DOCTORAL DISSERTATION

AUGMENTED REALITY SMART GLASSES AS ASSEMBLY OPERATOR SUPPORT
A framework for enabling industrial integration

OSCAR DANIELSSON
Informatics
AUGMENTED REALITY SMART GLASSES AS ASSEMBLY OPERATOR SUPPORT

A framework for enabling industrial integration
DOCTORAL DISSERTATION

AUGMENTED REALITY SMART
GLASSES AS ASSEMBLY OPERATOR
SUPPORT

A framework for enabling industrial integration

OSCAR DANIELSSON
Informatics
Oscar Danielsson, 2022

Title: Augmented reality smart glasses as assembly operator support
A framework for enabling industrial integration

University of Skövde 2022, Sweden
www.his.se

Printer: Stema Specialtryck, Borås

ISBN 978-91-987906-2-7
Dissertation Series, No. 48 (2022)
ABSTRACT

Manufacturing industry is seeing vast improvements in productivity and flexibility as the fourth industrial revolution continues to unfold. However, despite improved computation and automation capacity, there is still a role for operators to play in Industry 4.0, mirrored in the concept of Operator 4.0. Improved productivity and a more competitive global market have contributed to increasing manufacturing complexity, putting greater cognitive demands on operators. A technology that can support operators in this new manufacturing landscape is augmented reality (AR), specifically, head-worn AR smart glasses (ARSG). With ARSG, operators can receive information interactively in real-time, hands-free and overlaying their natural environment. ARSG are an emerging technology that is becoming more mature; there are early examples of their use in manufacturing industry, but ARSG are not yet widespread.

Because ARSG are an emerging technology, there is still uncertainty as to how ARSG can be integrated, like other production equipment, in assembly lines. When current literature was analyzed, it was found that there is a need for more knowledge particularly from the manufacturing engineering perspective of practically integrating ARSG on the industrial shop floor in the long term. This thesis therefore aims to create a framework that supports industry in making strategic and practical decisions about integrating ARSG in production as an assembly operator support tool. The framework is designed to guide industrial decision makers in evaluating the suitability of ARSG as support in an assembly station and, further to offer specific recommendations and rationales for actions to take. It has two main perspectives: the operators using the ARSG and the manufacturing engineers conducting the integration into the production systems. The framework was iteratively developed, using design science combining qualitative and quantitative methods into mixed methods. Three research questions were developed and answered as steps toward creating and evaluating the framework.

The results of the thesis show that ARSG integration should be considered in relation to the investment cost and efficiency gains. For instance, ARSG requires the digitalization of assembly instructions before it can be feasible. If operators are mostly stationary when working and have little need for spatial guidance, there might be cheaper alternatives to ARSG, such as monitors or pick-by-light, that merit prior consideration. The framework has been developed and tested iteratively with industrial experts from different fields, with the initial strawman design based on three literature reviews and previous research.
SAMMANFATTNING

Tillverkningsindustrin ser omfattande förbättringar i produktivitet och flexibilitet när den fjärde industriella revolutionen fortsätter att vecklas ut. Men trots förbättrad beräknings- och automationskapacitet så finns det fortfarande en roll för operatörer i Industri 4.0, vilket speglas i konceptet Operatör 4.0. Ökad produktivitet och mer konkurrens på en global marknad har bidragit till att öka tillverkningens komplexitet och de kognitiva krav som sätts på operatörer. En teknologi som kan stödja operatörer i det nya produktionslandskapet är förstärkt verklighet (engelska ”augmented reality, AR), specifikt den huvudburna varianten i formen av smarta AR glasögon (ARSG). Med ARSG kan operatörer ta emot information interaktivt, i realtid, överlagt på deras verkliga miljö och utan att behöva använda händerna. ARSG är en framväxande teknologi som blir alltmer mogen och det finns tidiga exempel på där de används inom tillverkningsindustrin; men ARSG är ännu inte vitt spridda.

I och med att ARSG är en framväxande teknologi så finns det fortfarande osäkerhet kring hur ARSG kan integreras likt annan produktionsutrustning i monteringslinjer. När den aktuella litteraturen analyserades så identifierades det ett behov av mer kunskap relaterat speciellt till beredningsperspektivet, att praktiskt integrera ARSG på industrigolvet i ett långt perspektiv. Målet med den här avhandlingen är därför att skapa ett ramverk som stödjer industrin i strategiska och praktiska beslut i integrering av ARSG i produktion som ett stödverktyg för monteringsoperatörer. Ramverket är designat för att vägleda industriella beslutsfattare i utvärderingen av lämpligheten av ARSG som stöd i en monteringsstation och att vidare ge specifika rekommendationer och motiveringar för handlingar att utföra. Det har två huvudperspektiv, operatörerna som använder ARSG och beredarna som utför integrationsarbetet in i produktionsystemen. Ramverket utvecklades iterativt genom användande av designvetenskap och kombinerandet av kvalitativa och kvantitative metoder till blandade metoder. Tre forskningsfrågor utvecklades och besvarades som steg mot att skapa och utvärdera ramverket.

Resultaten från avhandlingen visar att ARSG integrering ska övervägas i relation till kostnaden för investeringen och den ökade effektiviteten. Till exempel kräver ARSG digitaliserade instruktioner för att kunna användas. Om operatörer främst är stationära och har litet behov av spatial vägledning så kan det finnas billigare alternativ till ARSG, som bildskärmar eller ”pick-by-light,” som först ska övervägas. Ramverket har utvecklats och testsats iterativt med industriella experter från olika områden och med en initial halmgubbedesign baserad i tre litteraturstudier och tidigare forskning.
Here is my opportunity to formally express my eternal gratitude to all the wonderful individuals around me who gave me the strength to persevere through this challenging enterprise.

My first thank you goes to my supervisors. First, I want to thank Magnus Holm. You have relentlessly provided timely feedback to the very end as well as good travelling company —thank you! I also want to thank Lihui Wang. Your experience and insightful advice have helped me see a more straightforward path forward on more than one occasion. Furthermore, I also want to mention Peter Thorvald, who was my supervisor for a time. I acknowledge your efforts to provide methodological feedback to support me in my publication writing. Lastly, but in no sense least, I would like to express my gratitude to Anna Syberfeldt. You were the one who set all this in motion by luring an unsuspecting research assistant further down the path of academia, and now forever will it dominate my destiny. Throughout my studies, you have found the perfect balance of pushing and supporting me to achieve new heights.

Among the more important lessons I learned at the University of Skövde are those related to the importance of timely and clear communication, academic conventions, and loyalty. I have taken them to heart and will never forget them.

Thank you to all my colleagues at the University of Skövde for your company and support. And a special thank you to fellow Ph.D. student Patrik Gustavsson. I have enjoyed the support, laughs, and of course, the templates! I also want to thank everyone at Volvo Car Corporation for your time and support in this endeavor. Of course, I also especially want to thank my industrial mentor Rodney Lindgren Brewster. Thank you for all your advice and guidance throughout this project. You put the focus on reality in augmented reality!

To all my friends near and far, thank you! Rikard Johansson, thank you for being a good herald to my thesis. Mikael Mide, I hope to see your thesis soon (if you do not tire before). Joakim Kävrestad, you should not always try to stress quality so much.

I also want to express my gratitude to my family. Thank you to my mother, Ulrika Björnberg, for your love, food, and prayers. Of course, I also thank my father, Håkan Danielsson, for your love and help with all kinds of things in both academia and in life. Also, I want to thank my sister, Rebecka Danielsson, for your love and memes. Without you all, I would not have grown up to be who I am today. And thank you too, Violet Zand. I see us as a family now, and your love and ghorme sabzi has given me so much.
joy. I also extend my thanks to Nersi Ettehad, you are a remarkable man and role-model for me.

And for the final acknowledgment, I, of course, want to thank my love in life, Melina Ettehad! When we first met, I had just started this journey, and now we have endured this project together. With your love and support, I have found NRG+++, in order to continue to improve myself, finish these studies, and build a life together with you and PPPHH. In a sense, this thesis is the first chapter in the book of our life together.
PUBLICATIONS

This section lists the publications I have co-authored. Publications with high relevance are those that were directly planned as part of this thesis to answer the research questions. Publications with lower relevance are still relevant to the focus of the thesis but were not planned in direct connection with the thesis.

PUBLICATIONS WITH HIGH RELEVANCE

   I did the main write-up of the paper. The practical work consisted of designing and creating the demonstrator and experiments and performing the experiments. The practical work was a joint effort between myself and another Ph.D. student, Patrik Gustavsson; we each contributed half the work. My part was mainly developing the AR interface and co-developing and performing the experiments. My co-authors were involved throughout the process and provided invaluable guidance and support.

   I did the main write-up of the paper. I chose the method, performed all interviews and observations, and did the analysis. My co-authors were involved throughout the process and provided invaluable guidance and support.

   I did the main write-up of the paper. I chose the method, performed the literature review, and analyzed the papers. My co-authors were involved throughout the process and provided invaluable guidance and support.

   I did the main write-up of the paper. I performed the literature review and analyzed the papers. My co-authors were involved throughout the process and provided invaluable guidance and support.
I did the main write-up of the paper. I performed the literature review and analyzed the papers. My co-authors were involved throughout the process and provided invaluable guidance and support.

I did the main write-up of the paper. I created the initial strawman, implemented the web-based tool, and organized and led the data collection. My co-authors were involved throughout the process and provided guidance and support.

I did the main write-up of the paper. I created the strawman from the previous work, implemented the changes in the web-based tool, and organized and led the data collection. My co-authors were involved throughout the process and provided guidance and support.

---

**PUBLICATIONS WITH LOWER RELEVANCE**

I built the demonstrator, conducted the test, and presented the paper.

I built the demonstrator, conducted the test, and presented the paper.

I developed the augmented reality expert system (ARES).

I developed prototypes 1 and 3.

I upgraded the ARES expert system.

I performed the primary data collection, compiling the list of ARSG and their specifications.
CONTENTS

1. INTRODUCTION ............................................................................................................. 1
   1.1 Background .............................................................................................................. 1
   1.2 Problem description ................................................................................................. 2
       1.2.1 A framework with two perspectives ................................................................. 4
   1.3 Research purpose and aim ....................................................................................... 6
       1.3.1 Research objectives ......................................................................................... 7
       1.3.2 Justification of research objectives ..................................................................... 8
   1.4 Delimitations ........................................................................................................... 9
   1.5 Industrial collaboration ........................................................................................... 9
   1.6 Summary of appended papers ................................................................................ 10
       1.6.1 Paper 1: Assessing instructions in augmented reality for human-robot collaborative assembly by using demonstrators ...................................................... 11
       1.6.2 Paper 2: Operators perspective on augmented reality as a support tool in engine assembly ....................................................................................... 11
       1.6.3 Paper 3: Augmented reality smart glasses for industrial assembly operators: a meta-analysis and categorization ......................................................... 12
       1.6.4 Paper 4: Augmented reality smart glasses for operators in production: Survey of relevant categories for supporting operators .......................................... 12
       1.6.5 Paper 5: Augmented reality smart glasses in industrial assembly: current status and future challenges ................................................................. 12
       1.6.6 Paper 6: (In press) Integration of Augmented Reality Smart Glasses as Assembly Support: A Framework implementation in a Quick Evaluation Tool .................................................................................................................. 12
       1.6.7 Paper 7: Evaluation Framework for Augmented Reality Smart Glasses as Assembly Operator Support: Case Study of Tool Implementation 12
   1.7 Structure of the thesis .............................................................................................. 12

2. THEORETICAL BACKGROUND ................................................................................. 17
   2.1 Industrial shift: From past to Industry 4.0 ............................................................ 17
       2.1.1 Industry 4.0 .................................................................................................... 18
       2.1.2 Applying an Industry 4.0 perspective ............................................................... 19
       2.1.3 Operators in Industry 4.0: Operator 4.0 ......................................................... 20
       2.1.4 Industry 5.0 .................................................................................................... 20
   2.2 Manufacturing engineering ..................................................................................... 20
   2.3 Assembly ................................................................................................................ 21
6.1.2 Main strengths................................................................. 76
6.1.3 Main challenges.............................................................. 76
6.2 The framework: discussion.................................................. 77
  6.2.1 Main strengths.............................................................. 77
  6.2.2 Main challenges.............................................................. 77
  6.2.3 Other frameworks.......................................................... 78
  6.2.4 Generalizability.............................................................. 78
  6.2.5 Feedback.......................................................................... 79
  6.2.6 Further improvements...................................................... 79

7. CONCLUSIONS AND FUTURE WORK.................................... 83
  7.1 Thesis Summary.................................................................... 83
  7.2 Summarized RQ answers..................................................... 83
  7.3 Conclusions......................................................................... 85
  7.4 Scientific contribution......................................................... 85
  7.5 Future work......................................................................... 87

8. REFERENCES........................................................................... 91

9. PUBLICATIONS....................................................................... 101
LIST OF FIGURES

Figure 1.1: Global production volume of ARSG, estimated (2020) and forecasted (2021–2026) (Inside Market Reports, 2020). ................................................................. 3
Figure 1.2: The increasingly complex manufacturing environment creates a need for operator information support. ARSG can be such a support, but how to integrate them is a challenge. ................................................................. 4
Figure 1.3: Overview of the challenges in deciding when ARSG can be both used and enabled within industrial assembly and when other alternatives could be more efficient. ................................................................. 6
Figure 1.4: Overview of the research process and how the RQs (dark) and objectives (light) are interconnected. The gray section is for the prerequisites, blue for RQ 1, red for RQ 2, and purple for RQ 3. ................................................................. 8
Figure 1.5: An overview of how all publications relate to the RQs. ................................. 11
Figure 2.1: An overview of manufacturing processes, as defined by (Groover, 2010), of which assembly (blue) is a subset. ................................................................. 22
Figure 2.2: A taxonomy of AR showing the different ways to implement AR, adapted from Bimber and Raskar (2006), Peddie (2017). ................................................................. 24
Figure 3.1: Three forms of mixed methods research, adapted from Creswell (2014). .... 31
Figure 3.2: The overarching method for developing the framework, based on the combination of the models by Lings and Lundell (2004) and Blandford and Green (2008), as presented by Thorvald et al. (2019). ................................................................. 36
Figure 3.3: Flowchart that shows the objective dependencies. ..................................... 42
Figure 4.1: Step four in the demonstrator assembly task. The test person and the robot collaborate with the help of the interface instructions on the right. ................................. 46
Figure 4.2: The three perspectives (dark and bold) and their respective categories, from paper 3. ........................................................................................................... 47
Figure 4.3: The workflow through which the framework operates through a set of decisions. ......................................................................................................................... 47
Figure 5.1: Overview of the development, testing, and evaluation of the framework. .... 59
Figure 5.2: Screenshot of the first page of the tool implementation of the framework, translated from Swedish. .................................................................................. 61
Figure 5.3: The survey results from (Danielsson et al., 2022). Some numbers are underlined to distinguish, for example 1 and i from 11. .......................................................... 63
LIST OF TABLES

Table 2.1: Four clusters of key enabling technologies and a residual sub-category (technological generics), adapted from Culot et al. (2020)........................ 18
Table 3.1: Graphic overview of the research objectives and of the methods, data, and type and (if mixed methods) sequence of qualitative and quantitative methods used. .......... 32
Table 4.1: Summary of what operators look at in instructions, based on observations of 35 operators................................................................................................. 49
Table 5.1: Composition in groups for first iterative improvement of the framework. ...60
Table 5.2: Summary of the pilot test group participants, their self-estimations, and the framework results............................................................................................................ 61
Table 5.3: Survey statements in the last step of evaluating the web-based tool and related motivations, as reported by Danielsson et al. (2022). The Likert scale ranged from 1 “I disagree” to 5 “I agree.” .......................................................... 62
Table 5.4: Focus group participant affiliations, as presented in Danielsson et al. (2021a). ................................................................................................................................ 64
Table 5.5: The framework in its entirety, translated from Swedish. .......................... 66
Table 6.1: Added questions from all focus groups in paper 6. ................................. 79
ABBREVIATIONS

AGV  Automated guided vehicle
AR   Augmented reality
ARSG Augmented reality smart glasses
BLE  Bluetooth low energy
CAD  Computer-aided design
CSF  Connected smart factory
FOV  Field of view
HRC  Human–robot collaboration
IAR  Industrial augmented reality
ICT  Information and communication technologies
IoT  Internet of things
Mbps Megabits per second
ms   milliseconds
NED  Near-to-the-eye display
RQ   Research question
SAR  Spatial augmented reality
SG   Smart glasses
SIP  Single inspection point
SUS  System usability scale
TCP  Transmission control protocol
TRL  Technology readiness level
UR3  Universal Robots model 3
VCC  Volvo Car Corporation
PREFACE

If you are an industrial reader with a practical focus on evaluating the framework, it is suggested that you start reading at Chapter 5. The framework is presented at the end of Chapter 5.

This thesis was written as part of the defense of my Ph.D. degree. The work within it continues my previous work, described in my dissertation for a Licentiate degree (Danielsson, 2020). Because this thesis continues my licentiate thesis, there are extensive similarities between them. The licentiate thesis laid the theoretical foundation for this thesis, answering research question (RQ) 1 and partially answering RQ 2. This thesis adds the realization and validation of a framework for making strategic decisions regarding augmented reality smart glasses (ARSG). In this thesis, RQ 2 is fully answered and a third RQ is added and answered.

Papers 1–5 were also part of the licentiate thesis and are appended to this doctoral thesis since they are still relevant. The appended papers 6–7 are unique to this thesis.
INTRODUCTION
CHAPTER 1
INTRODUCTION

In this chapter, the background and a description of the problem to be solved are presented. Then the research purpose and aim of the thesis are explained, followed by the research questions (RQs) to be answered and explanations of their relevance. The limitations of the thesis come next, followed by an explanation of the industrial collaboration within this thesis. The appended papers are then summarized and, finally, the thesis structure is outlined.

