attribute is that some industrial robots in collaborative assembly applications are designed with a friendly appearance to increase the operators' acceptance (Kock et al., 2011; Zanchettin et al., 2013).

4 Summary of appended papers

This chapter presents the findings from the appended papers. First, Paper I shows the findings from Study A. Second, Papers II and III show the findings from Study B. The results in Papers II and III were based on the multiple-case Study B, which included multiple manufacturers.

4.1 Paper I –Exploring the attributes of industrial robots in collaborative assembly applications

Study A resulted in one paper, Paper I. This interview study with four manufacturers aimed to identify the attributes of industrial robots in collaborative assembly applications as compared to traditional robot applications. Two of the manufacturers in the study had industrial robots in collaborative assembly applications in their assembly, whereas the other two were in the pre-study phase, i.e., they had carried out lab experiments for implementing robots in collaborative assembly applications. Table 5 summarizes the attributes being mapped into three areas: flexibility, safety, and assembly applications.

In the flexibility area, the table shows that industrial robots in collaborative assembly applications can be easy to program and have lightweight designs promoting portability. In traditional robot applications, the application is often inflexible, requiring ample programming. In the safety area, the predominant attributes are that the robots used in collaborative assembly applications are inherently safe, allowing them to be used in a fenceless application, yet the paper indicated uncertainty in some safety assessments. The findings also point out that traditional robot applications are commonly fenced, simplifying safety assessments, yet traditional robot applications still commonly lack inherent safety attributes. Finally, in the assembly application area, Paper I identified that the attributes of industrial robots in collaborative assembly applications commonly are that they can work in close proximity to humans and support them with repetitive and precise tasks. However, the findings also showed that industrial robots in collaborative assembly applications could be slow in a coexisting state.

Table 5 – Attributes of industrial robots in collaborative assembly applications compared to traditional robot applications

Type	Flexibility	Safety	Assembly application
Industrial robots in collaborative assembly applications	Some robot brands easy to program Some robot brands with a lightweight design promote portability	Used in collaborative assembly applications Inherent safety Fluctuating uncertainty in safety assessments	Slow in collaborative assembly application Can work in close proximity to humans and support repetitive and precise tasks
Traditional robot applications	Programing experienced as more demanding Commonly immovable due to fenced application and robust design	Fenced application Inherent safety limited Less uncertainty in the safety assessments because of fenced applications	Are fast in fenced applications Limited, although possible, use in collaborative assembly applications

Paper I contributed to the current body of research by providing insights from the manufacturing industry and mapping the findings to literature-based areas. To practitioners, Paper I provided a list of attributes manufacturers could consider when evaluating industrial robots in collaborative assembly applications.

4.2 Paper II – Challenges when implementing industrial robots in collaborative assembly applications

Paper II identified the critical challenges when implementing industrial robots in collaborative assembly applications. A detailed description of the implementation process phases was presented in chapter 3. In this paper, a literature review resulted in three critical areas when implementing industrial robots in collaborative assembly applications: safety, knowledge, and attributes. Additionally, based on coding procedures, the challenges identified in the data analysis were mapped into each area and the three implementation phases (pre-study, collaborative assembly application design, and factory installation).

Table 6 summarizes the findings from Paper II. The table shows the safety, knowledge, and attribute challenges in the implementation phases. In Paper II, the main findings in the pre-study phase were critical challenges to assessing safety, which are partly due to the lack of operator involvement. In addition, it was a challenge to evaluate the outcome of the pre-study because knowledge was lacking concerning industrial robots in collaborative assembly operations. Finally, in the attribute area, the industrial robots in assembly applications are often slow compared to manual assemblies, leading to limited application scopes in the pre-study. Another attribute challenge was that the integrated vision system, although highly useful, was challenging to use.

Table 6 – Mapping of implementation challenges for industrial robots in collaborative assembly applications

	Area	**Challenges**
Pre-study	Safety	Safety not assessed – for example, safe grippers and tools Operators not participating – leads to an inability to evaluate operator safety aspects
	Knowledge	Lack of knowledge regarding collaborative application equipment such as cameras, grippers and feeders Lack of knowledge concerning how to perform previous manual tasks within collaborative applications Justifying the cost of collaborative application difficult due to slow cycle times Unclear how collaborative applications can be useful in assembly Unclear how to industrialize the collaborative application concept Pre-study scope limited to one product variant – leads to uncertainty when scaling up to multiple variants in later implementation phases
	Attributes	Slow speed compared to manual assembly Difficult to determine the collaborative application scope due to slow cycle times Integrated vision system imperative but challenging to utilize due to parts characteristics
Collaborative Assembly Application Design	Safety	Lack of knowledge about collaborative application safety – leads to extensive application design limitations focused on coexisting level of collaboration. The lack of safety knowledge involves design parameters such as collaborative application programming, the manipulated parts, the grippers, and other application equipment. Operators feeding parts to the collaborative application also subjected to safety risks No internal safety assessment for collaborative applications - leads to an ad-hoc approach
	Knowledge	Lack of skills in collaborative application programming – leads to an extensive learning curve and a challenge to develop collaborative application task allocation.
	Attributes	A trade-off between higher speeds and a slower coexisting application Complex collaborative application programming – leads to limitations on how many product variants can be programmed; thus, flexibility is not thoroughly evaluated
Factory Installation	Safety	Ensuring safety for operators – even those who only need to feed the collaborative application. Increasingly difficult to identify final safety aspects, such as sharp edges and risk of laceration.
	Knowledge	Integrators lack collaborative application knowledge - leads to increased time for installation with ad-hock problem-solving Lack of collaborative application knowledge in assembly and project team – leads to ad-hoc installation Lack of skills in collaborative application programming hinders flexibility Operators can lack the confidence to solve collaborative application stops and cannot feed it correctly Way of working difficult to standardize because no overreaching strategy exist
	Attributes	The 7-axle industrial robot in collaborative assembly applications need an ergonomic approach Extensive assembly station adoptions needed to implement collaborative applications Difficult to reach collaborative application repetitiveness and robustness while increasing flexibility

The main findings of the collaborative assembly application design phase showed that safety became an increasingly difficult task, partly because safety had not been assessed in the pre-study phase. The findings also identified that it was challenging to design safe industrial robots in collaborative assembly applications because of multiple aspects that are not a concern in industrial robot applications. Such aspects encompass the manipulated parts and collaborative assembly application equipment. In the knowledge area, the main challenge was a lack of programming and collaborative assembly application design skills causing time-consuming design efforts. Finally, in the functionality area, flexibility and speed trade-offs were significant challenges.

Lastly, the factory installation phase contained safety challenges for operators feeding parts to the industrial robots in collaborative assembly applications and in finalizing critical safety details. These knowledge challenges showed a lack of knowledge in the workforce concerning industrial robots in collaborative assembly applications, resulting in ad-hoc approaches and a lack of operator confidence. Moreover, one case company found that the system integrator they hired also lacked knowledge about these collaborative assembly applications, leading to increased time for problem-solving. Finally, concerning the attributes, the findings showed a need to make several changes to its design when installing the industrial robots in collaborative assembly applications. Moreover, achieving flexibility (both product and application flexibility) while ensuring robust programming was a significant challenge.

Paper II contributed to the scientific community by mapping the critical challenges in the three implementation phases to the significant areas of safety, knowledge, and attributes. The paper also contributes to filling the gap of what challenges exist when implementing industrial robots in collaborative assembly applications.

4.3 Paper III – Enablers supporting the implementation of industrial robots in collaborative assembly applications

As concluded in Paper II, there are critical challenges when implementing industrial robots in collaborative assembly applications. Thus, Paper III aimed to identify the enablers for such implementations. Paper III also discussed the degree of newness that the industrial robots in collaborative assembly applications had in the study. Additionally, Paper III mapped the enablers to the 7M dimensions.