1.1 BACKGROUND

During the Hannover Fair in 2011, the concept “Industry 4.0” (Industrie 4.0), first coined by the German government, was publicly introduced (Drath and Horch, 2014). The term refers to the prediction of a fourth industrial revolution (Drath and Horch, 2014). There have been other initiatives similar to Industry 4.0, such as the Advanced Manufacturing Partnership in the United States and Factories of the Future in the European Union (Culot et al., 2020), but the first of these initiatives was Industry 4.0. In this thesis, the term “Industry 4.0” is used to refer to this phenomenon.¹

The definitions and possible outcomes of Industry 4.0 vary from source to source, but the most common expectations are improvements in productivity and flexibility leading to mass customization (Culot et al., 2020). A risk of increased unemployment has also been connected to some Industry 4.0 technologies, such as the Internet of things (IoT), artificial intelligence (AI), and robotics (Sanchez, 2019).

There has been a worldwide increase of the number of industrial robots used in manufacturing. The number of industrial robots increased by a compound annual growth rate (CAGR) of 9% between 2015 and 2020 (International Federation of Robotics, 2021). Based on this growth, there could be reason to believe that assembly workers

¹ For further reading, see Chapter 2.
are rapidly becoming redundant. There are concerns that Industry 4.0 will have negative long-term effects on employment, resulting in what is known as technological unemployment (Hungerrland et al., 2015). Similar fears were expressed during the three earlier industrial revolutions as well, but were not realized (Hungerrland et al., 2015, Rainnie and Dean, 2020).

Operators will continue to have an important role in the future since not all assembly work is so routine that operators are easily replaceable (Pfeiffer, 2016). Previous attempts to create fully automated factories have not been successful, so Industry 4.0 focuses on human-centered (semi-)automation (Nelles et al., 2016). Despite concerns that the number of assembly workers needed will continue to decline, humans are still likely to continue to be an integral part of production in the near future, although their role is likely to change. Kotynkova (2017) described three scenarios for how the work situation might change through Industry 4.0: the automation, hybrid, and specialization scenarios. In the automation scenario, systems are directing humans. Operators mostly respond to real-time information, which devalues less-skilled workers. In the hybrid scenario, tasks are monitored and controlled through cooperative and interactive technologies, networked objects, and people. This creates pressure to increase operator flexibility. She finally described the specialization scenario, in which qualified workers maintain a dominant role through the use of cyber–physical systems as decision-making tools (Kotynkova, 2017). The commonality between all three scenarios is their increased complexity. This increased complexity in the operators’ work environment means that they will need to be highly flexible to adapt to this new dynamic work environment (Longo et al., 2017).

1.2 PROBLEM DESCRIPTION

The role of operators and the demands put on them are likely to change in response to Industry 4.0 (Rauch et al., 2020). There will be a need to reduce hierarchies to enable faster decisions, and production will need to be more flexible (Lasi et al., 2014). Operational flexibility needs to be increased, which will necessitate the training and skill development of operators (Salunkhe and Fast-Berglund, 2020). One proposed solution to help operators handle the increased information is to present the information with the aid of augmented reality (AR) and thereby increase operator efficiency (Wang et al., 2016, Enrique et al., 2021). AR is part of a set of Industry 4.0-enabling technologies that can increase operational flexibility (Salunkhe and Fast-Berglund, 2020).

There are three general forms in which AR can be implemented, i.e., the technology can be worn on one’s head, held in one’s hands, or placed in the environment (Bimber and Raskar, 2006, Peddie, 2017). This thesis has limited its focus to head-worn implementations of AR, specifically augmented reality smart glasses (ARSG). ARSG are defined in this thesis as:

---

A wearable device with one or two screens in front of the user’s eyes that can merge virtual information with physical information in the user’s field of view (FOV). (Danielsson et al., 2020a, p. 1299)

---

* A fuller explanation is given in Chapter 2.
With the help of AR, operators can manipulate digital objects naturally while moving around in their environment. Digital information can be seen dynamically in the real world in their FOV and in the correct context. AR has therefore become one of the most promising approaches in facilitating mechanical assembly processes (Wang et al., 2016).

It took a long time before AR managed to find a place in factories (Syberfeldt et al., 2016b, Syberfeldt et al., 2017). This was mainly due to industrial constraints related to ergonomics, color coding, training of operators, and the proposed solutions’ reliability (Uva et al., 2018). There have been recent advances, and there are now examples of AR implementations for operators in manufacturing (Campbell et al., 2019). The field of AR as a whole is predicted to have a CAGR of around 74% up to 2025 (BIS Research, 2018), and ARSG itself is estimated to have a CAGR of 33.7% up to 2026 (Inside Market Reports, 2020). These forecast data are presented in Figure 1.1.

![ARSG global production volume](image)

**Figure 1.1:** Global production volume of ARSG, estimated (2020) and forecasted (2021–2026) (Inside Market Reports, 2020).

As AR has moved from only being possible in laboratory environments to actually being implementable in production, more and more companies are faced with issues arising from the integration process. As described by Masood and Egger (2020), there is still a lack of a global industry-based perspective when it comes to AR implementation in industry. A general challenge that is amplified with Industry 4.0 technologies is that developing technology and implementing technology are two different processes (Kessler et al., 2022). Also, when AR is to be used in specific domains, the characteristics of these domains affect what technological aspects of AR are important and therefore what is feasible. For instance, in tourism AR can integrate GPS-based location analysis and AR in clinical intervention can be related to medical image analysis (Ling, 2017). AR in the manufacturing industry is no exception. For instance, GPS-based localization is not suitable for indoor environments (Chatzopoulos et al., 2017).
and is thus inappropriate for use in manufacturing. It is therefore important to understand what particular limitations and opportunities AR has in the context of industrial use, as illustrated in Figure 1.2.

**Figure 1.2:** The increasingly complex manufacturing environment creates a need for operator information support. ARSG can be such a support, but how to integrate them is a challenge.

### 1.2.1 A FRAMEWORK WITH TWO PERSPECTIVES

There are situations in which ARSG can help operators perform assembly tasks by providing easier access to information (Kloberdanz, 2017). The ARSG market is growing and is projected to continue its growth (Inside Market Reports, 2020), with industrial applications already existing (Campbell et al., 2019). But there are challenges in how to use ARSG within the manufacturing industry. A general problem for Industry 4.0 technology is to have a common language, to enable all components to exchange information (Villagrán et al., 2019). For ARSG to add value, they need to be integrated into the current industrial IT systems (Masood and Egger, 2020). Therefore, besides considering the demand that ARSG should be useful for operators, the actual integration of ARSG into production environments needs to be considered. The word “integration” can be defined as: “The making up or composition of a whole by adding together or combining the separate parts of elements; combination into an integral whole: a making whole or entire” (Oxford English Dictionary, N.D.). “Integration” is used here to indicate that when ARSG are used by operators in a production system, they should become part of the production system. It is one thing to buy a couple of ARSG devices and let operators try them out for a week; it is something entirely different to have ARSG devices in use that add net positive value to operators and can be integrated, maintained, updated, and replaced as easily as the screwdrivers in the operators’ hands.
This thesis, therefore, considers two perspectives, i.e., the operator perspective and the manufacturing engineering perspective, which together form a framework to guide strategic decisions regarding ARSG in industrial assembly. A framework in this context is defined as: “a set of beliefs, ideas or rules that is used as the basis for making judgements, decisions, etc.” (Hornby, 2005, p. 616). The term “framework” is used similarly to how it was used by Berkemeier et al. (2019) to formalize knowledge gathered during their research on ARSG systems for intralogistics services.

As visualized in Figure 1.3, operators (colored blue) are the actors who use ARSG, while the actors from the manufacturing engineering perspective (colored red) are the ones who enable ARSG to be used within an industrial assembly environment. The operator perspective is needed to identify in what cases operators can use ARSG and what demands the operators will put on ARSG as a value-adding assembly support tool. The manufacturing engineering perspective is needed in order to understand how to practically realize ARSG in the assembly workplace. Manufacturing engineers and technicians need to decide how to integrate ARSG so that they work for the operators without disrupting production. They also need to consider robustness over time, as ARSG in production will need maintenance and updating due to attrition and changing needs. This thesis explores the combination of these two perspectives to help decision makers in the manufacturing industry decide when ARSG could be suitable, what to consider in these cases, and the cases in which alternatives to ARSG would be more suitable.
Figure 1.3: Overview of the challenges in deciding when ARSG can be both used and enabled within industrial assembly and when other alternatives could be more efficient.

1.3 RESEARCH PURPOSE AND AIM

The purpose of this thesis is to improve our understanding of the challenges encountered in the process of integrating ARSG into a production system as operator support. It aims to achieve this purpose by developing and evaluating a framework. This framework should support the manufacturing industry in evaluating an assembly station, first, to estimate how suitable ARSG are to support operators and, second, to provide practical guidance about what to consider when integrating ARSG as a support tool in that station. Three RQs were formulated to guide the work in this thesis to achieve this goal.

**RQ 1:** What do operators require in an ARSG-based interface and system so that it supports them in industrial assembly?

If ARSG does not help operators improve their work in a specific case, there is no point in investing in ARSG for operators there. The first question, therefore, focuses on the operator perspective as regards ARSG. The answer to this question will clarify what functionality operators need in order to use ARSG efficiently. This information can
then provide specifications for ARSG to meet the operators’ needs and help determine what functionalities ARSG should support.

**RQ 2:** What do manufacturing engineers and technicians need in ARSG so that the technology can be integrated into, maintained, and updated in a production system?

If it is not feasible to integrate ARSG into a production system, it does not matter how much value they could add to operators. The second question therefore focuses on the enablers of the technology and their needs. To integrate ARSG into a production system “like any other production equipment,” many practical issues need to be known and considered, such as how information can be sent to and from ARSG. Are there any ARSG related risks or work hazards to consider? Answering this question will indicate the limits to and possibilities of integrating ARSG in production systems, setting boundaries on the capacity in which ARSG can be used for assembly on an industrial shop floor.

**RQ 3:** When and how can the operators’, manufacturing engineers’, and technicians’ needs for ARSG be met?

Since both perspectives explored in RQ 1 and RQ 2 are different and relevant, whether and how they can be simultaneously addressed must be investigated. By engaging industrial experts in developing and evaluating a framework, we can explore how industry can be supported in strategic decisions regarding ARSG integration into production as an assembly operator support tool.

### 1.3.1 RESEARCH OBJECTIVES

The RQs have been divided into a set of objectives to ensure that they are answered sufficiently and that the aims of the thesis are achieved. Figure 1.4 presents a graphic overview of how the RQs and their objectives are interconnected. In summary, the prerequisites must be achieved first to ensure that the ensuing RQs are worth pursuing. Then RQ 1 and RQ 2 can be addressed in parallel, as both perspectives are explored. Finally, RQ 3 can be addressed once the data for RQ 1 and RQ 2 are gathered.

Prerequisite: Is the thesis relevant to industrial partners and novel for the scientific community?

- P.1. Ensure relevance and feasibility for industrial partners at the management level.
- P.2. Conduct a literature review of ARSG in manufacturing.

**RQ 1:** What do operators require in an ARSG-based interface and system so that it supports them in industrial assembly?

1.1. Conduct a literature review of ARSG in manufacturing from an operator perspective.

1.2. Ascertain whether operators are willing to work with ARSG.

1.3. Identify operators’ needs in information systems.

**RQ 2:** What do manufacturing engineers and technicians need in ARSG so that the technology can be integrated into, maintained, and updated in a production system?

2.1. Conduct a literature review of ARSG in manufacturing from a manufacturing engineering and technical perspective.

2.2. Gather experience from manufacturing engineers and technicians about relevant challenges in implementation, updating, and maintenance.

**RQ 3:** When and how can the operators’, manufacturing engineers’, and technicians’ needs for ARSG be met?
3.1. Combine the data gathered from RQ 1 and RQ 2.
3.2. Synthesize these data into a framework.
3.3. Evaluate the practical usefulness of the framework for industry in making strategic decisions about ARSG.

![Figure 1.4](image)

**Figure 1.4:** Overview of the research process and how the RQs (dark) and objectives (light) are interconnected. The gray section is for the prerequisites, blue for RQ 1, red for RQ 2, and purple for RQ 3.

### 1.3.2 JUSTIFICATION OF RESEARCH OBJECTIVES

Here the relevance of each research objective is justified. By justifying each objective of each RQ, the RQs will be satisfactorily answered.

**P.1.:** To the objective of ensuring that the thesis research is feasible and that its results will be relevant to the industrial partner is a prerequisite before advancing to the other objectives.

**P.2.:** This objective explores previous work within the research area, establishing a theoretical foundation on which to ensure scientific novelty and a solid understanding of the research area.

**1.1.:** Through this objective, the previous theoretical foundation is expanded to better understand the current feasibility and challenges regarding the operator perspective on ARSG. It thereby establishes a theoretical foundation for the operator perspective of the framework.

**1.2.:** Operators need to be willing to work with ARSG to do so efficiently. Through this objective, the research resolves whether ARSG can be accepted by the intended end-users, validating the premise of the thesis.

**1.3.:** This objective concerns the fact that operators will use ARSG to access information more efficiently. Through this objective, a baseline is established regarding how operators currently interact with information. It also provides an understanding of what information interactions are suitable for transfer to ARSG.
2.1.: This literature review fosters a theoretical understanding of the perspective of those who are to integrate and maintain ARSG in production. This objective is essential in order to understand technological maturity and the manufacturing engineering processes related to integrating, updating, and maintaining production tools.

2.2.: This objective complements the first objective through the practical perspective of manufacturing engineers and technicians regarding introducing new technology in a production system so that it can be taken into account in the framework.

3.1.: RQs1 and 2 provide two complementary perspectives on the framework. In this objective, the data gathered when researching those questions are structured, representing a first step towards synthesizing the information into a framework.

3.2.: The purpose of this objective is to integrate the two previous research questions into a cohesive whole. Both perspectives should be integrated in the framework, which should provide enough support to enable decision-makers to make strategic decisions regarding ARSG being used as an operator support tool in assembly.

3.3.: The framework synthesized in objective 3.2 must be validated to ensure its practical usability. Decision makers must be able to use it to gather information on the suitability of ARSG in their work situation.

1.4 DELIMITATIONS

ARSG, manufacturing engineering, and operator support are all complex areas of research and practice in and of themselves. It has therefore been necessary to delimit the scope of this thesis. The framework focuses on ARSG as operator support in industrial assembly. There are other relevant areas where ARSG can provide value, such as logistics and maintenance, but these perspectives are not part of the framework.

Other aspects that could have been relevant to the framework have not been included due to resource constraints; these include financial, legal, and disability aspects.

A term closely connected to AR in industry is industrial AR (IAR) (Campbell et al., 2019, Fraga-Lamas et al., 2018, Quandt et al., 2018). This term is acknowledged, and while it could be argued that IAR would be a more precise and more applicable term, the broader term AR is favored and used throughout the thesis. Another term sometimes used instead of AR is mixed reality (MR), for instance when Microsoft introduced their HoloLens device as an MR rather than AR device (Berkemeier et al., 2019). As Berkemeier et al. (2019) noted, this definition of MR has undermined the long-established mixed reality continuum of Milgram and Kishino (1994), causing communication problems. This new meaning of MR is not recognized in this thesis.

The framework’s focus is on supporting practitioners in industry with little to no experience of ARSG and who work on operator support in assembly. The framework provides an evaluation of their specific case. It estimates how likely it is that ARSG will be a suitable alternative and what to consider when gathering information and making a purchasing decision. There are no limitations as to the assembly industry from which the case for the framework can be chosen.

1.5 INDUSTRIAL COLLABORATION

This thesis research has been developed in close collaboration with Volvo Car Corporation (VCC), which is the industrial partner for this thesis. Their interest in this research lies in the potential to create a more attractive and ergonomic workplace that is also more capable of accommodating varying volumes and tasks. VCC has identified
AR as one technology that shows potential for VCC in different areas (Volvo Cars Media Relations, 2019). More specifically, the results of this thesis have the potential to improve decision making and the integration of operator support through ARSG, which can promote flexible and collaborative production, reduced adaptation time when introducing new products or variants, and an increased ability to handle rejects. Two of VCC’s core values, technological advance and human well-being, are well aligned with ARSG and the focus of this thesis, which can enhance worker efficiency. VCC, being a commercial actor, has a need to consider profitability to a larger extent than academia needs to. Therefore, there always lies a risk that research with a commercial partner slides into the area of commissioned research. Several factors have been in place to mitigate this risk. First, VCC has previous experience working with academia, which provide some insight in the goals of academia. They have their own PhD program (Volvo Cars, 2022) and collaborate with several universities (Billing, 2022, Brolin, 2020, Chalmers, 2021). Second, there have been four academic supervisors connected to this Ph.D. research project, who have ensured that the focus has continually been primarily to generate new general knowledge. And third, as is presented in Chapter 3, by evaluating the applicability of design science it was motivated how the research in this thesis contributes and disseminates new knowledge.

The collaboration has been an active partnership benefitting both partners. VCC has provided an industrial mentor who has given practical advice, administered access to strategic resources, and given valuable insights into the focus of and challenges facing VCC and industry at large. Strategic resources include facilities, equipment, and several staff members who have participated in discussions and research. My contribution to VCC has been disseminating the current state of research in the field of the thesis and the interim research results to VCC, internally and externally.

1.6 SUMMARY OF APPENDED PAPERS

In this section, the publications that are highly relevant to this thesis are briefly summarized in chronological order. Figure 1.5 provides an overview of how both the low and high relevance publications are related to the resulting framework. The lower relevance publications are within the topic of the thesis but not created in relation to the RQs so they are not further specified here. Their contribution is further discussed in Chapter 6.
1.6.1 PAPER 1: ASSESSING INSTRUCTIONS IN AUGMENTED REALITY FOR HUMAN-ROBOT COLLABORATIVE ASSEMBLY BY USING DEMONSTRATORS

The first paper created a demonstrator to determine whether demonstrators can be used as a testbed for AR assembly instructions. The demonstrator investigated whether an AR-based interface can guide test persons through a simulated human–robot collaborative assembly process. The results showed this could be done but that instructions need to be more precise and that future tests should be done in a more controlled environment. The paper relates to the first objective of the prerequisite.

1.6.2 PAPER 2: OPERATORS PERSPECTIVE ON AUGMENTED REALITY AS A SUPPORT TOOL IN ENGINE ASSEMBLY

The second paper investigated the operators’ perspective on assembly instructions. Operators’ interactions with instructions were observed during assembly. The operators were also interviewed to determine, further, how they interact with instructions and their views of how instructions could better support them. Through the observations, the most common instructions that operators looked at during assembly were identified. The interviews then gave deeper insights into how operators would prefer to work and interact compared with how they currently do. ARSG was described to the operators as a possible support tool during the interviews, and 21 out of 28 operators clearly expressed a positive view of using ARSG, which shows a high acceptance of the technology. The paper relates to the second and third objectives of RQ 1.
1.6.3 PAPER 3: AUGMENTED REALITY SMART GLASSES FOR INDUSTRIAL ASSEMBLY OPERATORS: A META-ANALYSIS AND CATEGORIZATION

The third paper performed a structured literature review of other literature reviews of AR in the manufacturing industry in the last five years. We reviewed the seven identified papers by summarizing and analyzing all keywords, thematic fields, and similar categorizations to identify those related to operators, assembly support, and ARSG. Thirteen subcategories were defined from the perspectives of operators, manufacturing engineering, and technological maturity. The paper relates to the second objective of the prerequisite.

1.6.4 PAPER 4: AUGMENTED REALITY SMART GLASSES FOR OPERATORS IN PRODUCTION: SURVEY OF RELEVANT CATEGORIES FOR SUPPORTING OPERATORS

The fourth paper of this thesis is a literature review that presents a deeper analysis of the operator perspective on ARSG and the related categories identified in the third paper. The findings are summarized in a table showing the current status of and future challenges facing each category. The paper relates to the first objective of RQ 1.

1.6.5 PAPER 5: AUGMENTED REALITY SMART GLASSES IN INDUSTRIAL ASSEMBLY: CURRENT STATUS AND FUTURE CHALLENGES

The fifth paper of this thesis is a literature review that presents a deeper analysis of the two perspectives and related categories that paper 4 did not cover: manufacturing engineering and technological maturity. The findings are summarized in a table showing the current status of and future challenges facing each category. The paper relates to the first objective of RQ 2.

1.6.6 PAPER 6: (IN PRESS) INTEGRATION OF AUGMENTED REALITY SMART GLASSES AS ASSEMBLY SUPPORT: A FRAMEWORK IMPLEMENTATION IN A QUICK EVALUATION TOOL

The sixth paper presents the first version of the framework, implemented as an online tool. The results pertaining to the previous objectives were combined into a strawman version of the framework, iteratively improved through expert input, and evaluated through an online survey. The paper relates to the second objective of RQ 2 and all objectives of RQ 3.

1.6.7 PAPER 7: EVALUATION FRAMEWORK FOR AUGMENTED REALITY SMART GLASSES AS ASSEMBLY OPERATOR SUPPORT: CASE STUDY OF TOOL IMPLEMENTATION

The seventh paper presents the final version of the framework, implemented as an online tool, just as in paper 6. A new strawman was created based on the first version of the framework and the feedback it received, combined with the knowledge and experience gathered in the previous objectives. This strawman was then improved through focus groups and evaluated through three industrial case studies. The paper relates to the second objective of RQ 2 and all objectives of RQ 3.

1.7 STRUCTURE OF THE THESIS

In Chapter 2, the theoretical background to the field and the state of current research are presented in detail. This is followed, in Chapter 3, with the philosophical paradigm on which this research is based and the methodology used. Chapter 4 presents the
basic research for the framework. Chapter 5 presents the framework in its entirety and how it was developed and evaluated. Chapter 6 provides a discussion of the results presented in this thesis and of the Ph.D. research project as a whole. Chapter 7 summarizes the thesis and the RQs it set out to answer, presents the conclusions that have been drawn, and identifies possible future work.
THEORETICAL BACKGROUND
CHAPTER 2
THEORETICAL BACKGROUND

Augmented reality can be a key technology for improving the transfer of information from the digital world to the physical world of the operator. (Zolotová et al., 2020, Augmented operator - operator uses augmented reality section, para. 1)

In this chapter, the theoretical background to this thesis is presented; the central theoretical concepts are defined, and the current state of research is summarized. Papers 3–5 give a deeper analysis of the current state and future challenges in relation to the operator, manufacturing engineering, and technological maturity perspectives. First, the industrial shift that is often referred to as Industry 4.0 is explained, as is the operators’ role within it. Manufacturing engineering is then defined and delimited to what is relevant to this thesis. This is followed by similarly defining and delimiting assembly. Finally, the topic of AR is presented and the subtopic of ARSG is further explored.

2.1 INDUSTRIAL SHIFT: FROM PAST TO INDUSTRY 4.0
A common view is that there have been three major industrial revolutions. It is also widely believed that a fourth revolution is currently ongoing. These four industrial revolutions have been summarily explained by Rojko (2017), whose explanations are briefly reproduced here. The first industrial revolution occurred during the 19th century and was characterized by mechanization and mechanical power generation. At the start of the 20th century, the second industrial revolution came with industrialization and mass production, made possible by electrification. The third industrial revolution started in the 1960s when automation and microelectronics were introduced, and industry was digitalized. The fourth industrial revolution is currently happening, triggered by the development of information and communication technologies (ICTs). The “smart” automation of cyber–physical systems (CPS), which have decentralized control and advanced connectivity through the IoT, forms the technological basis of this revolution. This technology makes it possible to reorganize classical hierarchical automation systems so that they become self-organizing cyber–physical production systems, enabling flexible mass customizable production and flexible production
quantities (Rojko, 2017). CPS are generally defined as having two subsystems: a physical subsystem containing the physical processes and a computational subsystem containing the computational and networking processes (Legatiuk et al., 2017). The fourth industrial revolution is connected to the strategic initiative Industry 4.0, initiated by the German government (Rojko, 2017).

The first public presentation of Industry 4.0 and its basic concept was during the Hannover Fair in 2011, and it has become known worldwide since then (Rojko, 2017). Industry 4.0 was the first initiative connected to the fourth industrial revolution (Rojko, 2017). It inspired other similar initiatives, including the Industrial Internet in North America (Annunziata and Evans, 2012, Rojko, 2017), Industrie du future in France (French Government, 2015, Rojko, 2017), Made in China 2025 in China (Rojko, 2017, Wübbeke et al., 2016), and Made in Sweden 2030 in Sweden (Teknikföretagen, 2015). The coming decade will likely introduce radically different approaches to how products will be manufactured, given the technological developments and numerous initiatives globally. Culot et al. (2020) described the term “Industry 4.0” as prevalent; as the first initiative, it is the chosen term for this thesis.

2.1.1 INDUSTRY 4.0

Industry 4.0 has evolved significantly since its initial conceptualization, which has led to several ambiguities (Culot et al., 2020). To reduce this ambiguity, Culot et al. (2020) performed a structured literature review of Industry 4.0 that mapped and analyzed how to define the concept. Their findings can be summarized as follows: Industry 4.0 has evolved. Initially, Industry 4.0 only described the impact of emerging technologies within manufacturing. This range has now expanded to also encompass several other sectors, such as consumers and society at large. They identified key enabling technologies for Industry 4.0 addressed in the current literature, and categorized them into four main clusters (and a residual sub-category, “technological generics”): physical/digital interface technologies, network technologies, data processing technologies, and digital–physical process technologies, as seen in Table 2.1. They categorized AR under visualization technologies, within the physical/digital interface technologies cluster. Posada et al. (2015) identified visual computing as another term both related to visualization and relevant to Industry 4.0. Visual computing includes technologies that process or generate visual content or visual information, and AR is one such technology (Segura et al., 2020). AR can therefore be seen as part of Industry 4.0. More specifically, AR, as part of visual computing, is a technology that is relevant as support for operators in Industry 4.0, connected to the term “Operator 4.0” (see section 2.1.3) (Segura et al., 2020).

Table 2.1: Four clusters of key enabling technologies and a residual sub-category (technological generics), adapted from Culot et al. (2020).

<table>
<thead>
<tr>
<th>Physical/digital interface</th>
<th>Network</th>
<th>Data processing</th>
<th>Digital/physical process</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internet of things</td>
<td>Cloud computing</td>
<td>Simulation and modeling</td>
<td>3D printing</td>
<td>Technological generics</td>
</tr>
<tr>
<td>Cyber–physical systems</td>
<td>Interoperability and cybersecurity solutions</td>
<td>Machine learning and artificial intelligence</td>
<td>Advanced robotics</td>
<td></td>
</tr>
<tr>
<td>Visualization technologies</td>
<td>Blockchain technology</td>
<td>Big data analytics</td>
<td>New materials</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Energy management solutions</td>
<td></td>
</tr>
</tbody>
</table>
2.1.2 APPLYING AN INDUSTRY 4.0 PERSPECTIVE

Culot et al. (2020) believe that the primary challenge for the scientific community regarding Industry 4.0 is methodology. Their study also identified three implications that scholars, policymakers, and the business community should align their efforts towards. The first implication is that Industry 4.0 requires a context-specific approach. This means that the context of the specific country, industry, or company should drive what is focused on. The second implication is that Industry 4.0 needs a multi-disciplinary approach since its scope extends outside industry. The third implication is that the technological landscape of Industry 4.0 is still in flux, so, for instance, lists of key enabling technologies often lack more recent developments.

In line with the first implication, this thesis focuses on the technological context of visualization technologies within the physical/digital interface cluster. The national context is Sweden, and this thesis is aligned with three out of six key areas of strengthening production in Sweden in 2023 identified in Teknikföretagen (2015). The key area with which this thesis is most aligned regarding the operator perspective is “4. Human-centered production systems,” specifically that “future production systems are highly complex and have [the] capability to adapt to changes” (Teknikföretagen, 2015, p. 11). In describing this key area, it is argued that traditional production work will evolve into more complex work requiring skills such as collaboration, expertise, and practical problem solving. ICT tools that support operators are one proposed solution. The thesis’ context is also partly aligned with key area “2. Flexible manufacturing processes,” which are, in turn, interconnected with the fourth key area. The increased diversity and complexity of production that strengthening the second key area will lead to cannot be realized without increased skill among operators. The third key area, “3. Virtual production development and simulation,” is closely related to the manufacturing engineering perspective in this thesis. In this key area, there is a need for information management to support processes of product and process development as well as the testing of new industrial development. The framework of this thesis is implemented as a tool to support both integration and strategic decisions regarding ARSG as an operator support tool in production.

As regards the second implication, this thesis has two main perspectives, operators and manufacturing engineers and technicians. Several aspects of this research are multi-disciplinary. The technological maturity of ARSG affects what is both possible and economic to implement. Ergonomics and safety affect the work conditions of operators, and the design of instructions affects their efficiency. While not explored here, the field of ARSG as operator support also has highly relevant implications for society at large. Operator integrity is affected when using ARSG since they have the capacity to audio and video record all operator interactions. Moreover, as stated regarding the fourth key area of Teknikföretagen (2015), physical and cognitive support will help workers with, for example, age, knowledge, and language limitations, thereby addressing the demographic problem that Swedish industry is facing.

Finally, regarding the third implication, the continual improvement of technology within Industry 4.0 has affected the strategic decisions of this thesis during its creation. The field of AR, and more specifically, ARSG, has made large improvements, which are explored in paper 5. Table 2.1 summarizes a current view of Industry 4.0, as propounded by Culot et al. (2020). The scope of this thesis is not to give a comprehensive definition of Industry 4.0 but rather a brief overview concerning ARSG to show how ARSG currently fit into Industry 4.0.
2.1.3 OPERATORS IN INDUSTRY 4.0: OPERATOR 4.0
Operators and their work environment will be affected by Industry 4.0 through new interactions not only between humans and machines but also between the digital and physical worlds (Romero et al., 2020). Since most current literature on Industry 4.0 is mainly theoretical, there is a lack of data and practical experience concerning how aspects of Industry 4.0 will affect operators (Rauch et al., 2020). Virmani et al. (2021) identified 24 key roadblocks that hinder Industry 4.0 implementation in the manufacturing industry. It is, however, clear that operators will be a central part of future production systems due to their cognitive abilities (Rauch et al., 2020). To reflect how the role of operators is changing, the term “Operator 4.0” has been defined, referring to a smart and skilled operator who works closely integrated with technology (Romero et al., 2016). An Operator 4.0 typology was introduced by Romero et al. (2016) in which the term “Augmented Operator” was suggested. Through AR technology, transfer of digital information can be transferred to the physical world of a smart operator in a non-intrusive way. Romero et al. (2016) see significant advantages to this in the form of faster cycle times, improved reliability, reduced failure rates, and traceability. Zolotová et al. (2020) also identified AR as a suitable technology to help Operator 4.0 handle an increased cognitive load. AR can also greatly improve the ability to perform traditional tasks and permit the definition of new tasks and scenarios for Operator 4.0 (Segura et al., 2020). How to practically implement Operator 4.0, however, is still an emerging field of research (Margherita and Bua, 2021).

2.1.4 INDUSTRY 5.0
The European Commission describes Industry 4.0 as digitally transforming European industry, accelerating production processes, and changing the role of workers (Directorate-General for Research and Innovation and European Commission, 2021). The Commission further describes Industry 5.0 as having human-centric, sustainable, and resilient aspects. It has been suggested that Industry 4.0 solely concerns improving the efficiency of production; this ignores the human cost in terms of reduced employment numbers and could lead to political resistance (Nahavandi, 2019). Industry 5.0 is proposed as a solution to meet this resistance through integrating operators with intelligent production systems (Nahavandi, 2019). Industry 5.0 is closely related to Industry 4.0, and alternative names for Industry 5.0 are Industry 4.0 Plus, Industry 4.0 Symmetrical, and Industry 4.0-S (Vural and Nezih, 2018). Although the focus is a bit different, AR is relevant to both Industry 4.0 and 5.0 through augmenting operators with tools to handle more complex tasks.

2.2 MANUFACTURING ENGINEERING
The word manufacture is defined as “to make (a product, goods, etc.) from, of, or out of raw material; to produce (goods) by physical labour, machinery, etc., now esp. on a large scale” (Oxford English Dictionary, 2005). Manufacturing engineering, in turn, is the branch of engineering that relates to using engineering procedures in manufacturing processes and methods of production for industrial products (Matisoff, 1986). Planning manufacturing practices, R&D for tools, processes, machines, and equipment, and integrating facilities and systems that produce high-quality products with optimal capital investment are all part of manufacturing engineering (Matisoff, 1986).

Manufacturing engineering can be divided into four basic functional areas: manufacturing planning, manufacturing operations, manufacturing research, and manufacturing control (Matisoff, 1986). Of these four areas, this thesis relates primarily to manufacturing operations and manufacturing research. Since the framework of the thesis is
intended as a tool for improving the decision process related to operator support, it relates to manufacturing research. Manufacturing operations relate to the thesis, whose goal is the improvement of existing procedures.

ARSG constitute a technology that can enable more efficient operator work procedures in a manufacturing system by improving operator access to updated information. However, ARSG are currently used to only a limited extent (Campbell et al., 2019). Although some assembly stations have digital instructions, paper-based instructions are currently more common in manufacturing (Parsable, 2021). If the widespread procedure of printing out and distributing paper-based instructions to each station could instead be digitalized and displayed in ARSG, this could mean a significant improvement as regards logistics and error sources.

2.3 ASSEMBLY

Within the manufacturing field, several types of processes can be used in product creation. A classification of manufacturing processes and their relationships, defined by Groover (2010), is presented in Figure 2.1. As Figure 2.1 shows, in blue, assembly is a subset within manufacturing. A description of assembly is that it is the aggregation of those processes in which different parts and subassemblies are combined in order to form a complete and geometrically designed assembly or product, through either individual, batch, or continuous processes (Nof et al., 1997). Assembly consists of one or more assembly tasks, which can be divided into two categories: parts mating and parts joining (Nof et al., 1997). Parts mating is described as two or more parts being aligned or brought into contact with each other. Four types of mating tasks are described: peg in hole, hole on peg, multiple pegs in holes, and stacking. Furthermore, Nof et al. (1997) described parts joining as a step done after parts mating, a step when fastening is applied so that the parts are kept together. Eight types of parts joining are described: screw fastening, retainers, press fittings, snap fittings, welding and related metal-based joining methods, adhesives, crimping, and riveting (Nof et al., 1997).
All types of assembly are included in the definitions given in the above section. It is important to be able to assess assembly complexity to allow comparison of different assembly setups. Falck et al. (2016) described criteria with which to assess the complexity, i.e., high or low, of basic manual assembly steps.

### 2.4 AUGMENTED REALITY

An early fictional example describing the concept of merging information into our vision was the “character marker”:

> It consists of this pair of spectacles. While you wear them every one you meet will be marked upon the forehead with a letter indicating his or her character. (Baum, 1901, p. 94)
A non-fictional example came six decades later in the form of a head-mounted display (HMD) that could show computer-generated line drawings in a person’s FOV (Sutherland, 1968). In 1992 this was further improved when it became possible to superimpose and stabilize computer graphics in a specific position on a real-world object in a person’s FOV (Caudell and Mizell, 1992). In possibly the first instance of using the term “augmented reality,” the authors described the technology in the following way:

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

(Caudell and Mizell, 1992, p. 660)

AR is defined as having three characteristics in this thesis, characteristics previously defined by Azuma et al. (2001, p.34):

- combines real and virtual objects in a real environment;
- runs interactively, and in real time; and
- registers (aligns) real and virtual objects with each other.