Paper III presented the industrial robots in collaborative assembly applications in two newness levels, 4 or 3. Those levels are the highest, or newest, levels. Based on the case companies' previous experience with industrial robots in collaborative assembly applications or traditional robot applications, it was possible to map the level of newness as shown in Table 7. For example, the case companies without any traditional robot application experience were mapped on level 4. If the case company had experience with traditional robot applications, they were mapped into level 3. None of the case companies had any previous experience fully implementing industrial robots in collaborative assembly applications, thus not fulfilling the criteria for levels 2 or 1.

Table 7 - Newness levels identified in Study B

Level of Newness	Pre-study	Collaborative assembly application design	Factory installation	Start-up
4.	**C7**			**C8, C2**
3.	**C1, C4**		**C3, C5, C6**	
2.				
1.				

The enablers presented in Paper III were categorized into the 7M dimensions, see Table 8. Manufacturing companies commonly use the 7M dimensions to mitigate problems when implementing technologies into production processes, and the newer the technology is, the longer it takes to implement (Bergman and Klefsjö, 2013). Therefore, the purpose of the 7M dimensions was to map the enablers when implementing industrial robots in collaborative assembly applications. The management dimension shows that allowing financial risk-taking and a long-term strategy instead of focusing on short-term gains are enablers.

Findings in the man dimension emphasized that the operators could have a predominant role when implementing industrial robots in collaborative assembly applications. Moreover, that increasing skills in collaborative assembly application equipment, programming, and safety are enablers. Findings in the method dimension suggested that a focus on a company-owned implementation (instead of hiring a system integrator) is an enabler. Nevertheless, using external actors for specific issues is identified as an enabler. Another enabler is starting with coexisting applications, which results in a more uncomplicated safety and design. Two findings were predominant in the measure dimension that focused on operators being relieved from unergonomic and tedious tasks and on cycle time as the primary evaluation in the pre-study. The cycle time focus was necessary because the high newness of industrial robots in collaborative assembly applications resulted in uncertainties when evaluating the pre-study.

The enablers in the machine dimension mainly focused on the application's attributes, such as limited floor space utilization and portability. Nevertheless, using the friendly appearance of some industrial robots in collaborative assembly applications is an enabler because it could increase the operators' acceptance. In the material dimension, the findings showed that identifying industrial robots in collaborative assembly applications equipment is an enabler, including the potential use of external safety scanners. Moreover, the use of 3D printers could support quick setup and testing because it is conceivably cheaper to do in-house printing than to buy various grippers and fixtures for each collaborative assembly application modification. Finally, in the milieu dimension, the findings suggested that a focus on operators feeling safe as well as being safe was an enabler.

Table 8 – Enablers mapped to 7M dimensions

DIMENSION	ENABLERS			
MANAGEMENT	Allow risk-taking	Focus on non-critical applications to allow trail-and-error in the assembly line	Ensuring long-term strategic fit	
MAN	Operator Confidence	Increase skills: Safety, programming, collaborative application equipment	Utilize prior skills in robot programming	Disseminate operator knowledge
METHOD	Use of external experts in pre-study Increase skills in application design	Internal and external actors in safety assessment Use of movies and 3D-simulation of conceptual design	Focus on company-owned implementation Focus on a coexisting application -simplifies safety and implementation effort	Developing CE-certification skills
MEASURES	Cycle times main focus in pre-study	Number of operators relieved from unergonomic and tedious tasks		
MACHINE	Use *Friendly* appearance Use portability (context-dependent)	Utilizes limited floor space	Utilize integrated vision system	Utilize force sensors and low carrying capacity
MATERIAL	Use of 3D-printers	Identify feeding systems, grippers, fixtures	The use of external safety scanners could support higher speeds	
MILIEU	Focus on that operators should *feel* safe			

In Paper III, the enablers for industrial robots in collaborative assembly applications implementation were mapped to the 7M dimensions and categorization in their level of newness. The enablers in Table 8 can support manufacturing companies as suggested ways to mitigate the challenges in their industrial robots in collaborative assembly applications implementation.

In Paper III, two findings stand out from the current literature. First, using 3D printers in industrial robots in collaborative assembly applications has not been mentioned as an enabler in prior research. Second, before this paper, little attention has been paid to focusing on a company-owned implementation of industrial robots in collaborative assembly applications.

5 Supporting the implementation of Industrial robots in collaborative assembly applications

This chapter presents proposed ways to support the implementation of industrial robots in collaborative assembly applications. In addition, the chapter includes the three first phases in the implementation process, their critical challenges, and their main enablers. These challenges and enablers are divided into the critical areas of safety, knowledge, and attributes. Finally, in the proposed implementation process, this chapter shows which main enablers can mitigate critical challenges in the three implementation phases. Thus, this chapter provides answers to the posed objective and research questions.

5.1 Management and predominant attributes

This section focuses on management and the predominant attributes and provides a context for the forthcoming implementation phases. Notably, the management dimension, presented in Paper III, suggested more strategy-focused enablers that manufacturing companies could consider when implementing industrial robots in collaborative assembly applications. The main enablers within the management dimension are seen as more holistic and thus could not be mapped into a specific implementation phase. The main management enablers are holistic because they can support manufacturing companies in each area (safety, knowledge, and attributes) and all three phases. It is likely that manufacturing companies should consider the main management enablers from the start of the implementation, and thus it is important to identify the main management enablers to support the implementation of industrial robots in collaborative assembly applications.

Paper III indicated that, for industrial robots in collaborative assembly applications, focusing on long-term strategic goals could lead to the acceptance of less efficient applications and could focus more on creating knowledge than, for instance, on short-term financial gains. Bauer et al. (2016) demonstrated that manufacturing companies implementing industrial robots in collaborative assembly applications should build long-term knowledge rather than gain short financial paybacks. Moreover, Paper III suggests that knowledge of industrial robots in collaborative assembly applications could be increased by allowing (financial) risk-taking. Simões et al. (2020) discussed that allowing risk-taking could be significant for its successful implementation.

Finally, Paper III indicated that there should be a focus on non-critical (non-bottleneck application with low throughput impact) applications allowing trial and error in the assembly application. Hence, allowing trial and error can support how well implemented the industrial robots in collaborative assembly applications are in the intended assembly application. In addition, allowing trial-and-error could be a significant enabler when implementing technologies that are new to the manufacturing company (Trott and Simms, 2017). Paper III showed that industrial robots in collaborative assembly applications are often new to the manufacturing company.

To summarize the management enablers, the three main enablers are: focus on long-term strategic goals, allowing financial risk-taking, and focus on non-critical applications to allow trial and error in assembly applications.

The first research question investigates the predominant attributes of industrial robots in collaborative applications. The attributes of the industrial robots in collaborative assembly applications were presented in Paper I, mapping them into three critical areas, namely, flexibility, safety, and assembly application. The predominant attributes in the flexibility area are ease of programming, portability, and lightweight design. Regarding portability, as seen in Paper I and identified by Kock et al. (2011) and Simões et al. (2020), one key attribute for flexibility in industrial robots in collaborative assembly applications can be their portability. The findings show that some robots' inherent safety is a predominant attribute that allows collaborative applications in the safety area. The inherently safe and flexible, yet sometimes slow, attributes of collaborative applications concur with the findings of Hentout et al. (2019). In Paper I, the findings within the safety area show that uncertainties exist in assessing safety for collaborative applications. Finally, the predominant attributes in the assembly application area are that industrial robots in collaborative assembly applications are commonly slow yet can work closely and fencelessly with humans, supporting them in repetitive and precise tasks.