Although this definition is around 20 years old and AR technology has improved significantly since its publication, it is still widely cited since what constitutes AR remains unchanged. The 2001 definition is similar to an earlier definition (Azuma, 1997) and, similarly, is not limited to any specific technological implementations of AR, such as HMDs. The AR definitions are also not limited to the visual sense; all senses, such as hearing, touch, and smell, can be included (Azuma et al., 2001). The most common form of AR is visual AR. In this thesis, AR is limited to visual augmentation.

2.4.1 PROS AND CONS OF AR

In their comprehensive survey of AR assembly research, Wang et al. (2016) found, among other things, that AR has the potential to improve the performance of users. AR as an operator support tool has been shown to have the potential to reduce assembly time and procedural tasks (Dalle Mura and Dini, 2021).

There are also limitations related to AR in assembly, such as complex assembly processes, time-consuming authoring processes, integration with enterprise data, and intuitive interfaces (Wang et al., 2016). While technological advancements, especially within the field of computer vision, opens up new possibilities related to AR, there are still challenges to overcome (Stübl et al., 2022). Sunlight and reflective surfaces can affect AR tracking negatively and human users might not accept systems not designed with their needs in mind (Stübl et al., 2022).

2.4.2 AR TAXONOMY

AR can be implemented in several ways, and many taxonomies have been made of the different forms of AR implementation. Bimber and Raskar (2006), for instance, defined three main forms of AR: head-attached, handheld, and spatial. Another way to categorize AR is as wearable and non-wearable (Peddie, 2017). In the non-wearable category, there are three sub-categories: mobile devices (e.g., smartphones and tablets), stationary devices (e.g., televisions and personal computers), and head-up displays. In the wearable category there are different forms of “near-to-the-eye displays, or NEDs” (Peddie, 2017 (p. 29)), divided into headsets, helmets, and contact lenses.
The technologies in both definitions can be categorized as of three main types: devices placed on the head in front of the eyes, devices carried in one or both hands, and devices placed in the environment. The AR taxonomy used here has adapted elements from both of these taxonomies and is presented in Figure 2.2.

The different of AR implementations vary in their advantages and disadvantages. Handheld solutions can be implemented on a smartphone or tablet, for instance, and can therefore be a very fast and cost-effective way to create an AR experience since these are well-established platforms familiar to the general population and for which several development tools are available. A severe limitation for operators, however, is that they require at least one of the user’s hands. Handheld solutions are further limited in that they require operators to place the device between themselves and the physical object(s) they want to augment. Handheld implementations are therefore not considered in this thesis.

With a spatial solution, the technology to display AR is mostly integrated into the environment (Bimber and Raskar, 2006). This removes the need for an operator to wear as much equipment, which reduces the ergonomic strain that a wearable or handheld solution naturally creates through its weight. However, a spatial solution is also limited to augmenting objects that have an unblocked path for the light from the spatial augmented reality (SAR) projector to the object. This is therefore likely to impose limitations for operators who need information from many different positions, with multiple SAR equipment likely being needed to fully implement this support. Any objects between the SAR and the work area can obstruct the information for the operator, further limiting how SAR can be effectively implemented. A significant functional drawback is that SAR is limited in depth; it cannot project digital information in mid-air but rather needs a surface to project on (Uva et al., 2018). This can be partially compensated for through visual design such as color coding to indicate distance (Schmidt et al., 2016). In the other two implementations, wearable and handheld, each individual operator equipped with AR has a personal AR FOV in the form of their own device. Since the AR in SAR is projected onto objects directly in the real environment rather than through individual equipment, it naturally follows that all operators sharing a real world FOV will share their AR FOV when using SAR. Therefore, they cannot see personalized information simultaneously. While allowing operators to view AR without wearing equipment, spatial solutions are still not considered in this thesis due to the above limitations.
Two central advantages of a wearable, head-attached solution are that it is always in an operator’s FOV while simultaneously keeping their hands free. Because the technology is head-attached, it is also mobile, following the operator wherever he or she moves. This makes this type the most suitable for operators. To the best of the author’s knowledge, no implementations of working AR contact lenses are commercially available at the present time. The only implementations of AR in the head-attached category are thus headsets and helmets, as seen in Figure 2.2. The larger size of helmets has no inherent advantage over headsets and is of a larger size because the relevant technologies are not yet compact enough to fit a smaller device. It is therefore likely that helmet implementations will be phased out as the technology continues to advance. Both implementations are therefore treated as part of the category of augmented reality smart glasses (ARSG) in this thesis. Another related term is “smart glasses” (SG). These two terms are used in various ways in the literature. The term “smart glasses” is used for glasses with AR capability in some sources (Kulak et al., 2020, Sedarati and Baktash, 2017), while sometimes the term “augmented reality smart glasses” is used instead (Han et al., 2019). Lastly, ARSG and SG are sometimes used interchangeably (Kim et al., 2019, Ro et al., 2018). In this thesis, ARSG are defined as a subset of SG, that is, as SG with the capacity to display AR. SG are defined as a device equipped with one or two screens in front of the user’s eyes, allowing the user to see both the real world and digital information simultaneously.
RESEARCH METHODOLOGY
In this chapter, the overall research approach applied in this thesis is presented. The choices made are justified and the types of data collected, and how, are briefly described. This thesis took the overall research approach of combining the methodology of design science with a mixed methods-approach.

3.1 PHILOSOPHICAL PARADIGM: PRAGMATISM
This research was conducted in the field of informatics, specifically in the sub-field of industrial informatics. The definition of industrial informatics follows the one presented in University of Skövde (2011). According to this definition, industrial informatics handles how IT-based engineer tools are integrated with other relevant parts. These parts can include other IT-based engineer tools, physical equipment and current business systems. Further, it also relates to what demands are put on these tools based on, for instance, distributed production and users (University of Skövde, 2011).

Industrial informatics is engineering research. Engineering works with problems in the real world and with limited resources and can be described as a method for using heuristics to create the best possible change within the limitations of these resources (Koen, 1985). Within engineering, all useful tools are considered, regardless of which discipline they belong to (Nair and Bulleit, 2020). Another way to describe engineering is that it is constantly evolving, driven by the emergence of better design heuristics (Bulleit, 2015). In this thesis, the focus is on finding ways to improve current practice by better understanding operator support using ARSG, which is an emerging field.

This thesis follows the philosophical paradigm of pragmatism, a worldview commonly viewed as arising from actions, situations, and consequences rather than the antecedent conditions of post-positivism (Creswell, 2014). Applications, what works, and solutions to problems are what pragmatism emphasizes (Patton, 1990). The focus is on the problem that the research should solve, rather than on specific methods, and all
available approaches are used to understand the problem (Rossman and Wilson, 1985).

There are some similarities between engineering and pragmatism. Engineering works with incomplete and changing knowledge; this is compatible with pragmatism, which answers questions through iterative, corrective responses based on experience (Nair and Bulleit, 2020). Because the topics addressed in this thesis are complex and emerging, it is impossible to know the optimal methods to use beforehand. Pragmatism has the advantage of allowing for a wide choice of methods, which can contribute to a broader understanding of the subject.

### 3.2 MIXED METHODS

Research can be categorized into three primary research paradigms: qualitative, quantitative, and mixed methods (Creswell, 2014). Qualitative research is inductive: it builds from particulars to general themes, and the data are in most cases collected in the test person’s setting. In the quantitative paradigm, the relationships between variables measured and analyzed are evaluated using statistical procedures. Mixed methods combine the other two paradigms, and both qualitative and quantitative data are collected and integrated into the research (Creswell, 2014).

In mixed methods research, both qualitative and quantitative methods are used, concurrently or sequentially (Venkatesh et al., 2013). A synthesis of both methods usually provides the most informative, complete, balanced, and useful research results (Johnson et al., 2007). Both the qualitative and quantitative perspectives are needed to create a holistic understanding, since neither on its own can encompass all research (Newman and Benz, 1998).

Figure 3.1 presents three types of mixed methods, i.e., convergent parallel mixed methods, explanatory sequential mixed methods, and exploratory sequential mixed methods, as described by Creswell (2014). In convergent parallel mixed methods research designs, both qualitative and quantitative data are collected at roughly the same time, and the results are then compared or related to one another and interpreted. In explanatory sequential mixed methods research designs, quantitative data are gathered and analyzed, followed the gathering of qualitative data to give a deeper understanding of the quantitative data. Finally, in exploratory sequential mixed methods research designs, qualitative data are first gathered and analyzed, followed by gathering quantitative data used to validate the qualitative findings of the first step.
3.2.1 SUMMARY OF METHODOLOGY FOR RESEARCH AIM

In this section, an overview of the methodology for the thesis as a whole is presented. A graphic overview of the research objectives, methods used, data collected, sequence in which the data were analyzed, and paradigms used is presented in Table 3.1. The table is color-coded to give a clearer overview of the methodological coverage of the research objectives. Red signifies qualitative entries, whereas quantitative entries are highlighted in blue. In the “Summary” column, there are three colors. For purely qualitative objectives (such as 1.1), the entry is highlighted in red, whereas for purely quantitative objectives (such as 1.2), the entry is highlighted in blue. If both qualitative and quantitative data are used for an objective, then the “Summary” column is highlighted in green.

![Three forms of mixed methods research](image-url)
### Table 3.1: Graphic overview of the research objectives and of the methods, data, and type and (if mixed method) sequence of qualitative and quantitative methods used.

<table>
<thead>
<tr>
<th>Prerequisite</th>
<th>Qualitative</th>
<th>Quantitative</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>Data</td>
<td>Method</td>
<td>Data</td>
</tr>
<tr>
<td>0.1</td>
<td>Group discussion</td>
<td>Improvement</td>
<td>Survey</td>
</tr>
<tr>
<td>Interview</td>
<td>Improvement</td>
<td>Experiment</td>
<td>Feasibility</td>
</tr>
<tr>
<td>0.2</td>
<td>Meta-analysis</td>
<td>Relation-hierarchies</td>
<td>Scoping review</td>
</tr>
<tr>
<td>1.1</td>
<td>Rapid review</td>
<td>Research papers</td>
<td>Qualitative</td>
</tr>
<tr>
<td>1.2</td>
<td>Interview</td>
<td>Patterns</td>
<td>Observation</td>
</tr>
<tr>
<td>1.3</td>
<td>Rapid review</td>
<td>Research papers</td>
<td>Qualitative</td>
</tr>
<tr>
<td>2.1</td>
<td>Interview</td>
<td>Expert knowledge</td>
<td>Qualitative</td>
</tr>
<tr>
<td>Focus group</td>
<td>Expert knowledge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>Rapid review</td>
<td>Research papers</td>
<td>Qualitative</td>
</tr>
<tr>
<td>3.1</td>
<td>Synthesis</td>
<td>Previous objectives</td>
<td>Qualitative</td>
</tr>
<tr>
<td>3.2</td>
<td>Pilot test</td>
<td>Expert knowledge</td>
<td>Qualitative</td>
</tr>
<tr>
<td>3.3</td>
<td>Case study</td>
<td>Expert knowledge</td>
<td>Survey</td>
</tr>
</tbody>
</table>

### 3.2.2 JUSTIFICATION FOR USING MIXED METHODS

It is important not to regard mixed methods as a panacea; mixed methods research may seem to combine the best of two extremes, but it should be used only when it serves certain purposes (Venkatesh et al., 2013). According to Venkatesh et al. (2013), there are seven purposes for which mixed methods research are suitable: complementarity, completeness, developmental, expansion, corroboration/confirmation, compensation, and diversity. In this thesis, a developmental purpose has been pursued. A developmental research design is a form of iterative design in which new questions are derived from previous research (Venkatesh et al., 2013). Two perspectives are investigated in this thesis, the operator and manufacturing engineering perspectives. They have different agendas and thus different views. Mainly qualitative methods have been used, to gain a deeper understanding of these perspectives.

There are some inherent risks in conducting mixed methods research from a pragmatist perspective, which Hathcoat and Meixner (2017) formulated as the conditional incompatibility thesis. This thesis identifies a risk in mixed methods research that when actions taken within a single study have inconsistent philosophical prescriptions, they can challenge the what-works maxim in a mixed methods approach if they are not addressed. There are many pragmatists in mixed methods research who de-emphasize philosophical aspects in favor of the what-works maxim, which they see as a problem. They conclude that the perceived incompatibility instead results from the researcher’s actions, for instance, methodological decisions, questions colored by philosophical assumptions, and approaches to data interpretation; the incompatibility is not due to any inherent incompatibility between qualitative and quantitative data (Hathcoat and Meixner, 2017). This has been handled in this thesis in different ways. For instance, the established method of a structured literature review was used in paper 4.
(Danielsson et al., 2019), following the method of Booth et al. (2016). In papers 6 and 7 (Danielsson et al., 2021a, Danielsson et al., 2022), the combined use of the “method triangle” and “five iterative steps” as described by Thorvald et al. (2019) was used.

3.3 DESIGN SCIENCE

In this thesis, design science was chosen as the main research method. In design science, there are two basic activities: building and evaluating (March and Smith, 1995). An artifact is constructed for a specific purpose through the building activity, whereas the evaluation activity determines its performance (March and Smith, 1995).

In natural science, the aim is to understand and explain phenomena; in contrast, design science aims to develop ways to achieve human goals (March and Smith, 1995). Since design science focuses on creating artifacts to help gain knowledge, it can be seen as a more pragmatic methodology. Through practical implementation, more effective ways of doing things are found. Concerning this, a common critique of design science is that design takes place all the time without it being science. Design choices, therefore, need to be justified and evaluated both before and after they are made (Oates, 2005). The process of creating the artifacts generates new knowledge and is therefore science.

Design science can generate one of the following four types of products, i.e., constructs, models, methods, and implementations, according to March and Smith (1995). Constructs are defined by them as the basic concepts used to characterize phenomena. Furthermore, models are described as using a combination of constructs to describe tasks, situations, or artifacts. Finally, methods are described as the ways to perform activities and then be used to create specific implementations to achieve the goals.

3.3.1 DESIGN SCIENCE SUITABILITY EVALUATION

The decision as to whether or not to choose design science can be challenging. To support evaluating the suitability of design science, Hevner et al. (2004) developed seven guidelines that describe what is important in design science research. According to them, the purpose of the guidelines is to assist in understanding how to perform effective design science research. They therefore advise against mandatory or mechanical use of the guidelines; instead, the guidelines should be viewed as a basis for determining whether or not something is good design science research. The guidelines should still be addressed in some way for design science research to be complete (Hevner et al., 2004). In this section, the seven guidelines, based on Hevner et al. (2004), are briefly described, followed by an explanation of how they each apply to this thesis.

**Guideline 1:** Design as an artifact. A central aspect of design science is the creation of artifacts that address relevant problems. The created artifacts show the feasibility of the design process. The creation also serves as proof of concept that something can be done. This also makes it possible to change how tasks and problems are conceived. In this thesis, two main parts adhere to guideline 1. The first is the creation of an AR demonstrator that provided a proof of concept, and that showed the feasibility of the planned design. Through the process of creating the artifact, important lessons were learned regarding the challenges and limitations of AR as an operator support tool. The lessons learned here, in combination with an emerging market, motivated the shift of focus towards ARSG.

The second artifact was the framework that summarizes the knowledge gathered and organized within this thesis. Both the design process and evaluation of this framework artifact provided new knowledge.
Based on these two artifacts, it is concluded that this thesis follows guideline 1.

Guideline 2: Problem relevance. As resources are finite, new knowledge in and of itself is insufficient motivation in applied science. A problem needs to be relevant; that is, solving the problem needs to lead to a better situation in an actual application, otherwise the solution to the problem has no value.

The aim of this thesis is to support strategic decisions regarding the integration of ARSG into current production systems. As described in Chapter 1, this is an area in need of more research. Volvo Car Corporation, a global manufacturer, supported the work in this thesis based on their interest in how it can support their business. These were the premises for initiating this thesis. To ensure relevance before allocating unnecessary resources, a prerequisite for further research was set and two objectives were defined.

Based on this, it is concluded that this thesis follows guideline 2.

Guideline 3: Design evaluation. The focus of design science is on making improvements to ameliorate real problems. Therefore, the design must be evaluated to determine whether it provides an actual improvement. The things that are relevant to measure vary with each application field, but it is important that the measurements should be both relevant and comparable.

As presented in Table 3.1, a set of various evaluation methods was used in this thesis to evaluate the different objectives. The evaluations were chosen based on the premise of achieving wide coverage of qualitative and quantitative evaluations. The results of the evaluations have been accepted and published in scientific publications and have thereby also been evaluated through the peer-review process. At the time of writing this thesis, it was not feasible to evaluate ARSG integration into a real production system. Other evaluations, as described in the publication list, have instead provided data to support the answering of the research objectives.

Based on this, it is concluded that this thesis follows guideline 3.

Guideline 4: Research contributions. For an activity to count as research, it must create new knowledge. Design science differs from ordinary product development in that the designed artifact contributes to solving unsolved problems or solving old problems in new ways. The development of new constructs, models, or instantiations can also be a contribution to research. Finally, design science can contribute through the creation of new evaluation methods and new evaluation metrics.

Given the vast number of publications available and limited resources to analyze them, it can never be guaranteed that any result is a unique contribution. To the best of the author’s knowledge, there is currently no other framework that provides strategic support in integrating ARSG as assembly operator support in production from the perspectives of both operators and manufacturing engineering.

Based on this, it is concluded that this thesis follows guideline 4.

Guideline 5: Research rigor. This guideline is related to how the research is done, for instance, the replicability of the process and what assumptions are made. In design science, there is a need for balance between, on one hand, the need to simplify real, and therefore complex, problems in order to make quantifiable measurements/calculations and, on the other hand, the need for the results to still be relevant.

During the work on this thesis, there was close collaboration with different industries, particularly with VCC. Throughout the work, there was ongoing dialogue with industrial managers and experts to ensure that the thesis remained relevant to the manufacturing industry. Three literature reviews were conducted as part of the thesis to
identify current knowledge and research practice. For more detail, a thorough review of the data collection methods is presented in section 3.4.

Based on this, it is concluded that this thesis follows guideline 5.

**Guideline 6:** Design as a search process. The complexity of the real world makes problems usually solved by design science too complex for an exhaustive search of solutions to be possible. The goal of design science is therefore not to find the best solution; instead, the goal is to find a solution that improves the current practice and/or theory.

It is not feasible to design and evaluate a framework for integrating ARSG as assembly operator support and to consider all possible solutions. The focus of the research in this thesis was determined through an iterative and explorative process in which feasibility, previous work, and industrial relevance guided the delimitation decisions made. The framework was thus developed and evaluated through an iterative approach.

Based on this, it is concluded that this thesis follows guideline 6.

**Guideline 7:** Communication of research. It does not matter if a research project is both valuable and accurate if no one knows about it or cannot understand it. The last guideline is that information regarding any research done should be disseminated in a format that different audiences can understand, according to their needs. For those who focus on technology, it should be clear how the results can be implemented, and for those who focus on management, the strategic value of implementing the results should be clear.

The main intended users of the framework are manufacturing engineers, who focus on technology. Users focused on integration can also use the detailed recommendations for guidance in the process of integrating ARSG in a production system. Since the framework also presents an estimation of the suitability of ARSG in specific cases, it can also support investment decisions made by managers.

Results of the intermediate steps leading up to the framework have also been disseminated. A demonstrator that showed the proof of concept has been used to communicate the value of the research at fairs and similar events. This has been presented to different audiences, including industrial managers, who have expressed interest in the research based on these presentations and have engaged in discussions regarding implementation. As well, scientific contributions were made in the form of seven publications and by attending several conferences where the research results were presented and discussed.

Based on this, it is concluded that this thesis follows guideline 7.

In summary, the applicability of all seven guidelines laid out by Hevner et al. (2004) has been evaluated for this thesis, which was found to follow them. Design science was therefore a suitable methodology to follow.

### 3.4 FRAMEWORK METHOD

The specific methods used in the papers presented in this thesis are described in each respective paper. Due to the central role of the framework and its development however, the methods used to create and evaluate it are described in this section. More details are provided in papers 6 and 7.
3.4.1 METHOD TRIANGLE AND STRAWMAN METHOD
To apply design science in developing the framework, the method developed by Thorvald et al. (2019) was applied. It is presented in figure 3.2. The first part of their method involved the three perspectives on a method, presented by Lings and Lundell (2004), called the “method triangle” by Thorvald et al. (2019). The second part was the five iterative steps of a general method development process, as first presented by Blandford and Green (2008).

Figure 3.2: The overarching method for developing the framework, based on the combination of the models by Lings and Lundell (2004) and Blandford and Green (2008), as presented by Thorvald et al. (2019).

Due to the complexity of the framework as a topic, it is not possible to foresee all relevant aspects beforehand. An iterative design strategy has therefore been implemented in the development of the framework to allow for a gradual improvement process. Since ARSG in general, and ARSG implemented as operator support in production in particular, still constitute a developing field, it can be hard even for practitioners in the field to have a good understanding of what needs to be considered when developing a framework. We therefore chose to use the strawman approach (not to be confused with the strawman logical fallacy). The strawman refers to a draft proposal created by a smaller group to help a larger group focus its discussions (Schiola, 2011). The strawman approach is well suited for use within an iterative design process (Thorvald et al., 2019).

3.5 ETHICAL CONSIDERATIONS
The Swedish Research Council has a set of recommendations regarding research ethics, and this thesis has based its considerations on these recommendations (Vetenskapsrådet, 2017). As Vetenskapsrådet (2017) describes, research ethics
changes over time as science progress. There are many recommendations presented, but 8 general rules are laid out that covers much of the recommendations. These rules are:

1. You shall tell the truth about your research.
2. You shall consciously review and report the basic premises of your studies.
3. You shall openly account for your methods and results.
4. You shall openly account for your commercial interests and other associations.
5. You shall not make unauthorised use of the research results of others.
6. You shall keep your research organized, for example through documentation and filing.
7. You shall strive to conduct your research without doing harm to people, animals or the environment.
8. You shall be fair in your judgement of others’ research. (Vetenskapsrådet, 2017, p. 10)

Rules 1-3 and 5-6 are self-explanatory and have been followed by the author and, in part, through support of the supervisor-team. In regard to rule 4, there have been no direct commercial interests linked to the specific results of the thesis. The commercial associations and commercial interests in the research topic have been presented in Chapter 1.

In regard to rule 7, several interviews, user tests, and observations were performed during this thesis research. The observations and some of the interviews involved assembly workers in their work environment, which can be argued to be an especially sensitive situation. It was generally important to ensure informed consent from all research participants. All research participants were informed about the purpose of the research, their role, the expected results, and how the results were to be used. During the observations, this information was given after the observations so as not to affect the results. The experiments for the demonstrator in paper 1 included human–robot collaboration (HRC), and even though the robot model, UR3 (Universal Robots), is designed for HRC, all tests were supervised and care was taken to ensure the safety of all participants. It was estimated that the precautions described here and in the respective publications were sufficient not to warrant an evaluation per Swedish legislation (SFS, 2003). I have followed rule 8 to the best of my ability.

3.6 DATA COLLECTION AND ANALYSIS
Mixed methods research entails gathering and analyzing both qualitative and quantitative data. This section presents how the data were collected and analyzed for the different RQs and objectives. Each objective is presented separately and with its analysis. In the last part of the section, the RQs and their objectives are schematically connected to show their dependencies.

3.6.1 APPLICABILITY TO PREREQUISITE
Prerequisite: Is the thesis relevant to industrial partners and novel for the scientific community?

The purpose of this prerequisite is to ensure that this thesis makes a valuable contribution to both theory and practice. The aim is to create a framework helping the man-
ufacturing industry make strategic decisions regarding ARSG as a support tool for operators. For there to be a practical contribution, this goal should be relevant to the manufacturing industry. There needs to be a knowledge gap that this thesis helps to fill for there to be a theoretical contribution. These two aspects are addressed in the two objectives described below. This prerequisite was first addressed in a publication that was part of my licentiate thesis (Danielsson, 2020).

**Prerequisite, O 1: Ensure relevance and feasibility for industrial partners at the management level.**

The industrial partner, VCC, was active in the initiation of this thesis, proposed the initial direction of operator support and AR, and has been an active partner in all stages of the thesis research. Therefore, it can be argued that industrial relevance has been a central aspect since the start of this thesis. VCC has provided several resources, such as material, staff time, and facilities, and has provided input to strategic decisions regarding the focus of the thesis. In particular, an industrial mentor from VCC, Rodney Lindgren Brewster, has had a coordinating role between academia and industry. He has continually articulated an industrial perspective on design decisions and the focus of the thesis as well as providing valuable insight into how to disseminate academic results efficiently to industrial managers. The industrial perspective has not been limited to VCC.

The demonstrator created for paper 1 served as both proof of concept and a way to disseminate results to the public and industrial managers. The tests performed assessed the feasibility of the initial intended research focus, i.e., AR for HRC assembly support, and also allowed the dissemination of the concept. Quantitative evaluation was done through surveys; qualitative evaluation was done through unstructured interviews and group discussions with industrial representatives and using the demonstrator as a basis allowed for effective evaluation of the combined results.

**Prerequisite, O 2: Conduct a literature review of ARSG in manufacturing.**

To map the relevant literature, a structured scoping review of AR in manufacturing was performed. The method of Booth et al. (2016) was used as a basis for the literature review. Relevant search words were identified and inserted into four major search engines, and all literature identified was analyzed. The data were extracted from the literature in two iterations. First, quantitative data were extracted from the reviews in the form of identified keywords, topics, and themes. Second, these data were arranged into tables, and a qualitative analysis was performed by sorting out data relevant to ARSG. Each of the keywords, topics, and themes was read, interpreted, and, if found to be relevant to the focus of the thesis, extracted. The list of all relevant keywords, topics, and themes was then analyzed and sorted into three perspectives (operators, manufacturing engineering, and technological maturity). A quantitative search for literature, followed by a quantitative extraction of relevant words that were then analyzed qualitatively, was how this objective was addressed.

3.6.2 APPLICABILITY TO RQ 1

**RQ 1: What do operators require in an ARSG-based interface and system so that it supports them in industrial assembly?**

There are two aspects to this RQ. The first aspect is how operators view instructions. This aspect can provide better insight into how operators think about interfaces and information, and it can also identify what operators need in order to feel safe with an interface. The second aspect is what information needs to be conveyed to operators to ensure that they can perform their tasks efficiently. There are three objectives for this RQ that address these two perspectives to create a holistic answer as to how they can...
both be addressed. This RQ and its objectives were first addressed in a publication that was part of my licentiate thesis (Danielsson, 2020).

**RQ 1, O 1: Conduct a literature review of ARSG in manufacturing from an operator perspective.**

The literature review described in this objective is an extended version of the review described in objective 0.2. The purpose is to provide a theoretical basis for the two perspectives of RQ 1: how operators view instructions, and what information needs to be presented to them. The chosen method for the literature review was a rapid review. Rapid reviews do not have a formal definition, according to Tricco et al. (2015). They chose to define rapid reviews based on Khangura et al. (2012), who said some steps of a systematic literature review could be simplified to enable faster results. Which steps to simplify varied in their findings.

Data collection for the literature review was done iteratively based on keywords from the previous literature review presented in paper 3 (Danielsson et al., 2019). The review was not systematic; rather, each topic was explored, and when sufficient coverage to understand the topic had been gained, the review moved on to the next topic. The topics were analyzed per paper, with each paper on a topic being qualitatively read and analyzed.

**RQ 1, O 2: Ascertain whether operators are willing to work with ARSG.**

The work on this thesis started in September 2015. At the time, only limited ARSG were available. Furthermore, to the best of the author’s knowledge, there were no examples of ARSG used by production operators. An important aspect was therefore to ensure operator acceptance of ARSG. During the work on this thesis, this situation changed, and there are now examples of operators working with ARSG in production (Campbell et al., 2019). This has, in retrospect, further strengthened the findings of paper 2.

To address this objective, operators were interviewed. The interviews were recorded to facilitate analysis. The recordings were analyzed both qualitatively and quantitatively. Quantitative data were gathered during the interviews through survey questions asked at the start. Qualitative data came from open-ended questions to the operators about their interactions with instructions. Quantitative data were also gathered from the literature, as described in the above paragraph, which provided empirical examples affirming results previously found during the interviews.

**RQ 1, O 3: Identify operators’ needs in information systems.**

The purpose of this objective is to understand the needs of the end-users so that ARSG can better support them. In paper 2, operators were observed in their working environment, which yielded data on how they were interacting with information in production. The observations provided mainly quantitative data, i.e., by counting the number of times operators looked at instructions and by asking them after the observation what usually made them look at instructions. In the analysis, it was possible to quantify different information interactions by type. Operators were also interviewed, and the interviews gave qualitative insight into how and why the operators interacted with different types of information and into their views of how this could be improved. The literature review connected with objective 1.1 also provided qualitative insights from theory.
3.6.3 APPLICABILITY TO RQ 2

RQ 2: What do manufacturing engineers and technicians need in ARSG so that the technology can be integrated into, maintained, and updated in a production system?

There are two aspects to this RQ. The first aspect is the perspectives of manufacturing engineers and technicians who work with the integration, maintenance, and updates of production systems. This perspective considers what they generally need to know and have access in order to perform their tasks. The second aspect is the technological maturity, i.e., what is the state of the technology needed for integrating ARSG and for ARSG themselves. This RQ and its objectives were first addressed in a publication that was part of my licentiate thesis (Danielsson, 2020).

RQ 2, O 1: Conduct a literature review of ARSG in manufacturing from a manufacturing engineering and technical perspective.

This objective was addressed by conducting a rapid review, and as in objective 1.1, iterative data were collected based on the results of the literature review in objective 0.2. As in objective 1.1, data collection continued until they sufficiently covered the topic to facilitate understanding. Each paper was read and analyzed qualitatively, and then integrated into the cohesive results for each topic.

RQ 2, O 2: Gather experience from manufacturing engineers and technicians about relevant challenges in implementation, updating, and maintenance.

This objective was addressed in papers 6 and 7 through the use of focus groups, a survey, case studies, and an expert interview. The focus groups used a strawman of the framework as a basis for discussion, and qualitative data were gathered. The focus groups conducted for paper 6 were iterative, with each focus group providing qualitative information that improved the framework design for the next group. The focus groups conducted for paper 7 were instead static, and all were presented with the same strawman. The analysis was then conducted in parallel, and all focus groups’ discussions of each question in the framework were analyzed one by one. The first version of the framework was disseminated to industrial representatives connected to production, and they were encouraged to test the framework and evaluate it through a survey. This provided quantitative data on how manufacturing engineers viewed the perspectives presented in the framework. The second version of the framework was evaluated through case studies, in which industrial representatives tested the framework, reviewed the results, and engaged in qualitative discussion of the framework’s utility. A leading expert on ARSG integration into production was also interviewed in an unstructured interview to provide qualitative insight from an expert.

3.6.4 APPLICABILITY TO RQ 3

RQ 3: When and how can both the operators’ and the manufacturing engineers’ and technicians’ needs for ARSG be met?

This RQ considers two perspectives, and they, in turn, each have two common perspectives. The “when” perspective concerns the strategic investment decision of whether or not one should invest in ARSG, considering when it is both feasible and profitable. The “how” perspective focuses on what needs to be considered once the decision has been made to invest in ARSG. These perspectives should be considered for the two aspects of this thesis, which are explored in RQ 1 and RQ 2: the operator and the manufacturing engineering perspectives.
RQ 3, O 1: Combine the data gathered from RQ 1 and RQ 2.
The main evaluation was conducted through the previous RQs, where practical and theoretical data was collected. In this step, the gathered data were combined into one set of data.

RQ 3, O 2: Synthesize into a framework.
Synthesis into a framework was done using a strawman base followed by an iterative design process involving industry experts. To make the framework easy to use, it was integrated into a webpage as an online tool. As this objective involved creating an artifact that was then evaluated in objective three, it can also be considered design science. The framework and its tool implementation were developed in two main stages, described in detail in papers 6 and 7, respectively.

RQ 3, O 3: Evaluate the practical usefulness of the framework for industry in making strategic decisions about ARSG.
For each of papers 6 and 7, the framework and its tool implementation were evaluated in two steps. The first step was part of the framework refinement, which was conducted in focus groups for both papers. The second step was to evaluate the final form for the respective papers. In paper 6, this was done quantitatively by gathering data from industrial representatives who used the tool implementation and then evaluated it using a Likert-scaled survey. In paper 7, this was done using case studies in which the tool was used for specific purposes in a varied set of industrial companies, and the practical usefulness of the framework was qualitatively evaluated by discussing the results and their relevance with industrial representatives from the companies. In this way, this objective was evaluated using an explanatory sequential mixed method, as described in Figure 3.1.

3.7 DEPENDENCIES AND FLOWCHART FOR RESEARCH AIM
This section shows how all the research objectives depend on each other. Figure 3.2 provides a graphic overview of these dependencies. As in Table 3.1, qualitative entries are red, quantitative ones are blue, and mixed method entries are green.
Figure 3.3: Flowchart that shows the objective dependencies.

Figure 3.3 starts with the prerequisite for the thesis. The two objectives of the prerequisite can run independently and in parallel. Since both objectives need to be met to ensure that the thesis provides novel value, RQ 1 and RQ 2 cannot start until the prerequisite is met. Once the prerequisite is met, RQ 1 and RQ 2 can run in parallel. Both RQ 1 and RQ 2 explore their perspectives’ theoretical aspects through separate literature reviews (1.1 and 2.1), which are deepened explorations of the literature review in 0.2. Therefore objectives 1.1 and 2.1 both depend on 0.2. Objectives 1.2 and 1.3 are independent of each other and provide part of the operator perspective data for objective 3.1. Objective 2.2 correspondingly provides part of the manufacturing engineering perspective data for objective 3.1. In contrast to the prerequisite and RQ 1 and RQ 2, the three objectives of RQ 3 all depend on each other in sequential order from 3.1 to 3.3. Objective 3.1 combines the data from the previous steps to form a basis for the framework. Objective 3.2 then develops the framework from this basis, and the framework is then evaluated in objective 3.3. Objectives 3.2 and 3.3 are then iterated to refine the results based on the first evaluation.
FRAMEWORK BASIS
CHAPTER 4
FRAMEWORK BASIS

He who knows only his own side of the case, knows little of that. His reasons may be good, and no one may have been able to refute them. But if he is equally unable to refute the reasons on the opposite side; if he does not so much as know what they are, he has no ground for preferring either opinion. (Mill, 1865, p.21)

This chapter presents the results of the first stage of the research performed in this thesis, i.e., the preparatory work for the framework. A large portion of this chapter is directly based on my licentiate thesis and its results concerning the framework that is presented in this thesis (Danielsson, 2020). The framework was developed based on guidance obtained from addressing RQ 1 and RQ 2.

4.1 RELEVANCE AND NOVELTY

Before starting the main work of creating the framework for this thesis, it was essential to ensure that the framework would be relevant to industry and contribute knowledge to the scientific community. Therefore, a prerequisite was set: “Is the thesis relevant to industrial partners and novel for the scientific community?”

4.1.1 INDUSTRIAL RELEVANCE

For the prerequisite set for this thesis, two objectives were defined to evaluate it. The first objective was “ensure the relevance and feasibility for industrial partners at management level.”