5.2 Pre-study

In the pre-study phase, manufacturing companies aim to identify significant application safety and task planning procedures and identify assembly application requirements and business needs. Moreover, manufacturing companies (or sometimes external actors) develop conceptual industrial robots in collaborative assembly applications. Therefore, the focus of the pre-study is idea generation and investigating feasibility.

5.2.1 Critical challenges

In the pre-study phase, the critical challenge within *safety* was the inability to evaluate operator safety, because operators did not participate in the pre-study. Moreover, safety challenges propagated into later implementation phases because operator safety and safe collaborative application equipment (grippers, fixtures, and feeding systems) were unassessed in the pre-study phase. As a result, the safety of industrial robots in collaborative assembly applications is a significant challenge (e.g., Villani et al., 2018; Bauer et al., 2016).

The findings in Paper II identified several critical challenges within the *knowledge* area. First, there is often a lack of knowledge regarding safe application equipment, thereby preventing extensive evaluations of conceptual design. Second, there is an inability to evaluate the outcome of the pre-study, specifically how these collaborative assembly applications can be useful and financially viable in assembly and how to industrialize the concept stemming from its commonly limited application scope (limited to one product variant) during the pre-study. Third, it is challenging to automate manual tasks into an industrial robot in a collaborative assembly application. Other researchers have recognized the automation of manual assembly tasks as a significant challenge when implementing collaborative assembly applications (Charalambous et al., 2015; Siciliano and Khatib, 2016; Simões et al., 2020).

The findings in Paper II also indicated that the challenging *attributes* are that the industrial robots in collaborative assembly applications are slow (compared to manual assembly). Thereby, it is challenging to evaluate their usefulness in collaborative assembly applications, and the integrated vision system is complex to utilize due to various characteristics of parts.

5.2.2 Main enablers

As many critical challenges propagate into later stages, this work suggests that manufacturing companies spend ample time during the pre-study to mitigate those challenges by considering the main enablers presented below. Specifically, there are several challenges in *knowledge* and *safety* that need to be mitigated.

During the pre-study of industrial robots in collaborative assembly applications, it seems imperative to involve operators because they can contribute to the areas of *safety* and *knowledge*. Thus, as suggested in Paper III, the involved operators could participate in safety events supporting the identification of some safety aspects. Moreover, this work's findings suggest that the operator's involvement could increase knowledge about manual assembly tasks, also suggesting they can support automating manual assembly tasks, thus concurring with the works from Charalambous et al. (2015) and Simões et al. (2020).

The involved operator can provide insights from daily work and, if they have been involved since the pre-study, their experiences working with industrial robots in collaborative assembly applications. This finding concurs with previous literature that has emphasized that involving operators is an integral approach to implementing industrial robots in collaborative assembly applications (Bauer et al., 2016; Charalambous et al., 2015; Kopp et al., 2020; Simões et al., 2020). This work adds that they should be specifically involved in safety-related events as well. Finally, interesting to note is that many challenges occurring in two later implementation phases could have been mitigated by involving operators in the pre-study phase, as is explained further in the sections below.

To mitigate the critical *safety* challenges, the main enablers are to evaluate the safety, to some extent, in the pre-study phase, thus ensuring a proactive approach to safety. To that end, Djuric et al. (2016) argued that safety should proactively evaluate safety aspects specifically related to collaborative assembly applications. In summary, the findings in this work concur with the more proactive approach to safety so that some safety-related challenges can surface, providing an opportunity to mitigate them early.

Regarding *knowledge*, because of the evaluation challenge, this work suggests following the findings in Paper III that a main enabler in the pre-study is focusing on evaluating cycle time as the predominant measure, hopefully simplifying the evaluation of their usefulness. Additionally, Paper III indicated that an enabler to simplify the evaluation was to focus on the number of operators relieved from unergonomic and tedious tasks. This finding concurs with Bauer et al. (2016), namely that it is an enabler to have operators do more cognitive tasks instead of unergonomic and tedious tasks, somewhat supporting the financial justifications. Thus, these two enablers could support the implementation of industrial robots in collaborative assembly applications by mitigating the critical knowledge challenge of evaluating their usefulness and financial aspects.

The findings in Paper III indicated that collaborating with external experts in the pre-study could increase knowledge about industrial robots in collaborative assembly applications. Moreover, as stated in Paper III, the findings show that seeing movies and 3D simulations of the industrial robots in the collaborative assembly applications concept could increase *knowledge*. These movies and 3D simulations can also support the evaluation of the conceptual collaborative assembly applications.

This work also suggests a focus on increasing *knowledge* about collaborative assembly application equipment in this phase (grippers, fixtures, and feeding systems). This enabler identifies what constitutes safe collaborative assembly equipment and what equipment could be usable in the design phase because this can become a critical challenge in later implementation phases.

A critical challenge in the pre-study concerned the integrated vision system; however, this work argues that the integrated vision system could be more useful in the collaborative assembly application design phase because this is where manufacturing companies are more focused on flexibility. Therefore, the flexibility attribute might require the use of an integrated vision system. The flexibility and use of the integrated vision system will be explained further in the next chapter.

5.3 Collaborative assembly application design

In the collaborative assembly application design phase, manufacturing companies design (or buy) collaborative assembly applications equipment, such as safe grippers, fixtures, and feeding systems. Moreover, the goal of this phase is to design an industrial robot in a collaborative assembly application that more closely represents its use in daily operations. This phase also involves verifying the design either at the manufacturing company or a system integrator facility.

5.3.1 Critical challenges

Regarding *safety* in the collaborative assembly application design phase, Paper II suggested that one challenge involved achieving safe programming, safe parts (parts may be sharp), and collaborative application equipment. Moreover, there is often an ad-hoc approach to safety because it is unclear how to conduct the internal safety assessment for industrial robots in collaborative assembly applications. The findings in Paper II suggested that it is a challenge to achieve more than a coexisting level of collaboration because there is a lack of understanding on how to ensure safety, even at the coexisting level. According to Bauer et al. (2016), it can be tough to achieve higher levels of collaboration (beyond the coexisting level) in industrial robots in collaborative assembly applications because there are critical challenges to assessing their safety.

Concerning *knowledge* in the collaborative assembly application design phase, the critical challenges faced are programming the robot (i.e., achieving application flexibility) and designing the industrial robots in collaborative assembly applications (i.e., task allocation, application layout, and equipment). According to the findings in Paper II, programming industrial robots in collaborative assembly applications is a challenge, even for manufacturing companies experienced in robot programming. Furthermore, previous research has identified that robot programming is a significant and time-consuming challenge when designing industrial robots in collaborative assembly applications (Bauer et al., 2016; Kopp et al., 2020).

Paper II presented a critical *attribute* challenge: industrial robots in collaborative assembly applications are slow in their safe, coexisting mode (i.e., speed and separation monitoring). Paper II indicated a trade-off between a faster non-collaborative assembly application and a slower collaborative assembly application at a coexisting level of collaboration. As stated previously, one predominant attribute of industrial robots in collaborative assembly applications is their ease of programming (at least some brands). However, the findings in Paper II suggested that there is a critical challenge to ensure production flexibility, because complex programming leads to an inability to evaluate how many product variants can be programmed. Interestingly, one predominant attribute of industrial robots in collaborative assembly applications is that some brands are easy to program, yet the present work and previous research suggest that manufacturing companies find the programming challenging.

5.3.2 Main enablers

Paper III showed that involving internal and external actors in the *safety* assessment can invoke multiple perspectives about collaborative assembly application safety. This is important, because there is often an ad-hoc approach to safety assessment in the collaborative assembly application design phase. Moreover, Bauer et al. (2016) found that involving multiple actors in the safety assessments can be a benefit.