When the research for this thesis started, the areas of interest for VCC were AR and human–robot collaboration (HRC). As described in Chapter 2, AR in actual production was limited at that time. To explore these topics and how they could be relevant to VCC, a demonstrator was created, described in paper 1 (Danielsson et al., 2017). The demonstrator consisted of an HRC cell in which an operator could assemble a model car, supported by a Universal Robot, model 3 (Universal Robots), and an AR interface, as seen in Figure 4.1. The demonstrator was evaluated on four test groups of high-
school students, using a system usability scale (SUS) and observation of the performance. The SUS consists of 10 Likert-scaled questions and is a simple and reliable tool for evaluating usability (Brooke, 2013).

Three of the four groups scored above 75 out of 100 on the SUS test, whereas the fourth group diverged with a score of 32.5. The average of all groups was 66.45, which, according to Bangor et al. (2008), is a result between “OK” and “Good,” indicating a need for continued improvement. The observations showed that more than half of the assembly steps were performed with at least one error, showing that there were limits to the design. Some clear limitations were that instructions were shown on a screen behind the work area, rather than as an overlay in the users’ FOV, and the poor placement of text instructions in the upper right corner of the screen, leading to some users not registering the text. The form of AR visualization, i.e., a screen behind the work area, was in itself a limiting factor. Apart from the need for improved design, the concept was seen as promising if ARSG could instead be used to enable visualization more directly in the users’ FOV.

Paper 1 also describes how the demonstrator was presented to industrial representatives from VCC to assess future industrial relevance. The demonstrator was described as relevant by the representatives. The demonstrator also saw continued use after the publication of paper 1 and was used to demonstrate the relevant technologies to industrial representatives from different companies. With the demonstrator, the technological concepts could be better understood by more than field experts; this allowed for wider dissemination and more feedback on whether and how the technology was relevant to industry. The ensuing discussions with VCC regarding the industrial relevance led to a focus on ARSG for assembly operators in this thesis, whereas HRC was instead examined in other projects.

The conclusion is that objective 0.1 was achieved, as the focus of the thesis is both feasible and relevant to the industry. This was ensured through close involvement of VCC in the strategic decisions and evaluation of the results of paper 1.

![Figure 4.1](image-url): Step four in the demonstrator assembly task. The test person and the robot collaborate with the help of the interface instructions on the right.
4.1.2 SCIENTIFIC NOVELTY

The second objective of the prerequisite was “conduct a literature review of ARSG in manufacturing.” This was done through the work presented in paper 3 (Danielsson et al., 2019), which is a structured literature review exploring previous works related to ARSG in manufacturing. The review was conducted by searching for literature reviews in four databases: IEEE Xplore, ScienceDirect, Scopus, and Google Scholar. The search was for surveys or reviews related to AR and at least one of the four terms industry, manufacturing, assembly, and maintenance. The search was limited to 2015–2019 due to the rapid technological development in the field and since reviews themselves look at previous work. The systematic method used to identify papers to include makes it plausible that the identified papers represent all relevant review papers given the parameters set, or that they are at least a good representation of all relevant review papers. With the analyzed papers being review papers, they in themselves represent aggregated AR research within the industrial assembly field.

Seven review papers were identified and further analyzed. The analysis consisted of identifying the topics covered in these reviews to create a meta-study of what had previously been covered regarding ARSG in industrial assembly. This was done by reviewing all keywords, themes, and topics in the literature reviews. All terms that were directly related to the three perspectives relevant to this thesis were sorted under the respective perspectives to gain an overview of previous research. Besides the operator and the manufacturing engineering perspectives, a third perspective was added, that of technological maturity. The technological maturity perspective was seen as relevant based on the findings of the review and was added as a third perspective. This perspective relates to what facilitates the realization of the other two perspectives. An overview of the perspectives is seen in Figure 4.2

During the analysis of the review papers, broad insight into the current state of AR in industry was attained. The review papers’ conclusions and projections of future work showed research gaps related to this thesis. For instance, the reviews identified needs for better real-time tracking of industrial applications (Wang et al., 2016), greater hardware maturity (Fraga-Lamas et al., 2018), and AR integration with other systems (Damiani et al., 2018).
In relation to the focus of this thesis, the findings of the literature reviewed in paper 3 generally described how ARSG can be used for assembly, technical improvement of ARSG capacity, and simplified authoring of instructions. However, the perspective of integrating ARSG into a production system and ensuring long-term functionality was not found.

In summary, the reviewed papers identified a need for AR technology to mature further; at the same time, the technology was said to be nearing a maturity level permitting industrial application. In relation to this thesis, the combination of the operator and the manufacturing engineering perspectives in relation to the application of ARSG in assembly was not identified. This indicates that the framework developed in this thesis is a novel contribution to the scientific community, fulfilling objective 0.2. It was therefore concluded that the prerequisite was fulfilled: the planned focus of this thesis would both be relevant to the manufacturing industry and make a novel contribution to the scientific literature.

4.2 OPERATOR PERSPECTIVE

The end-users of ARSG as assembly support are the operators, so one perspective of the thesis and the framework is the operator perspective. This was formulated in RQ 1: “What do operators require in an ARSG-based interface and system so that it supports them in industrial assembly?”

4.2.1 PREVIOUS RESEARCH FROM THE OPERATOR PERSPECTIVE

To gain a more comprehensive understanding of the operator perspective, a literature review was conducted to fulfill objective 1.1: “Conduct a literature review of ARSG in manufacturing from an operator perspective.”

Paper 4 (Danielsson et al., 2020a) used the mapping of the operator perspective in paper 3 (Danielsson et al., 2019) as its basis. The six categories related to the operator perspective (see Figure 4.2) were reviewed and the findings were analyzed and summarized into the current status and future challenges identified in the literature. The results of this summary harmonized with those from the literature reviewed in paper 3, namely, that there are clear improvements in the field, but that it is not yet mature. In relation to the “Assembly instructions” category, for instance, there are large variations in the design and distribution of instructions (Johansson et al., 2017). In the “Training” category, a limitation in current research was identified: many AR experiments have used students and oversimplified tasks, for instance, to assemble LEGO models (Werrlich et al., 2017).

In relation to identified future challenges, it was said to be harder to handle routine tasks when product life-cycles iterate faster and variants increase in number (Hold et al., 2016). One aspect related to rapid changes was identified by the industrial mentor for this thesis, Rodney Lindgren Brewster. The single inspection point (SIP) stations at VCC consist of operators looking for specific quality risks, which vary depending where there are current disruptions. These instructions update more frequently and vary more than for other comparable stations, and the identified challenge is that it seems hard for operators to stop inspecting for quality issues that have been resolved. That is, the main challenge was not to learn how to do new tasks but to stop doing irrelevant old tasks. These challenges are closely related to the increased complexity of the Industry 4.0 concept.
To summarize, objective 1.1 was covered in paper 4. It provided insight into the current maturity of the technology and identified challenges remaining to be solved in the future. It also identified valuable insights into how to efficiently enable ARSG for operators through the six categories related to the operator perspective.

4.2.2 OPERATORS’ NEEDS AND MOTIVATION

The operators themselves are an important aspect of the effective use of ARSG as assembly support. It is important both to consider operators’ ARSG needs in order to use ARSG efficiently and to consider their willingness to use ARSG. Therefore, objectives two and three for RQ1 are:

2. Ascertain whether operators are willing to work with ARSG.
3. Identify operators’ needs in information systems.

Both objectives 1.2 and 1.3 were addressed in paper 2 (Danielsson et al., 2018), which investigates how operators currently interact with assembly instructions. In order to address objective 1.3, operators were observed during assembly work and interviewed about their view of assembly instructions. The observation was performed by following an operator through an assembly cycle of eight consecutive stations and observing whenever they focused their eyes on any instructions. After an observation cycle was performed, the operator was asked what generally makes them look at instructions. Table 4.1 summarizes why operators look at instructions. A total of 35 operators were observed and 24 gave comments on what they specifically looked at. The identified reason why most operators looked at instructions was that some form of interaction or uncertainty had occurred. For instance, a red light was illuminated on the screwing machine when the torque of the screw did not meet requirements, whereas a green light was illuminated when it did. Also, when something unexpected happened, such as the line stopping, the operators would look at the interface to try to understand what had happened.

Table 4.1: Summary of what operators look at in instructions, based on observations of 35 operators.

<table>
<thead>
<tr>
<th>Reasons for looking at instructions</th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required torque for screwing machine</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Assembly time</td>
<td>4</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Something goes wrong</td>
<td>2</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Learning new steps</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Must look at station 240</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Deviations from normal</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Lose their place in the process</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>“When it’s needed”</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>When production stops</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>If the RFID tag does not react</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Checks more when interrupted</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Automatically check at beginning or end</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
The operators were also interviewed using semi-structured interviews. In the interviews, the operators were asked to elaborate on challenges and improvements in instructions. Easy access to information on the screens was useful to some operators when something went wrong or when they forgot. Another operator had many detailed suggestions on how the interfaces could be improved to better present information, such as a general overview of the current production state. There was a desire for more individual instructions, a finding also supported by (Johansson et al., 2017). The category “Assembly instructions” in paper 4 also identifies good practices for assembly instruction design; for instance, multimedia (both text and pictures) (Irrazabal et al., 2016) should be used when adapting instructions, depending on the operators’ experience level (Wolfartsberger et al., 2019), and instructions should be kept simple with a minimal amount of text (Mattsson et al., 2016).

In summary, objective 1.3 was realized, in that operators mostly need instructions to handle interactions and unexpected events. However, instructions can also be valuable to quickly update oneself when one has forgotten what to do next.

Twenty-one of the 28 interviewed operators sporadically expressed a positive view of ARSG; one instead expressed concerns and the remaining six were neutral. This indicates that the operators as a group were positively inclined to use ARSG, representing a response to objective 1.2. At the time of these interviews there were, to the best of the author’s knowledge, no examples of ARSG being used in assembly by operators. This situation has since changed and there are now examples of AR being used as assembly operator support (Campbell et al., 2019).

4.3 MANUFACTURING ENGINEERING PERSPECTIVE

To facilitate the integration of ARSG, it is also essential to understand the manufacturing engineering perspective. RQ 2 is therefore formulated as: “What do manufacturing engineers and technicians need in ARSG so that the technology can be integrated into, maintained, and updated in a production system?”

4.3.1 PREVIOUS WORK FROM THE MANUFACTURING ENGINEERING PERSPECTIVE

To get a more thorough understanding of the manufacturing engineers and the technology they should integrate and maintain in relation to this framework, objective 2.1 was defined as: “Conduct a literature review of ARSG in manufacturing from a manufacturing engineering and technical perspective.”

Paper 5 (Danielsson et al., 2020b) used the mapping of the manufacturing engineering perspective and technological maturity perspective in paper 3 as a basis (Danielsson et al., 2019). The manufacturing engineering perspective has three categories and the technological maturity perspective has four, as seen in Figure 4.2. These categories were reviewed, and the findings analyzed and summarized into the current status and future challenges identified in the literature reviewed. The general findings was that whereas the administrative tools related to ARSG and the ARSG themselves are still not fully mature for industrial use as assembly operator support tools, there have been considerable improvements, indicating that the industrialization of ARSG is very likely in the near future.

An important ability so that ARSG will be able to work continually is the ability to efficiently create and update assembly instructions, defined in paper 5 as the “Authoring” category. Authoring tools have improved with, for instance, preliminary improvements in automatic instruction generation (Kaipa et al., 2018, Pham and Xiao, 2018).
Future challenges lie in further improving the tools to provide robust support in efficient authoring.

The “Infrastructure” category of the manufacturing plants has also seen improvements that can support ARSG. One suggested improvement is, for instance, individual RFID markers in each product to decentralize product assembly status (Paelke, 2014). A digital coordinate system could also improve ARSG navigation inside factories (Yew et al., 2016). Future challenges include improving the data transfer rate and reducing latency (Li et al., 2018). There are also guidelines for evaluating AR equipment that needs to be further improved (Palmarini et al., 2017, Syberfeldt et al., 2017).

The two previous categories are related to the last category of the manufacturing engineering perspective, namely “Validation.” This category relates to how ARSG implementations can be validated as ready for industrial cases. One way that is still relevant is specialized learning factories (Hennig et al., 2019, Juraschek et al., 2018). There is also a drawback in that “published evaluation and test results often cover out-of-date hardware or prototype systems” (Paelke et al., 2018, p.26). A future challenge is how to conduct usability tests of visualization and, more generally, to have a more adaptable test platform (Paelke et al., 2018).

To summarize the manufacturing engineering perspective, several efforts are being made to automate and digitalize tools and factories so that ARSG become less work intensive to integrate. However, there are still challenges in making them accurate enough and in validating the designs for industrial environments.

The technological maturity perspective was added based on the findings of paper 3. Its categories relate to technologies that are needed in order to have mature ARSG; the technological maturity perspective should therefore be seen as a perspective that connects the other two perspectives.

The “Technological demands” category investigated how ARSG need to be improved to meet the demands put on them in industrial cases. Future challenges include the persistent lack of industrial standards regarding AR (Ji et al., 2019). There are also needs to improve certain technical aspects, such as extending the FOV (Syberfeldt et al., 2017), improving battery capacity (Wang et al., 2018), and integrating system data with enterprise data (Wang et al., 2016).

The “Enabling technology” category investigated three sub-categories: “Technological level,” “FOV,” and “Battery.” The first sub-category looked at the overall maturity of ARSG and their sub-components. Non-AR smart glasses (SG) have a technological readiness level (TRL) of 9, AR displays a TRL of 7, and tracking, interaction, and user interfaces (UI) a joint TRL of 5 (Lacueva-Pérez et al., 2018). Other sources estimated AR TRL to be in the range of 4 to 7 (Eckert et al., 2019, Harrison et al., 2019, Salvador et al., 2019). In the second sub-category, an experimental setup could achieve a FOV of 100 degrees diagonally (Dunn et al., 2017). The largest FOV identified in any commercially available ARSG was 52 degrees diagonally in the Hololens 2 (Danielsson et al., 2020b). In the last sub-category, it was found that one solution to improve ARSG battery durability is to outsource calculations from the ARSG and then send back the results (Um et al., 2018). There is also large variance in battery capacity among commercially available ARSG (Danielsson et al., 2020b). Future work should further improve the TRL levels and capacities.

The “ARSG” category expanded previous mappings of commercially available ARSG and listed their relevant technical specifications (Fang et al., 2019, Kumar et al., 2018, Syberfeldt et al., 2017). These specifications vary significantly among the listed ARSG, with, for instance, the weight varying between 69 and 579 grams and the FOV between
15 and 52 degrees diagonally. The large variation could partly be due to the dynamic emergence of the ARSG market and the fact that it is not yet clear what the optimal format of ARSG will be.

The “Tracking” category mapped technologies used by ARSG to track their environment and thereby enable AR. The industrial suitability of these technologies was also evaluated. A common solution to increase accuracy is to use a hybrid approach combining several tracking technologies to compensate for their different weaknesses (Chatzopoulos et al., 2017). Current improvements in terms of, for instance, the reduced size of microelectromechanical systems (MEMS) have introduced new challenges in the form of increased drift (Sheng-lun et al., 2017).

To summarize the technological maturity perspective, there have been clear improvements in ARSG enabling technology. However, there are still clear challenges in making ARSG a fully mature technological field, especially given the further restraints imposed by industrial needs.

4.3.2 MANUFACTURING ENGINEERING VIEWS

As with the operators, it is relevant to understand the needs of the manufacturing engineers who will integrate, update, and maintain the ARSG. Objective 2.2 is therefore defined as: “Gather experience from manufacturing engineers and technicians about relevant challenges in implementation, updating, and maintenance.”

It was decided to fulfill this objective using the strawman developed for paper 6 (Danielsson et al., 2022), further described in Chapter 5. The motivation for this decision was based on that AR in general is currently not widely used in industry (Rauch and Matt, 2021). It was therefore assumed that there is likely little experience among manufacturing engineers and technicians in working with ARSG. The knowledge gained from the previous objectives and earlier publications was therefore used to create a strawman design to focus the discussions.

The experience of manufacturing engineers and technicians was gathered through focus groups in which the strawman was used to guide the discussions. The strawman consisted of a set of questions seen as relevant to ARSG integration. In general, the feedback was that how to best implement ARSG depends on the specific production case and can vary significantly. Most feedback related to the variation within each question rather than to any significant questions being missing. One question was added: “A lot of expensive equipment is currently needed to guide operators in assembly work.” One example of variation feedback is that the shorter the cycle time for operators, the more likely it is that information about what to do will be more relevant than information about how to do something. At the same time, however, the feedback is dependent on the number of variants, and the more variants there are, the more relevant process information becomes. To integrate ARSG, it is important to consider what data are needed and where they are stored. Security issues need to be considered when transferring production data to the ARSG.

In summary, the manufacturing engineers and technicians provided practical insights not just into how to make ARSG part of a production line like any other production tool, but also into what value the ARSG adds. These insights provided an essential complement to the operator perspective already explored.

4.4 FRAMEWORK WORKFLOW

This section gives a holistic view of how the framework fits into the context within which it is to operate. Figure 4.3 is a flowchart that gives an overview of the context and flow of
general process for which the framework is designed. The purple sections mark the parts of
the flowchart that directly involve the framework. The process starts at the top of Figure
4.3, with deciding on an assembly station that needs better operator support. The following
step is to consider ARSG: Could they be an efficient way to support operators in the station
being evaluated? If there is already enough knowledge to make an informed decision ("yes
or no"), then use of the framework can be skipped and one can either specify what type of
ARSG, and possible support system, to purchase, or consider other options. In the unlikely
event that there are no other options, a new station can be chosen, and the process re-
started. If there are other options, it is effective to rank them to prioritize the best option to
further investigate.