Bauer et al. (2016) and Paper III reported that an enabling factor for implementing industrial robots in collaborative assembly applications is to start with a coexisting level of collaboration (human and operators in a collaborative assembly application but not working in the same space or on the same objects, see Table 4). Consequently, it is possible to create *knowledge* about the basics of industrial robots in collaborative assembly applications and their design. Furthermore, starting with a coexisting level of collaboration could simplify the *safety* assessments because of the low collaboration level. Interestingly, as presented earlier, manufacturing companies face challenges when designing industrial robots in collaborative assembly applications at a coexisting collaboration level, yet it is also an enabler to start at this level. This somewhat paradoxical finding indicates that even though manufacturing companies face challenges with low levels of collaboration, it is important to start as simple as possible to at least sidestep even more complex collaborative assembly applications so that the manufacturing company can still learn the fundamentals of their *attributes*, *knowledge*, and *safety*.

The findings in Paper III indicated that manufacturing companies could focus on a company-owned collaborative assembly application design phase instead of hiring an external actor, such as a system integrator. A company-owned design promotes *knowledge* creation supporting the design of industrial robots in collaborative assembly applications (Bauer et al., 2016). This work proposes that manufacturing companies use their experience from the company-owned design phase to create knowledge for the factory installation phase.

As shown in Paper III, the involved operator (starting at the pre-study phase) can provide experiences and suggestions in the collaborative assembly application design phase, thus increasing *knowledge* in this phase. To that end, Bauer et al. (2016) reported that involving operators in this design phase could benefit outcomes such as better ergonomics, task allocation, and robot acceptance.

The findings in Paper III suggested that increasing the robot programming skills of engineers could support the design of collaborative assembly applications. In addition, some operators could learn basic programming skills to benefit the design phase and later phases. As discussed by Simões et al. (2020), involvement and education of the workforce is an enabler when implementing industrial robots in collaborative assembly applications. Moreover, Kopp et al. (2020) identified programming skills as critical for successful industrial robots in collaborative assembly applications implementation.

Paper III indicated that, as the industrial robots in collaborative assembly applications reside in an open environment, it seems critical to identify *safe* equipment for the operator. Such equipment encompasses grippers, feeders, and fixtures with which the operator interacts. Previously, this has been less of an issue in traditional robot applications where fences separate operators from the application equipment. Thus, this enabler is important because it is a critical challenge to understanding safe, collaborative equipment in collaborative assembly applications. In previous research, Kopp et al. (2020) identified grippers and application layout as highly important, considering their safe design. Malik and Bilberg (2017) suggested that grippers and feeding systems are critical to the safe design of industrial robots in collaborative assembly applications.

Regarding *attributes*, based on the findings in Paper III, this work suggests that using 3D printers and integrated vision can promote quick application design and testing support flexibility. Nonetheless, as discussed earlier, utilizing the integrated vision system seems to be a challenging task for manufacturing companies, and this work merely suggests that it can be an important *attribute* to utilize. Yet, using integrated vision and 3D printers makes it possible to quickly test multiple collaborative assembly application setups without buying commonly expensive grippers and fixtures externally. In addition, Paper III suggested utilizing the *attributes* (presented in Paper I) of industrial robots in collaborative assembly applications, such as integrated force sensors and low payload (of same brands), to ensure a safe, collaborative assembly application. These enablers seem essential in the collaborative assembly application design phase, as they mitigate the critical challenges in increasing flexibility and assuring safety.

Paper III pointed out that it is possible to utilize safety scanners to allow faster robot speeds because, with safety scanners, the industrial robot stops when an operator enters the collaborative assembly application workspace. However, the collaborative assembly applications' safety area might increase. Thus, the trade-off might be that the assembly application needs more space as the safety area increases compared to the, potentially, slower collaborative assembly application design at a coexisting level of collaboration.

5.4 Factory installation

In the factory installation phase, manufacturing companies aim to install industrial robots in collaborative assembly applications in the assembly line. In this phase, the manufacturing company commonly uses product variant limitations and employs simplified tasks to finalize the installation. The goal of the factory installation phase is to have industrial robots in collaborative assembly applications that very closely represent the daily operations.

5.4.1 Critical challenges

Finally, in the factory installation phase, the findings in Paper II suggest that it is a critical challenge to finalize *safety* in industrial robots in collaborative assembly applications. Specifically, it is challenging to ensure operators are safe when feeding parts to the industrial robot in collaborative assembly applications.

Paper II suggested that ad-hoc industrial robots in collaborative assembly application installations are a critical challenge stemming from a lack of *knowledge* of their installation. Moreover, the one manufacturing company that hired a system integrator found that the integrator also lacked such knowledge. In the factory installation phase, the findings in Paper II indicated a challenge in identifying how to work with industrial robots in collaborative assembly applications. Paper II suggested a critical challenge that the factory installation phase suffered from multiple stops and re-adjustments of the collaborative assembly applications. Moreover, operators lacked confidence and felt uneasy working with the industrial robot in collaborative assembly applications. Previous research has pointed out that it can be challenging for operators to accept working with an industrial robot in collaborative assembly applications (Kopp et al., 2020).

In the factory installation phase, Paper II suggested that one critical challenge concerning the product flexibility *attribute* (i.e., increasingly robust and repetitive collaborative applications), specifically that it is challenging to achieve repetitiveness and robustness while increasing product flexibility, could prevent its flexibility (both product and application flexibility).

5.4.2 Main enablers

This work suggests that involving operators is one main enabler in the pre-study and collaborative assembly application design phases. As seen in the challenges for the factory installation phase, when installing the industrial robots in collaborative assembly applications, the operators lacked confidence and felt uneasy working with these collaborative assembly applications. Thus, it seems imperative that the manufacturers work proactively with this challenge and involve operators starting from the pre-study. Furthermore, by involving operators in the pre-study, it can be possible to disseminate their *knowledge* to other operators and the assembly workforce (e.g., technicians, engineers, managers) in the factory installation phase. Specifically, as suggested in Paper III, one main enabler is to disseminate the involved operator's knowledge to the other operators to increase their confidence in activities such as correcting part feeding and stopping (in case of failure) and re-starting the industrial robots in collaborative assembly applications. Simões et al. (2020) pointed out that operator confidence is critical when working with industrial robots in collaborative assembly applications.

Charalambous et al. (2015) and Paper III showed that the involved operators could collaborate with system integrators to increase the manufacturing company's and the system integrators' *knowledge*. Moreover, the involved operator can be a significant supporter when developing new ways of working with the industrial robots in collaborative assembly applications. Previous research has shown that the involved operators could support the identification of ways of working with industrial robots in collaborative assembly applications (Bauer et al., 2016; Charalambous et al., 2015).

One main enabler surfaced in Paper III, namely that efforts should be made to make the operators *feel* safe in addition to *being* safe when working with collaborative assembly applications. Previous research has found that the operators' feeling of safety is a significant enabler (Kopp et al., 2020; Zanchettin et al., 2013). Thus, this main enabler mitigates the critical challenge wherein operators feel uneasy working with industrial robots in collaborative assembly applications, a challenge that surfaced in the factory installation phase. However, it is unclear precisely how manufacturing companies should increase the operators' feeling of safety, and this work merely points out that this is important.

As presented by Kock et al. (2011), Zanchettin et al. (2013), and Paper III, the industrial robots in collaborative assembly applications are often *attributed* with a friendly look and smooth moments—possibly more predominant in certain brands—which can mitigate the operator's uneasiness and promote a feeling of safety, thus increasing acceptance. Moreover, Paper III suggested that the *attributes* of portability and limited use of floorspace could promote quick testing of the collaborative application in various assembly applications, promoting flexibility. However, portability is highly context-dependent, because the collaborative assembly application likely needs a portability focus from the pre-study, or design phase, and portability might not be possible in every collaborative assembly application.

5.5 A proposed implementation process when implementing industrial robots in collaborative assembly applications

The objective of this research was to support the implementation of industrial robots in collaborative assembly applications. This work has thus focused on the implementation process's three first phases: pre-study, collaborative assembly application design, and factory installation. The literature review and empirical findings suggest that the significant areas were safety, knowledge, and attributes when implementing industrial robots in collaborative assembly applications. Therefore, the proposed implementation process (see Figure 7), presents the main enablers that can mitigate the critical challenges within safety, knowledge, and attributes for the phase's pre-study, collaborative assembly application design, and factory installation.

The proposed implementation process is based on the main enabling factors from Paper III. In Paper III, the enabling factors were mapped into the 7M dimensions because the 7M dimensions serve to provide a manufacturing company with ways to mitigate problems when implementing technology into production processes (Bergman and Klefsjö, 2013).

Furthermore, the proposed implementation process can support managers in clarifying crucial enablers when implementing industrial robots in collaborative assembly applications. The proposed implementation process is likely most useful when industrial robots in collaborative assembly applications are new to the manufacturing company (i.e., a high level of newness. The newness level was important because many uncertainties exist when a technology is new to the manufacturing company (Tatikonda and Rosenthal, 2000).

Concerning the *attribute* area in the pre-study, it is important to mention that the critical challenges within this area (as seen in 5.2.1 and in Paper II) concerned their evaluation. Thus, the main enablers for these critical challenges are within the knowledge area, as they provide ways for manufacturing companies to mitigate the evaluation challenges. Hence, there are no main enablers in the attribute area (the enabling attributes to mitigate challenges) for the pre-study phase in the implementation process. The main enablers instead reside in the knowledge area.

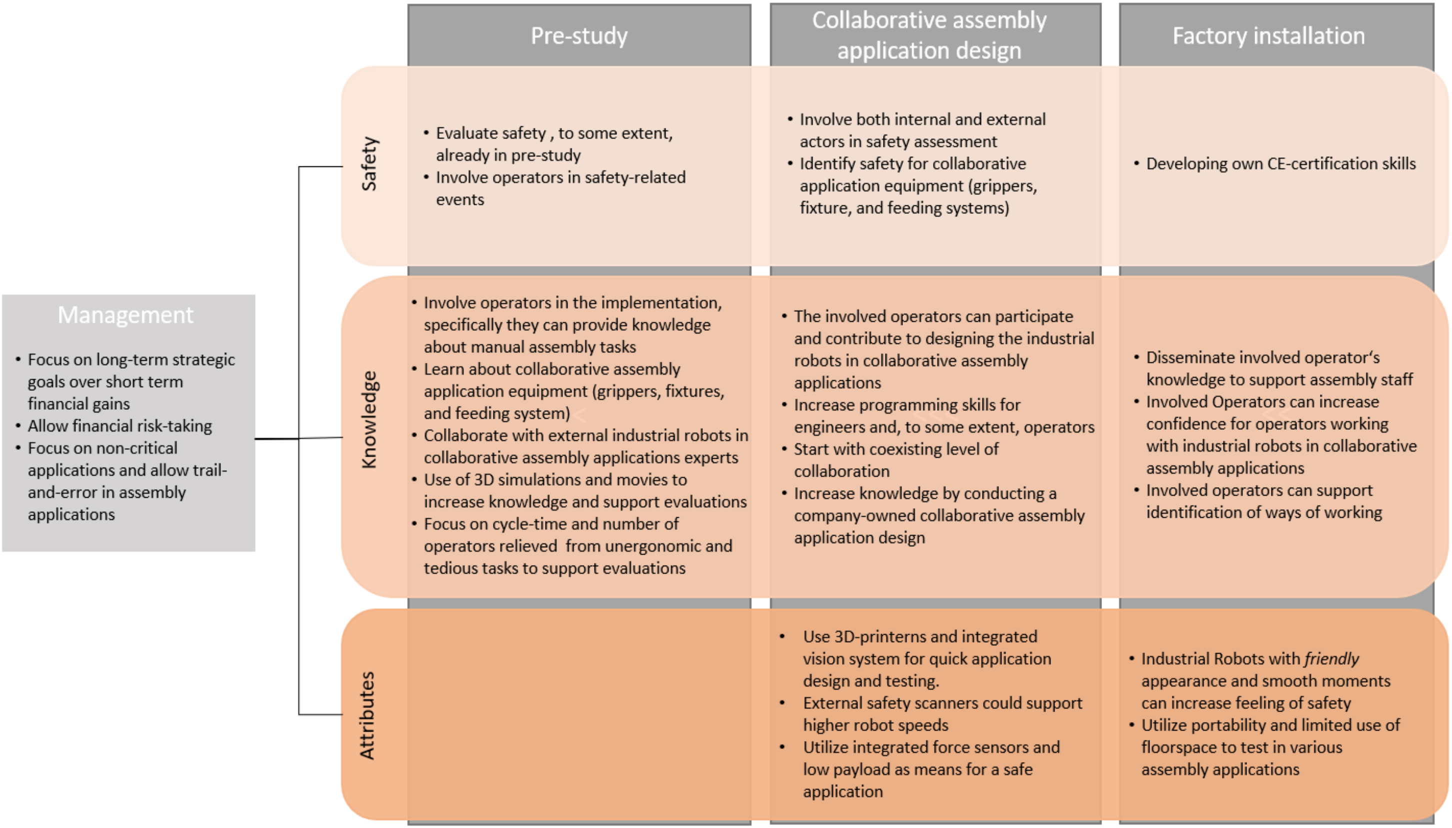

Figure 7 - The main enablers for the three first phases in the implemention process for industrial robots in collaborative assembly applications

6 Discussion, fulfillment of objective, contributions, and future work

This chapter firstly discusses the findings presented in chapter 5 and then presents the fulfillment of the work's objective, its contributions, limitations, and suggestions for future work.

6.1 Discussions

This work's results were derived from a standardized implementation process to ensure relevance to the theory and practitioners, hopefully easing the implementation of industrial robots in collaborative assembly applications, especially when it is a new technology to the manufacturing company.

It is imperative to discuss some results regarding safety presented in chapter 5, because safety surrounding industrial robots in collaborative assembly applications is a scorching topic in research (Bauer et al., 2016; Hashemi-Petroodi et al., 2020; Villani et al., 2018; Wang et al., 2019; Zanchettin et al., 2016). The results in chapter 5 do not submerge into specific aspects of the machine directive or robot standards, because the findings in the conducted studies did not encompass that scope. The work herein suggests the knowledge and approaches to safety assessments and standards that could be important, yet how companies work within these standards and assessments was not investigated.

In chapter 5, much attention was given to involving operators when implementing industrial robots in collaborative assembly applications. Through the course of this work's studies, the importance of involving operators has risen, and previous research has also suggested that such an approach is imperative (Bauer et al., 2016; Charalambous et al., 2015; Kopp et al., 2020; Simões et al., 2020). Naturally, involving operators in technology implementation projects could, for instance, in AMT implementation projects, be an enabler to increase knowledge about the technology and educate the assembly staff. Nevertheless, involving operators seems key, because doing so can mitigate critical challenges such as safety, acceptance, uneasiness, and automating assembly tasks when implementing industrial robots in collaborative assembly applications, specifically.