If it is not clear whether ARSG are suitable, or it is not clear how suitable they are, then the
framework should be applied. The first step is to answer the questions regarding the case
station. If the result is positive, this indicates that ARSG could be suitable and the detailed
recommendations should be evaluated. If the detailed recommendations indicate that
ARSG are not cost-effective enough, then other options should be considered. If it is instead
indicated that ARSG could be a cost-effective solution, the detailed recommendation evalu-
ation can then be used to formulate ARSG purchase specifications. If answering the
framework questions instead gives a negative result, then other options should be consid-
ered. If, when all options are considered, there is a more suitable way than ARSG to improve
operator efficiency at the station, then this should be considered first. If ARSG, when con-
sidering all other options, are still the best option, then the detailed recommendations
should be considered, or even reconsidered. If ARSG are still not considered suitable, then
another option should be considered. If ARSG are instead found suitable enough to be cost-
effective at this stage, considering the alternatives, then the evaluation of the detailed rec-
ommendations can be used as a basis for formulating ARSG purchase specifications.
In this overview, the operator and manufacturing engineering perspectives are both integrated. The operator perspective is mainly part of the first step, i.e., identifying a station that needs of improved support to operators to improve their efficiency. It is also part of considering other options, since these options also concern how operators can be utilized more efficiently. The manufacturing engineering perspective is part of the implementation step and considers what is feasible in regard to implementing the operator support. The next chapter describes the framework section of Figure 4.3 in more detail.
FRAMEWORK
CHAPTER 5
FRAMEWORK

All models are wrong, but some are useful
Now it would be remarkable if any systems existing in the real world could be exactly represented by any simple model. However, cunningly chosen parsimonious models often do provide remarkably useful approximations. (Box, 1979, p.202–203)

The overarching aim of the research presented in this thesis is to provide a framework to support practitioners in the manufacturing industry in making strategic decisions as well as to convey practical considerations regarding integrating ARSG as a support tool for assembly operators in production. The first section, “Scope and delimitations,” explains and justifies what the framework does and does not do. The second section, “Combined overview,” broadly presents how the framework was developed and evaluated. The third section, “First design of the framework,” shows how the framework was iteratively developed on a strawman basis into its first form, as presented in paper 6. The fourth section, “Second design of the framework,” shows how the framework was iteratively improved and evaluated, as presented in paper 7. The fifth section, “Framework fulfilment of RQ 3”, summarizes the results and the value that the framework provides and the connection to RQ 3. The framework is presented in the last section.

The creation of the framework was guided by RQ3: “When and how can both the operators’ and the manufacturing engineers’ and technicians’ needs for ARSG be met?”

5.1 SCOPE AND DELIMITATIONS
The developed framework, being a model of a real-world phenomenon, is inherently a simplification. Chapter 2 and papers 3–5, as presented in Chapter 4, show that the theoretical basis is broad and complex, emphasizing the need to limit the scope of the framework.

The intended users of the framework are mainly industrial practitioners with or without previous knowledge of ARSG. Within this user group, there are two intended per-
perspectives, those of: managers making investment decisions, and manufacturing engineers tasked with making the ARSG work in production “like any other production equipment.” No clear demarcation is intended between these perspectives, as both can be present in different intensities in a single person.

It is commonly known that industrial managers have a great need to prioritize the usage of time. As Chapter 2 briefly showed, ARSG are only one of many new technologies within Industry 4.0 and, in general, there are many ways in which production can be made more effective. The framework has therefore been limited in size to make it more accessible. Obtaining a preliminary result from using the framework within approximately 20 minutes was a guideline during its initial design.

Table 5.5 presents the final framework. The framework can be used manually, for instance by printing out the table and manually calculating the score and looking up recommendations for specific cases. This is time-consuming and error prone as well as hard to distribute. So, a tool-implementation was created in the form of a web-page, that serves as a distribution medium of the framework.

Another aspect of the framework is how broad or narrow it should be. Since the manufacturing industry produces everything from fighter planes to candy wrappers, there cannot be universal standards for the industry. In general, two choices can be made: to limit the scope of the framework to industries with specific criteria, or to keep the framework more broadly accessible at the cost of precision. The latter choice was made for the framework, prioritizing generalizability.

5.2 COMBINED OVERVIEW

The objectives for RQ 3 are:

1. Combine the data gathered from RQ 1 and RQ 2.
2. Synthesize them into a framework.
3. Evaluate the practical usefulness of the framework for industry in making strategic decisions about ARSG.

This section gives an overview of how these objectives were achieved.

Figure 5.1 presents an overview of how the framework was developed and evaluated. As described in my licentiate thesis, papers 1–5 formed the foundation for the work on the framework (Danielsson, 2020). For paper 6, the condensed results of this previous work formed the basis for a strawman design of the framework, implemented in an online tool; this fulfilled objective 3.1. Objectives 3.2 and 3.3 were fulfilled iteratively in papers 6 and 7. The strawman version was then iteratively improved through focus groups and a pilot test, involving experts from industry and academia. The results of this, Version I, were evaluated through an online survey. For paper 7, Version I was expanded into a new strawman, Strawman II, to form the basis of a new iteration with expanded functionality. Focus groups were used to design a Version II of the framework, which was evaluated using case studies.
5.3 FIRST DESIGN OF THE FRAMEWORK: PAPER 6

This section presents the work of paper 6, in which the first design of the framework was developed and evaluated (Danielsson et al., 2022). The first version of the framework provided a way to conduct a quick initial screening of suitable production cases. It did so by identifying critical issues and by giving an overall recommendation regarding the suitability of the case.

5.3.1 STRAWMAN I

The first strawman design was based mainly on the data and experience gathered for papers 1–5. Papers 1–6 in the list of publications of lower relevance to this thesis also contributed, mainly in the form of accumulated experience in the field of AR as assembly support. In its first draft, the framework was a set of questions with 5-point Likert-
type answer alternatives, implemented in an interactive spreadsheet. When it became clear that this was too limited, it was decided to implement the framework using a web-based tool with more individually designed answer alternatives to suit the different questions. This implementation format allowed follow-up questions to be asked if specific answer alternatives were chosen, which was done for five of the questions in the final version of the framework. A stable version of the tool became the first strawman (Danielsson et al., 2022).

5.3.2 ITERATIVE IMPROVEMENT OF THE FRAMEWORK

The strawman was then discussed in a focus group consisting of academic and industrial experts within the areas of manufacturing engineering related to production. One description of focus groups is that they are “(1) a small group of people, who (2) possess certain characteristics, (3) provide qualitative data (4) in a focused discussion (5) to help understand the topic of interest” (Krueger and Casey, 2014, p. 6). As expected, several flaws were identified in the strawman, such as too narrow a scope in some of the answer alternatives and important omitted questions that needed to be asked. The conclusions of the focus group discussions were implemented in an improved design and presented to a new focus group, in which the process was repeated. A third session was conducted with one participant. Table 5.1 gives an overview of the group participants.

Table 5.1: Composition in groups for first iterative improvement of the framework.

<table>
<thead>
<tr>
<th>Focus group 1</th>
<th>Focus group 2</th>
<th>Interview</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Academics</td>
<td>1 Academic</td>
<td>Manufacturing engineer</td>
</tr>
<tr>
<td>1 Senior manager</td>
<td>2 Senior managers</td>
<td></td>
</tr>
</tbody>
</table>

After the iterative improvements, the questions and answer alternatives were locked, and the focus group participants were invited to complete a survey in which each answer alternative was to be given a weighted value of 0–7, with 0 representing no ARSG suitability and 7 representing full ARSG suitability. Six industrial experts, also within the area of manufacturing engineering related to production, completed the survey. Three of the experts had already partaken in the focus groups. The median values of their answers were used to weight the answer alternatives (multiplied by 100 to fit the calculation requirements of the computer code). This then became the suitability score for each answer alternative, ranging from 0–700 theoretically, 50–550 in practice. The ARSG suitability score is calculated by summing up the score for each chosen answer alternative and dividing with the maximum possible score. The result is normalized to a value ranging from 1-100, which is the ARSG recommendation score. The questions, answer alternatives, and scores are presented in Table 5.5 (the recommendations are described in paper 7).

The iteratively improved framework was then pilot tested. Seven manufacturing engineers, who had not been involved in the previous steps, used the framework individually. After using the framework, they filled in a survey and participated in a discussion of their views of the framework. The results from the pilot test group are summarized in Table 5.2. Participants 1-5 worked in the automotive sector and participants 6 & 7 worked within grain handling equipment manufacturing. The results of the pilot test survey were deemed satisfactory enough to proceed to a full-scale test. The summarized conclusions of the pilot test discussions led to a final revision of the framework before the full-scale test. A translated screenshot of the framework can be seen in Figure 5.2.
### Table 5.2: Summary of the pilot test group participants, their self-estimations, and the framework results.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Role</th>
<th>Experience</th>
<th>Self-estimation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Production engineer</td>
<td>0–1 years</td>
<td>72</td>
<td>61</td>
</tr>
<tr>
<td>2</td>
<td>Production engineer</td>
<td>2–4 years</td>
<td>100</td>
<td>61</td>
</tr>
<tr>
<td>3</td>
<td>Production engineer</td>
<td>5 or more years</td>
<td>100</td>
<td>64</td>
</tr>
<tr>
<td>4</td>
<td>Manager</td>
<td>5 or more years</td>
<td>63</td>
<td>74</td>
</tr>
<tr>
<td>5</td>
<td>Production engineer</td>
<td>0–1 years</td>
<td>56</td>
<td>48</td>
</tr>
<tr>
<td>6</td>
<td>Process engineer</td>
<td>5 or more years</td>
<td>50</td>
<td>52</td>
</tr>
<tr>
<td>7</td>
<td>Manager</td>
<td>5 or more years</td>
<td>62</td>
<td>52</td>
</tr>
</tbody>
</table>

### The tool

Now the actual tool starts. Answer the following questions below. Sometimes you will receive follow up questions, answer them as well. Choose the answer you feel lies the closest if nothing completely fits.

**First estimation (does not affect your result)**

Grab the arrow below and drag to where you think your result will be.

- **Operators**
  1. The surface for each station where the operator works is:
     - 0–2 meters
     - 3–5 meters
     - 6–10 meters
     - The question is asked to estimate how much repetition training the operators receive and how much time there is to take on new information.
  2. The cycle time for the operators is:
     - Less than 2 minutes
     - Up to an hour
     - Several hours
     - Several days
     - None (craftsmanship)

**Figure 5.2:** Screenshot of the first page of the tool implementation of the framework, translated from Swedish.
5.3.3 EVALUATION
The first version of the framework was evaluated using a survey. The framework was
distributed through networking to industrial representatives working with production
in one form or another. The tool implementation of the framework then led them
through an introduction to ARSG, the tool, and the purpose of the tool. This was fol-
lowed by the contents of the framework, which they were encouraged to use to evaluate
a production case of their choosing. The ensuing step showed a result where the frame-
work generated a score in the range of 1–100 indicating how suitable the case was for
ARS integration. Any questions in the framework that generated a follow-up ques-
ton were presented first in a list of critical issues with specific recommendations for
how to address them. In the last step, the representatives were presented with a survey
about the framework. The survey questions and the reasons for including them are
presented in Table 5.3, as formulated by (Danielsson et al., 2022). The survey used a
Likert scale of 1–5.

Table 5.3: Survey statements in the last step of evaluating the web-based tool and related motivations, as reported by Danielsson et al. (2022). The Likert scale ranged from 1 “I disagree” to 5 “I agree.”

<table>
<thead>
<tr>
<th>Statement</th>
<th>Motivation</th>
<th>Average, (pilot average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I believe the questions were relevant for the evaluation of ARSG</td>
<td>The questions constitute the main data from which the result is generated, so it is important that the target user finds them relevant.</td>
<td>3.9 (4.0)</td>
</tr>
<tr>
<td>2. The tool guided me to make a decision</td>
<td>The purpose of using the tool is to assist decision making.</td>
<td>3.1 (3.3)</td>
</tr>
<tr>
<td>3. I think the tool recommendation is reliable</td>
<td>To evaluate the generated result of using the tool.</td>
<td>3.5 (4.0)</td>
</tr>
<tr>
<td>4. I would consider using this tool as part of my work</td>
<td>To determine whether test participants could envision practical use of the tool in their routine work.</td>
<td>3.8 (3.3)</td>
</tr>
<tr>
<td>5. The tool is good overall</td>
<td>To estimate general satisfaction with the tool.</td>
<td>3.6 (3.9)</td>
</tr>
</tbody>
</table>

5.3.4 RESULTS FOR THE FIRST DESIGN
The results of the survey are presented in Figure 5.3. R1–R5 represent the five state-
ments from Table 5.3. The total number of respondents was 22 and the numbers on the
x-axis show the number of answers for each answer alternative. For instance, for
R1 two respondents did not answer, one answered one, four answered three, eleven
answered four, and four answered five. The two horizontal lines for each statement
represent the average value for the main test and the pilot test. The averages for all
statements are above the middle value of three, i.e., 3.9, 3.1, 3.5, 3.8, and 3.6, respec-
tively, for the main test, indicating a positive view in the test population. There was
also room to provide free-text comments, and eight out of 22 respondents did so. Their
comments provided constructive feedback on areas in which to further improve both
the framework and the delivery of the framework in its tool implementation, as de-
scribed by Danielsson et al. (2022).
5.4 SECOND DESIGN OF THE FRAMEWORK: PAPER 7

This section presents the work of paper 7, in which the framework was further expanded and evaluated to provide more detailed practical and strategic guidance (Danielsson et al., 2021b).

5.4.1 STRAWMAN II

In paper 7, a second strawman was developed, based on previous experience (described in paper 6) and on the results of paper 6. The focus of this development cycle was to improve the functionality of the framework to provide more concise practical recommendations on what to consider when deciding whether ARSG are a profitable investment and how to go about the process of ARSG integration in a production system as an operator support tool. The new strawman consisted of adding a recommendation for each answer alternative to provide guidance for the corresponding production case. The questions and their answer alternatives were design locked and all focus was on increasing the functionality. This was done as a way to handle resources; the framework consists of two steps: answering questions, and receiving recommendations depending on the answers. The recommendations are therefore dependent on what the questions are, so focus groups would need to have two sessions: one round to refine the questions, and another round to develop recommendations. This was not feasible due to the time limitations of participating industry experts. A translated version of the tool implementation of the framework is presented in Figure 5.4. The three recommendations visible are translations of the final version of the framework recommendations.
5.4.2 ITERATIVE IMPROVEMENT OF FRAMEWORK FROM FIRST DESIGN

For the second version, a new round of focus groups with new participants was arranged. There were five groups, which had 2, 5, 3, 2, and 4 participants. The participant affiliations are shown in table 5.4. The new strawman was published online and made available to all focus group participants before the booked discussions. Participants were encouraged to test the framework, but it was not mandatory. During the focus group discussions, all questions and their answer alternatives were presented, one question at a time, and a thematic discussion was conducted based on the participants’ views. The participants were asked to imagine integrating ARSG into production “like any other production equipment” and what they would consider regarding profitability and challenges in practical implementation. The focus group sessions were recorded to minimize data loss risks.

Table 5.4: Focus group participant affiliations, as presented in Danielsson et al. (2021a).

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Global manufacturer in the automotive sector.</td>
</tr>
<tr>
<td>2</td>
<td>Global manufacturer of electric cars.</td>
</tr>
<tr>
<td>3</td>
<td>Global manufacturer of sheet metal machinery.</td>
</tr>
<tr>
<td>4</td>
<td>Global manufacturer in the field of safety and graphics, healthcare, and consumer products.</td>
</tr>
<tr>
<td>5</td>
<td>Global company working within the sectors of energy, industry, and infrastructure.</td>
</tr>
<tr>
<td>6</td>
<td>Swedish subcontractor for the automotive sector.</td>
</tr>
<tr>
<td>7</td>
<td>Global manufacturer of trucks, busses, and construction equipment.</td>
</tr>
<tr>
<td>8</td>
<td>Nordic supplier of industrial tools, metrology, service, and the aftermarket.</td>
</tr>
<tr>
<td>9</td>
<td>Swedish university doing research in close collaboration with local industries.</td>
</tr>
</tbody>
</table>
Each focus group discussion was analyzed sequentially, with suggestions, considerations, etc., being summarized in bullet-point lists. All groups were analyzed in parallel, each question being analyzed in light of the data from all five focus groups on the specific question, to synthesize the results of the five groups into one result. No conflicting views were identified, and several views were present in more than one group. This synthesis led to a set of recommendations and viewpoints of the combined groups that were then interpreted and mapped to the different answer alternatives to provide cohesive recommendations for each answer alternative. The summaries as well as the final version of the tool implementation of the framework were then disseminated to the focus group participants to allow for objections or feedback. No further objections and feedback were noted.

5.4.3 EVALUATION OF THE FINAL FRAMEWORK
The second, and final, version of the framework (paper 7) was evaluated using case studies. Three manufacturing companies participated in these case studies. Each case study included a group of two or three representatives of the company using the framework. Case 1 was a global manufacturer of sheet metal machinery. Case 2 was global manufacturer in the automotive sector. And case 3 was a Swedish manufacturer of grain-handling equipment. In each case study, a case was chosen by the company representatives, and the framework was applied according to the case. The overall score and critical issues were analyzed, as was the detailed list of recommendations, each of which was read through and discussed to evaluate how well it was believed to fit the case. All three groups were able to internally agree on one interpretation and they all found the recommendations to be relevant and applicable to their cases.

5.4.4 RESULTS
One of the groups criticized the answer alternatives in regard to question eight in the operator section; the response alternatives (i.e., very rarely, rarely, somewhat often, often, and very often) were seen as vague. No other criticism was expressed by any of the three groups, which found the recommendations given in the framework to fit the case chosen for evaluation.

5.5 FRAMEWORK FULFILMENT OF RQ 3
The framework has been iteratively developed and evaluated based on both theoretical and practical knowledge. As described above, the design was based on experience, data collection, and synthesis between 2013 and 2020. The evaluations tested the framework at different stages from the quantitative and qualitative perspectives. The results and the informal feedback from industrial representatives indicate that they see the framework as accurate and valuable. Based on this, it is concluded that the framework answers RQ 3 by providing detailed recommendations on how and when to integrate ARSG into production as an assembly operator support tool. The framework thus fulfills the aim of the thesis to “provide a framework that supports manufacturing industry in deciding whether or not to integrate ARSG for assembly operators, in order to guide their work in specific cases.”