Regarding safety in the pre-study, this work suggested that safety should be evaluated, to some extent, in the pre-study, whereas Kopp et al. (2020) and Malik and Bilberg (2017) reported that this should happen in later phases. This work suggests a pre-study safety evaluation because the findings in Paper II indicated major safety challenges in the later phases. Naturally, the safety evaluations in the pre-study are limited and dependent on the scope of the conceptual application, but discussions about safety should at least start in this phase so some knowledge about its challenges can surface and possibly be addressed early on.

Finally, flexibility (adaptability, quick layout changes, portability, and ease of implementation) is recognized as one of the key benefits of industrial robots in collaborative assembly applications (ElMaraghy and ElMaraghy, 2016; Hentout et al., 2019; Nolan, 2021). In chapter 5, the results indicate how manufacturing companies can tap into flexibility. The results show that adaptability requires skills in programming, which is one significant focus in the collaborative assembly application design phase. It also shows that quick layout changes can be enabled via 3D printing grippers and fixtures. The results showed that portability was mainly utilized to remove the robot if it stopped allowing an operator to do the tasks, yet purposefully designing for portability could support flexibility. Regarding ease of implementation, it became clear in Paper II that implementing industrial robots in collaborative assembly applications is currently a challenging task. The results in this thesis could serve to ease the three early phases of implementation, hopefully increasing flexibility and thereby the manufacturing companies' competitiveness.

6.2 Fulfillment of objective

This work is based on the problem that there are gaps in the literature concerning the implementation of industrial robots in collaborative assembly applications. Moreover, manufacturing companies strive to increase their assembly flexibility and reduce assembly costs by implementing these industrial robots in collaborative assembly applications, but few have been implemented despite their benefits. Consequently, this work's objective was to *support the implementation of industrial robots in collaborative assembly applications.* To that end, this work presents an implementation process with the main enablers mitigating critical challenges when implementing industrial robots in collaborative assembly applications, as seen in Chapter 5. The implemented processes cover the first three phases: pre-study, collaborative assembly design, and factory installation, and the literature-based areas of safety, knowledge, and attributes. Thus, these findings align with the objective of this thesis.

The theoretical framework reviewed general aspects of industrial robots in collaborative assembly applications, highlighting their attributes and context. Moreover, the theoretical framework provided an overview of the implementation enablers and challenges. Specifically, the framework stressed the areas of safety, knowledge, and attributes when implementing industrial robots in collaborative assembly applications.

Study A was an interview study that investigated the attributes of industrial robots in collaborative assembly applications. Moreover, the study concluded with mapping the attributes into the literature-supported areas of flexibility, safety, and assembly application. Study B was a multiple-case study exploring the challenges and enablers when implementing industrial robots in collaborative assembly applications.

Study B made two main conclusions. Firstly, it identified the challenges in the three first phases when implementing industrial robots in collaborative assembly applications. Furthermore, it mapped the challenges to the theory-based areas of safety, knowledge, and attributes within each phase. Secondly, the study identified the main enablers that could mitigate challenges when implementing industrial robots in collaborative assembly applications.

The enablers were mapped into the 7M dimensions as a way to ensure that a somewhat known frame of reference was used. Moreover, Study B used a newness perspective showing that the results can be useful when collaborative assembly applications are new to the manufacturing companies. In summary, the main enablers serve to mitigate the critical challenges in the pre-study, collaborative assembly application design, and factory installation phases, thus supporting the implementation of industrial robots in collaborative assembly applications. Hence, this chapter shows that this work's objective has been fulfilled.

The studies in this work aimed to answer the three research questions, stated below, contributing to the overall objective.

RQ1: *What are the predominant attributes of industrial robots in collaborative assembly applications compared to traditional robot applications?*

The answer to RQ1 is a list suggesting the attributes of industrial robots in collaborative assembly applications as compared to traditional robot applications within three significant areas: flexibility, safety, and assembly application. Mapping these three areas was important to show a clear relation to the extant literature. In addition, these attributes were used to support the findings in RQ2 and RQ3.

RQ2: *What are the challenges when implementing industrial robots in collaborative assembly applications?*

The answer to RQ2 is a display of critical challenges in the first three phases of the implementation process (pre-study, collaborative assembly application design, and factory installation). Moreover, the critical challenges were mapped within three literature-supported areas: safety, knowledge, and attributes. Finally, these critical challenges supported the overall objective of the research because they showed which enablers were significant.

RQ3: *What are the enablers when implementing industrial robots in collaborative assembly applications?*

The answer to RQ3 is a mapping of the enablers into the 7M dimension, suggesting that they can mitigate the critical challenges faced during the implementation of industrial robots in collaborative assembly applications.

6.3 Research contributions

This work stemmed from gaps identified in academia and industry and aimed to contribute to both these areas. The studies were conducted in a real-world manufacturing setting, and the paralleled theoretical reasoning provided support for these contributions.

6.3.1 Scientific contributions

This work contributes to the scientific community by suggesting ways to fill gaps in the literature. Mainly, this work contributes to filling the gap where ambiguity exists about the challenges and enablers when implementing industrial robots in collaborative assembly applications. The identified enablers within the implementation process serve to fill the gaps by providing the current research with ways to mitigate critical challenges within the areas of safety, knowledge, and attributes. Moreover, using the proposed implementation process as described in section 5.3 contributes to understanding enablers within the 7M dimensions. Therefore, this work contributes to the research area of implementing human–robot collaboration technologies to achieve a cost-reduced flexible assembly. The work also contributes to the operations management area (discussed in chapter 2) with ways to support the implementation of industrial robots in collaborative assembly applications in daily operations when they are new to the manufacturing company.

6.3.2 Practical contributions

This work was partly based on the industry's problem that, despite their benefits, few industrial robots in collaborative assembly applications have been implemented in the manufacturing industry. The proposed implementation process addresses the steps manufacturing companies can take to mitigate their challenges, especially when this technology is new to the manufacturer. Manufacturing companies can expect to support their implementation efforts and clarify some major challenges and uncertainties in the first three phases. Production managers can find the proposed implementation process useful when they strive to increase their flexibility in assembly.

6.4 Limitations of the work

This work focused on interviews and case studies, which means collecting data such as interviews, text, and observations. This method is applicable when carrying out real-life case studies and investigating a social or managerial phenomenon. Nonetheless, these methods can lack the sample size and numerically based facts that other methods can contribute. Therefore, this work is limited to the strengths and weaknesses of the interview and case study methods. Consequently, a survey could have provided a larger sample size supporting the results.

The studies investigated multiple manufacturing companies, indicating that the results could be generalizable. Specifically, the results could be applicable to manufacturing companies in numerous assembly-focused industries. However, the studies lack the deep investigation that a single case study provides. Additionally, there was insufficient data to present results for the last two phases of this work’s findings in chapter 5, namely, the start-up and operations phases, indicating a need for more research.

Lastly, this work consisted of theoretical analysis in human–robot collaboration, assembly, and managing new technology to ensure that the results and contributions are applicable to those research areas. However, this work could have benefited from focusing on recognized management theories to ensure a more accurate contribution to theory.

6.5 Future work

This work suggest multiple directions for future research. First, verifying the implementation process in ongoing industrial robots in collaborative assembly applications implementation projects could provide insights into its usefulness for manufacturing companies. Moreover, this work suggests verifying the implementation process when the industrial robot in collaborative assembly applications has a high level of newness to the manufacturing companies.

Second, the suggested process includes the three initial implementation phases. Therefore, future research could investigate the later stages of implementing industrial robots in collaborative assembly applications (i.e., start-up and operations) and identify the enablers in these phases.

Third, in Study B, the results indicated an approach of company-owned design and installation. However, Study B also found that the manufacturers hired system integrators when implementing traditional robot applications (or other automation equipment). Thus, future research could investigate if the role of the system integrator changes when manufacturing companies implement industrial robots in collaborative assembly applications.

Fourth, the operators working close to the industrial robots in collaborative assembly applications must be safe, yet they also need to *feel* safe. However, this work has not identified what factors should be considered for making the operators *feel* safe when working in a fenceless environment. Identifying the factors that make operators *feel* safe could be an exciting topic for future research.

Fifth, when implementing industrial robots in collaborative assembly applications, manufacturing companies face multiple challenges. The proposed implementation process herein suggests enablers for most of them, yet some challenges remain unanswered. Therefore, this work suggests future research directions to focus on either the collaborative assembly design phase or the factory installation phase to dive deep into these phases.

7 References

AALTONEN, I., SALMI, T. & MARSTIO, I. (2018) ‘Refining levels of collaboration to support the design and evaluation of human-robot interaction in the manufacturing industry’, *Procedia CIRP*. Elsevier B.V., 72, pp. 93–98

AKELLA, P., PESHKIN, M., COLGATE, E., WANNASUPHOPRASIT, W., NAGESH, N., WELLS, J., HOLLAND, S., PEARSON, T. & PEACOCK, B. (1999) ‘Cobots for the automobile assembly line’, *Proceedings of the 1999 IEEE International Conference on Robotics & Automation*, 1, pp. 728–733

BAINES, T. (2004) ‘An integrated process for forming manufacturing technology acquisition decisions’, *International Journal of Operations & Production Management*, 24(5), pp. 447–467

BARRATT, M., CHOI, T. Y. & LI, M. (2011) ‘Qualitative case studies in operations management: Trends, research outcomes, and future research implications’, *Journal of Operations Management*. Elsevier B.V., 29(4), pp. 329–342.

BAUER, W., BENDER, M., BRAUN, M., RALLY, P. & SCHOLTZ, O. (2016) ‘Lightweight robots in manual assembly – best to start simply!’, *Frauenhofer-Institut für Arbeitswirtschaft und Organisation IAO*. Stuttgart

BELLGRAN, M. & SÄFSTEN, K. (2009) *Production development: design and operation of production systems*. New York: Springer

BENITEZ, G. B., AYALA, N. F. & FRANK, A. G. (2020) ‘Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation’, *International Journal of Production Economics*, 228(July 2019).

BERGMAN, B. & KLEFSJÖ, B. (2013) *Quality: from Customer Needs to Customer Satisfaction*. 5:2. Lund, Sweden: Studentlitteratur

BRAUN, V. & CLARKE, V. (2008) ‘Using thematic analysis in psychology Using thematic analysis in psychology’, *Qualitative research in psychology*, 3(2), pp. 77–101

BRUCH, J. & BELLGRAN, M. (2014) ‘Integrated portfolio planning of products and production systems’, *Journal of Manufacturing Technology Management*, 25(2), pp. 155–174

BRUCH, J., RÖSIÖ, C. & GRANLUND, A. (2015) ‘User-supplier collaboration in production equipment development – a lifecycle perspective’, in *22nd International Annual EurOMA Conference EurOMA15*, pp. 1–10

CARDOSO, R. D. R., PINHEIRO DE LIMA, E. & GOUVEA DA COSTA, S. E. (2012) ‘Identifying organizational requirements for the implementation of Advanced Manufacturing Technologies (AMT)’, *Journal of Manufacturing Systems*. The Society of Manufacturing Engineers, 31(3), pp. 367–378

CHARALAMBOUS, G., FLETCHER, S. & WEBB, P. (2015) ‘Identifying the key organisational human factors for introducing human-robot collaboration in industry: an exploratory study’, *International Journal of Advanced Manufacturing Technology*, 81(9–12), pp. 2143–2155

CHO, H. S., WARNECKET, H. J. & GWEONT, D. G. (1987) ‘Robotic assembly: a synthesizing overview’, *Robotica*, 5(1987), pp. 153–165

COHEN, Y., NASERALDIN, H., CHAUDHURI, A. & PILATI, F. (2019) ‘Assembly systems in Industry 4.0 era: a road map to understand Assembly 4.0’, *International Journal of Advanced Manufacturing Technology*, 105(9), pp. 4037–4054.

DANNEELS, E. & ELKO, K. (2001) ‘Product Innovativeness From the Firm’s

Perspective: Its Dimensions and Their Relation with Project Selection and Performance', *Journal of Product Innovation Management: An International Publication of the Product Development & Management Association*, 18(6), pp. 357–373

DJURIC, A. M., URBANIC, R. J. & RICKLI, J. L. (2016) 'A Framework for Collaborative Robot (CoBot) Integration in Advanced Manufacturing Systems', *SAE International Journal of Materials and Manufacturing*, 9(2), pp. 457–464

ELMARAGHY, H. A. (2006) 'Flexible and reconfigurable manufacturing systems paradigms', *Flexible Services and Manufacturing Journal*, 17(4 SPECIAL ISSUE), pp. 261–276.

ELMARAGHY, H. & ELMARAGHY, W. (2016) 'Smart Adaptable Assembly Systems', *Procedia CIRP*, 44, pp. 4–13.

FAST-BERGLUND, Å., PALMKVIST, F., NYQVIST, P., EKERED, S. & ÅKERMAN, M. (2016) 'Evaluating Cobots for Final Assembly', in *Procedia CIRP*. Elsevier B.V., pp. 175–180

FASTH, Å., STAHRE, J. & DENCKER, K. (2010) 'Level of Automation Analysis in Manufacturing Systems', in *Advances in human factors, ergonomics, and safety in manufacturing and service industries,* pp. 233–242

FRYMAN, J. & MATTHIAS, B. (2012) 'Safety of Industrial Robots : From Conventional to Collaborative Applications Summary / Abstract Historical Overview of Industrial Robots and Safety Requirements', *In ROBOTIK 2012; 7th German Conference on Robotics*, (October 2012), pp. 1–5

GARCIA, E., JIMENEZ, M. A., DE SANTOS, P. G. & ARMADA, M. (2007) 'The evolution of robotics research', *IEEE Robotics and Automation Magazine*, 14(1), pp. 90–103

GOPINATH, V., ORE, F., GRAHN, S. & JOHANSEN, K. (2018) 'Safety-Focussed Design of Collaborative Assembly Station with Large Industrial Robots', *Procedia Manufacturing*. Elsevier B.V., 25, pp. 503–510

GUALTIERI, L., RAUCH, E. & VIDONI, R. (2021) 'Emerging research fields in safety and ergonomics in industrial collaborative robotics: A systematic literature review', *Robotics and Computer-Integrated Manufacturing*. Elsevier Ltd, 67(April 2020), p. 101998

HANNA, A., BENGTSSON, K., GÖTVALL, P. L. & EKSTRÖM, M. (2020) 'Towards safe human robot collaboration - Risk assessment of intelligent automation', *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*, 2020-Septe, pp. 424–431

HASHEMI-PETROODI, S. E., THEVENIN, S., KOVALEV, S. & DOLGUI, A. (2020) 'Operations management issues in design and control of hybrid human-robot collaborative manufacturing systems: a survey', *Annual Reviews in Control*. Elsevier Ltd, 49, pp. 264–276.

HENTOUT, A., AOUACHE, M., MAOUDJ, A. & AKLI, I. (2019) 'Human – robot interaction in industrial collaborative robotics : a literature review of the decade 2008 – 2017', *Advanced Robotics*, 1864(33:15–16), pp. 764–799

ISO (2011) 'ISO 10218-1: Robots And Robotic Devices - Safety Requirements For Industrial Robots - Part 1: Robots.'

ISO (2016) *ISO TS 15066:2016 Robots and Robotic devices - Collaborative Robots*. Geneva, Switzerland: Internatinal Organization for Stanrdadization

KARLSSON, C. ED. (2009) *Researching Operations Management*. New York, NY:

Routledge

KOCK, S., VITTOR, T., MATTHIAS, B., JERREGARD, H., KÄLLMAN, M., LUNDBERG, I., MELLANDER, R. & HEDELIND, M. (2011) 'Robot concept for scalable, flexible assembly automation: A technology study on a harmless dual-armed robot', *Proceedings - 2011 IEEE International Symposium on Assembly and Manufacturing, ISAM 2011*, (230902)

KOPP, T., BAUMGARTNER, M. & KINKEL, S. (2020) 'Success factors for introducing industrial human-robot interaction in practice: an empirically driven framework', *International Journal of Advanced Manufacturing Technology*. The International Journal of Advanced Manufacturing Technology, pp. 685–704

DE LUCA, A. & FLACCO, F. (2012) 'Integrated control for pHRI: Collision avoidance, detection, reaction and collaboration', *Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics*. IEEE, pp. 288–295.

MAGHAZEI, O. & NETLAND, T. (2017) 'Implementation of Industry 4 . 0 Technologies : What Can We Learn from the Past ?', in *Advances in Production Management Systems: The Path to Intelligent, Collaborative and Sustainable Manufacturing*, pp. 135–142.

MALIK, A. A. & BILBERG, A. (2017) 'Framework to implement collaborative robots in manual assembly: A lean automation approach', *Annals of DAAAM and Proceedings of the International DAAAM Symposium*, pp. 1151–1160

MATTHIAS, B. (2014) 'Industrial Safety Requirements for Collaborative Robots and Applications'. ERF 2014 Workshop: Workspace Safety in Industrial Robotics: trends, integration, and standards

MAXWELL, J. A. (2013) *Qualitative Research Design*. 3rd edn. Edited by I. Sage Publication. Thousand Oaks

MICHALOS, G., MAKRIS, S., PAPAKOSTAS, N., MOURTZIS, D. & CHRYSSOLOURIS, G. (2010) 'Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach', *CIRP Journal of Manufacturing Science and Technology*. CIRP, 2(2), pp. 81–91

MILES, M. B., HUBERMAN, A. M. & SALDANA, J. (2020) *Qualitative data analysis: a methods sourcebook*. Thousand Oaks: Sage

MIYAKE, Y. & SHIMIZY, H. (1994) 'Mutual entrainment based human-robot communication field', in *Proc. of 3rd. IEEE Int. Workshop on Robot and Human Communication (ROMAN'94), Nagoya, Japan*, pp. 118–123

NOLAN, A. (2021) *Making life easier, richer and healthier: Robots, their future and the roles of public policy*

QUENEHEN, A., POCACHARD, J., KLEMENT, N., ROUCOULES, L. & GIBARU, O. (2021) 'Lean techniques application towards efficient collaborative robot integration: an experimental study', *Production*, 31.

SHEN, Y., REINHART, G. & TSENG, M. M. (2015) 'A design approach for incorporating task coordination for human-robot-coexistence within assembly systems', *9th Annual IEEE International Systems Conference, SysCon 2015 - Proceedings*. IEEE, pp. 426–431

SICILIANO, B. & KHATIB, O. (2016) *Springer handbook of robotics*. 2nd edn, *Springer*. 2nd edn. Berlin Heidelberg

SIMÕES, A. C., SOARES, A. L. & BARROS, A. C. (2020) 'Factors influencing the intention of managers to adopt collaborative robots (cobots) in manufacturing organizations', *Journal of Engineering and Technology Management - JET-M*. Elsevier, 57(March 2019), p. 101574

SMALL, M. H. & YASIN, M. M. (1997) 'Developing a framework for the effective planning and implementation of advanced manufacturing technology', *International Journal of Operations and Production Management*, 17(5), pp. 468–489.

SOHAL, A. S. & SINGH, M. (1992) 'Implementing Advanced Manufacturing Technology: Factors Critical To Sucess', *Logistic s Information Management*, 5(1), pp. 39–46

SÄFSTEN, K. & GUSTAVSSON, M. (2019) *Forskningsmetodik: För Ingenjörer och Andra Problemlösare*. 1:1. Lund: Författarna och Studentlitteratur

SÄFSTEN, K., WINROTH, M. & STAHRE, J. (2007) 'The content and process of automation strategies', *International Journal of Production Economics*, 110(1–2), pp. 25–38.

TATIKONDA, M. V. & ROSENTHAL, S. R. (2000) 'Technology novelty, project complexity, and product development project execution success: A deeper look at task uncertainty in product innovation', *HPAC Heating, Piping, Air Conditioning*, 72(2), pp. 74–87.

TROTT, P. & SIMMS, C. (2017) 'An examination of product innovation in low- and medium-technology industries: Cases from the UK packaged food sector', *Research Policy*. Elsevier B.V., 46(3), pp. 605–623.

VILLANI, V., PINI, F., LEALI, F. & SECCHI, C. (2018) 'Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications', *Mechatronics*. Elsevier, 55(February), pp. 248–266

WANG, L., GAO, R., VÁNCZA, J., KRÜGER, J., WANG, X. V., MAKRIS, S. & CHRYSSOLOURIS, G. (2019) 'Symbiotic human-robot collaborative assembly', *CIRP Annals*. CIRP, 68(2), pp. 701–726

WEYER, S., SCHMITT, M., OHMER, M. & GORECKY, D. (2015) 'Towards industry 4.0 - Standardization as the crucial challenge for highly modular, multi-vendor production systems', *IFAC-PapersOnLine*. Elsevier Ltd., 28(3), pp. 579–584

WILLIAMSON, K. & BOW, A. (2002) *Research methods for students, academics and professionals : information management and systems*. 2nd edn. Wagga Wagga, New South Wales: Centre for Information Studies

WINROTH, M., SÄFSTEN, K. & STAHRE, J. (2007) 'Automation strategies: Existing theory or ad hoc decisions?', *International Journal of Manufacturing Technology and Management*, 11(1), pp. 98–114.

WOJTYNEK, M., LEICHERT, J. & WREDE, S. (2020) 'Assisted Planning and Setup of Collaborative Robot Applications in Modular Production Systems', *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*, 2020-Septe, pp. 387–394

YANCO, H. A. & DRURY, J. (2004) 'Classifying human-robot interaction: An updated taxonomy', *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics*, 3, pp. 2841–2846.

YIN, R. K. (2018) *Case Study Research and Applications: Design and Methods*. Sixth Edit. Thousand Oaks: SAGE Publications, Inc.

ZAHAVI, A., HAERI, S. N., LIYANAGE, D. C., TAMRE, M. & CENTRE, A. S. (2020) 'A Dual-Arm Robot for Collaborative Vision-Based Object Classification', in *2020 17th Biennial Baltic Electronics Conference (BEC)*. Tallinn: IEEE, pp. 1–5

ZANCHETTIN, A. M., BASCETTA, L. & ROCCO, P. (2013) 'Acceptability of robotic manipulators in shared working environments through human-like redundancy resolution', *Applied Ergonomics*. Elsevier Ltd, 44(6), pp. 982–989

ZANCHETTIN, A. M., CERIANI, N. M., MEMBER, S., ROCCO, P., DING, H. & MATTHIAS, B. (2016) 'Safety in Human-Robot Collaborative Manufacturing Environments : Metrics and Control', *IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING*, 13(2), pp. 882–893

ZHANG, J. & FANG, X. (2017) 'Challenges and key technologies in robotic cell layout design and optimization', *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 231(15), pp. 2912–2924