5.6 FINAL VERSION OF THE FRAMEWORK
This section presents the final version of the framework in its entirety (see Table 5.5). The framework has been implemented and, as of the publication of this thesis, is available as an online tool (in Swedish) at: https://www.arsg-quick-evaluation-tool.se.
Table 5.5: The framework in its entirety, translated from Swedish.

<table>
<thead>
<tr>
<th>Answer options</th>
<th>Recommendations</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operators</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. The surface of each station where the operator works:</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tooltip:</strong> The surface is per station. Do not count areas where the operator just repositions.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–2 meters</td>
<td>In general, there are more alternatives to ARSG at short distances, for instance, TV screens. But even at short distances, ARSG have the advantage that the information is in the operators’ field of view so that they do not have to switch focus by looking at a screen. If 3D functions are used, then ARSG can also show information directly over the work object.</td>
<td>350</td>
</tr>
<tr>
<td>3–5 meters</td>
<td>In general, there are more alternatives to ARSG at relatively short distances, for instance, TV screens. It can be hard to see details on TV screens, which can be mitigated by placing them on swing arms. But even at short distances, ARSG have the advantage that the information is in the operators’ field of view so that they do not have to switch focus by looking at a screen. If 3D functions are used, then ARSG can also show information directly over the work object.</td>
<td>450</td>
</tr>
<tr>
<td>6–10 meters</td>
<td>A big advantage of ARSG compared with TV screens is that they are mobile and can show information regardless of where the operator is. But for them to be able to keep themselves updated they need a wireless connection, which becomes a bigger challenge over somewhat longer distances.</td>
<td>300</td>
</tr>
<tr>
<td>More than 11 meters</td>
<td>A big advantage of ARSG compared with TV screens is that they are mobile and can show information regardless of where the operator is. But for them to be able to keep updated they need a wireless connection, which becomes a bigger challenge over very long distances.</td>
<td>400</td>
</tr>
<tr>
<td>I don’t know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
<td>-</td>
</tr>
<tr>
<td>2. The cycle time for the operators is:</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tooltip:</strong> The question is asked to estimate how many training repetitions the operators receive and how much time there is to absorb new information.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than 2 minutes</td>
<td>With shorter cycles the operators generally get more training and the tasks are often designed to need fewer instructions, so the need for information is reduced. The short cycles also allow less opportunity for complicated instructions such as animations or video sequences. But the short cycles also mean that the costs of instructions are spread over more units. In this case, ARSG can be especially interesting to ensure that everyone follows standards, even between shifts. Instructions can be limited to showing specific variations between variants and/or support in retraining muscle memory during changes; relearning can be especially challenging.</td>
<td>250</td>
</tr>
<tr>
<td>Up to an hour</td>
<td>The longer the cycles, the harder it becomes for operators to learn and remember instructions, especially with a high workload, and then ARSG can be an interesting alternative to give ongoing information support. ARSG can also ensure that everyone follows standards and can give support in retraining muscle memory during changes; relearning can be extra challenging.</td>
<td>400</td>
</tr>
<tr>
<td>Several hours</td>
<td>During such long cycles it becomes hard for operators to learn and remember instructions, especially with a high workload, and then ARSG can be an interesting alternative to give ongoing information support. ARSG can also ensure that everyone follows standards and can give support in retraining muscle memory during changes; relearning can be extra challenging.</td>
<td>500</td>
</tr>
<tr>
<td>Several days</td>
<td>During such long cycles it becomes very hard for operators to learn and remember instructions, and then ARSG can be an interesting alternative to give ongoing information support. ARSG can also ensure that everyone follows standards and can give support in relearning.</td>
<td>450</td>
</tr>
<tr>
<td>None (craftsmanship)</td>
<td>During craftsmanship work, programming step-by-step instructions can become very costly. But ARSG can also support through for example, two-way communication and distance guidance.</td>
<td>550</td>
</tr>
<tr>
<td>I don’t know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
<td>-</td>
</tr>
<tr>
<td>3. The work environment requires safety glasses.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tooltip:</strong> The question helps to estimate the ergonomics and risks to the equipment.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Never</td>
<td>Safety glasses are no hindrance to wearing ARSG.</td>
<td>150</td>
</tr>
<tr>
<td>For some stations</td>
<td>If safety glasses are only needed sometimes, a convenient alternative could be to wear ARSG when safety glasses are not needed. If that is not feasible, then either both need to be worn at the same time or ARSG have to be used as safety glasses. ARSG involve sensitive technology, so if safety glasses are needed it is important to assess the risk of damage to the ARSG in the environment. Fluids and particles pose a particular risk to the electronics. This risk could be reduced by enclosing the ARSG in an additional protective casing or by wearing safety glasses on top of the ARSG. Regardless of the solution, it will reduce the available options and may increase costs when customizing. It is important to review the ergonomics and functionality of the new solution.</td>
<td>200</td>
</tr>
<tr>
<td>For most stations</td>
<td>It is probably not suitable to switch between ARSG and safety glasses if they are needed at most stations. If this is not feasible, then either both need to be worn at the same time or ARSG have to be used as safety glasses. ARSG involve sensitive technology, so if safety glasses are needed it is important to assess the risks of damage to the ARSG in the environment. Fluids and particles pose a particular risk to the electronic. This risk could be reduced by enclosing the ARSG in an additional protective casing or by wearing safety glasses on top of the ARSG. Regardless of the solution, it will reduce the available options and may increase the costs when customizing. It is important to review the ergonomics and functionality of the new solution.</td>
<td>150</td>
</tr>
</tbody>
</table>
**Always**

If safety glasses are always needed, then either both need to be worn at the same time or ARSG have to be used as safety glasses. ARSG involve sensitive technology, so if safety glasses are needed it is important to assess the risk of damage to the ARSG in the environment. Fluids and particles pose a particular risk to the electronics. The risk could be reduced by enclosing the ARSG in an additional protective casing or by wearing safety glasses on top of the ARSG. Regardless of solution, it will reduce the available options and may increase costs when customizing. It is important to review the ergonomics and functionality of the new solution.

**I don't know**

This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.

---

**4. The operators share the workspace with moving vehicles during assembly work.**

*Tooltip: Only count vehicles that the operator risks colliding with and damage themselves, for instance, bicycles, forklifts, and the like.*

<table>
<thead>
<tr>
<th>Option</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Always</td>
<td>If safety glasses are always needed, then either both need to be worn at the same time or ARSG have to be used as safety glasses. ARSG involve sensitive technology, so if safety glasses are needed it is important to assess the risk of damage to the ARSG in the environment. Fluids and particles pose a particular risk to the electronics. The risk could be reduced by enclosing the ARSG in an additional protective casing or by wearing safety glasses on top of the ARSG. Regardless of solution, it will reduce the available options and may increase costs when customizing. It is important to review the ergonomics and functionality of the new solution.</td>
</tr>
<tr>
<td>I don't know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
</tr>
</tbody>
</table>

**5. What do the operators need to wear?**

*Tooltip: Count all types of head-worn equipment that the operators need. Here it's estimated how much space the operators need in order to wear a pair of AR smart glasses.*

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nothing</td>
<td>Other equipment on the head does not hinder ARSG. When choosing ARSG, it's important to also consider the ergonomics, as they weigh more than regular glasses and some models cannot be worn together with glasses.</td>
</tr>
<tr>
<td>Helmets to protect the skull</td>
<td>Helmets limit the supply of ARSG somewhat, especially if many different helmet models are used. It's also important to consider the ergonomics, as they weigh more than regular glasses and some models cannot be worn together with glasses and instead need polished glasses. It's also important to ensure compatibility between ARSG and ear protection.</td>
</tr>
<tr>
<td>Welding helmets or similar that cover the face</td>
<td>Generates a follow-up question.</td>
</tr>
<tr>
<td>Helmets that completely enclose the head</td>
<td>Generates a follow-up question.</td>
</tr>
<tr>
<td>I don't know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
</tr>
</tbody>
</table>

---

**FOLLOW-UP.** Your latest answer means that operators risk moving in traffic with smart AR glasses. Expand on how the operators come in contact with traffic.

*Tooltip: The purpose of this question is to estimate how to best adapt the usage of ARSG to the traffic situation.*

<table>
<thead>
<tr>
<th>Question</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>The operators come in direct contact with vehicles within their work area</td>
<td>ARSG take a lot of attention and should not be used where operators come into direct contact with vehicles. If the need for ARSG can be limited to where there is no contact this is preferable. It's recommended to also evaluate whether the contact can be built away, for instance, by shielding vehicles from operators. Where this is not possible, vehicles can be equipped with warning lights to reduce risks in general. Clear routines regarding where and when ARSG shall be used should be established, but the human factor will always exist, so implementation should first be done on a small scale. Eventually, ARSG could potentially offer protection through software and by warning of traffic.</td>
</tr>
<tr>
<td>The operators need to move through trafficked areas for some tasks</td>
<td>ARSG take a lot of attention and should not be used where operators come into direct contact with vehicles. If the need for ARSG can be limited to where there is no contact, this is preferable. It's recommended to also evaluate whether the contact can be built away, for instance, by shielding vehicles from operators. Where this is not possible, vehicles can be equipped with warning lights to reduce risks in general. Clear routines regarding where and when ARSG shall be used should be established, but the human factor will always exist, so implementation should first be done on a small scale. Eventually, ARSG could potentially offer protection through software and by warning of traffic.</td>
</tr>
<tr>
<td>The operators need to move through trafficked areas to get to and from their workstations</td>
<td>ARSG take a lot of attention and should not be used where operators come into direct contact with vehicles, so they should preferably only be used at the work stations. It's recommended to also evaluate whether the contact can be built away, for instance, by shielding vehicles from operators. Where this is not possible, vehicles can be equipped with warning lights to reduce risks in general. Clear routines regarding where and when ARSG shall be used should be established, but the human factor will always exist, so implementation should first be done on a small scale. Eventually, ARSG could potentially offer protection through software and by warning of traffic.</td>
</tr>
<tr>
<td>There is traffic directly next to the work environment but it is delimited from the operators</td>
<td>ARSG take a lot of attention and should not be used where operators come into direct contact with vehicles, so they should preferably only be used at the work stations. As an extra precaution, vehicles can be equipped with warning lights to reduce risks in general. Clear routines regarding where and when ARSG shall be used should be established, but the human factor will always exist, so implementation should first be done on a small scale. Eventually, ARSG could potentially offer protection through software and by warning of traffic.</td>
</tr>
<tr>
<td>I don't know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
</tr>
</tbody>
</table>

---

**5. What do the operators need to wear on their heads?**

*Tooltip: Here it's specified exactly how limited the room is for the operator to wear equipment on the head.*

| Equipment sits so tightly that there is only room for regular glasses | If current equipment does not have room for ARSG, it needs to be replaced or modified so that there is room in front of the eyes and around the ears for ARSG. It's also important to consider ergonomics, as ARSG weigh more than regular glasses and some models cannot be worn together with glasses and instead need polished glasses. It's also important to ensure compatibility between ARSG and ear protection. When there is a lot of equipment worn on the head, it's also important to make a holistic evaluation of all relevant aspects to ensure optimal performance and comfort. |

---

**CHAPTER 5 FRAMEWORK**

**Chapter 5 Framework**

**5. What do the operators share the workspace with moving vehicles during assembly work?**

*Tooltip: Only count vehicles that the operator risks colliding with and damage themselves, for instance, bicycles, forklifts, and the like.*

<table>
<thead>
<tr>
<th>Option</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Always</td>
<td>If safety glasses are always needed, then either both need to be worn at the same time or ARSG have to be used as safety glasses. ARSG involve sensitive technology, so if safety glasses are needed it is important to assess the risk of damage to the ARSG in the environment. Fluids and particles pose a particular risk to the electronics. The risk could be reduced by enclosing the ARSG in an additional protective casing or by wearing safety glasses on top of the ARSG. Regardless of solution, it will reduce the available options and may increase costs when customizing. It is important to review the ergonomics and functionality of the new solution.</td>
</tr>
<tr>
<td>I don't know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
</tr>
</tbody>
</table>

---

**FOLLOW-UP**

Your latest answer means that operators risk moving in traffic with smart AR glasses. Expand on how the operators come in contact with traffic.

*Tooltip: The purpose of this question is to estimate how to best adapt the usage of ARSG to the traffic situation.*

<table>
<thead>
<tr>
<th>Question</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>The operators come in direct contact with vehicles within their work area</td>
<td>ARSG take a lot of attention and should not be used where operators come into direct contact with vehicles. If the need for ARSG can be limited to where there is no contact this is preferable. It's recommended to also evaluate whether the contact can be built away, for instance, by shielding vehicles from operators. Where this is not possible, vehicles can be equipped with warning lights to reduce risks in general. Clear routines regarding where and when ARSG shall be used should be established, but the human factor will always exist, so implementation should first be done on a small scale. Eventually, ARSG could potentially offer protection through software and by warning of traffic.</td>
</tr>
<tr>
<td>The operators need to move through trafficked areas for some tasks</td>
<td>ARSG take a lot of attention and should not be used where operators come into direct contact with vehicles. If the need for ARSG can be limited to where there is no contact, this is preferable. It's recommended to also evaluate whether the contact can be built away, for instance, by shielding vehicles from operators. Where this is not possible, vehicles can be equipped with warning lights to reduce risks in general. Clear routines regarding where and when ARSG shall be used should be established, but the human factor will always exist, so implementation should first be done on a small scale. Eventually, ARSG could potentially offer protection through software and by warning of traffic.</td>
</tr>
<tr>
<td>The operators need to move through trafficked areas to get to and from their workstations</td>
<td>ARSG take a lot of attention and should not be used where operators come into direct contact with vehicles, so they should preferably only be used at the work stations. It's recommended to also evaluate whether the contact can be built away, for instance, by shielding vehicles from operators. Where this is not possible, vehicles can be equipped with warning lights to reduce risks in general. Clear routines regarding where and when ARSG shall be used should be established, but the human factor will always exist, so implementation should first be done on a small scale. Eventually, ARSG could potentially offer protection through software and by warning of traffic.</td>
</tr>
<tr>
<td>There is traffic directly next to the work environment but it is delimited from the operators</td>
<td>ARSG take a lot of attention and should not be used where operators come into direct contact with vehicles, so they should preferably only be used at the work stations. As an extra precaution, vehicles can be equipped with warning lights to reduce risks in general. Clear routines regarding where and when ARSG shall be used should be established, but the human factor will always exist, so implementation should first be done on a small scale. Eventually, ARSG could potentially offer protection through software and by warning of traffic.</td>
</tr>
<tr>
<td>I don't know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
</tr>
</tbody>
</table>

---

**5. What do the operators need to wear on their heads?**

*Tooltip: Count all types of head-worn equipment that the operators need. Here it's estimated how much space the operators need in order to wear a pair of AR smart glasses.*

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nothing</td>
<td>Other equipment on the head does not hinder ARSG. When choosing ARSG, it's important to also consider the ergonomics, as they weigh more than regular glasses and some models cannot be worn together with glasses.</td>
</tr>
<tr>
<td>Helmets to protect the skull</td>
<td>Helmets limit the supply of ARSG somewhat, especially if many different helmet models are used. It's also important to consider the ergonomics, as they weigh more than regular glasses and some models cannot be worn together with glasses and instead need polished glasses. It's also important to ensure compatibility between ARSG and ear protection.</td>
</tr>
<tr>
<td>Welding helmets or similar that cover the face</td>
<td>Generates a follow-up question.</td>
</tr>
<tr>
<td>Helmets that completely enclose the head</td>
<td>Generates a follow-up question.</td>
</tr>
<tr>
<td>I don't know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
</tr>
</tbody>
</table>

---

**FOLLOW-UP**

Choose the alternative that best describes the operator's equipment on the head:

*Tooltip: Here it's specified exactly how limited the room is for the operator to wear equipment on the head.*

| Equipment sits so tightly that there is only room for regular glasses | If current equipment does not have room for ARSG, it needs to be replaced or modified so that there is room in front of the eyes and around the ears for ARSG. It's also important to consider ergonomics, as ARSG weigh more than regular glasses and some models cannot be worn together with glasses and instead need polished glasses. It's also important to ensure compatibility between ARSG and ear protection. When there is a lot of equipment worn on the head, it's also important to make a holistic evaluation of all relevant aspects to ensure optimal performance and comfort. |

---

67
### CHAPTER 5 FRAMEWORK

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>There is room for smart AR glasses as big as safety glasses, but the operator’s ears are covered</td>
<td>Many models of ARSG are worn with frames so if the ears are covered this needs to be considered. It’s also important to consider ergonomics, as ARSG weigh more than regular glasses and some models cannot be worn together with glasses and instead need polished glasses. lt’s also important to ensure compatibility between ARSG and ear protection. When there is a lot of equipment worn on the head, it’s also important to make a holistic evaluation of all variants of equipment that operators can choose from to determine whether it’s possible to introduce ARSG.</td>
<td>200</td>
</tr>
<tr>
<td>There is room for smart AR glasses as big as safety glasses and the operator’s ears are not covered</td>
<td>It’s important to consider ergonomics, as ARSG weigh more than regular glasses and some models cannot be worn together with glasses and instead need polished glasses. When there is a lot of equipment worn on the head, it’s also important to make a holistic evaluation of all variants of equipment that operators can choose from to determine whether it’s possible to introduce ARSG.</td>
<td>350</td>
</tr>
<tr>
<td>I don’t know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
<td>-</td>
</tr>
</tbody>
</table>

6. The operators’ need for instructions can be limited to specific connected times.

**Tooltip:** Estimates the duration of the periods that ARSG are needed by each operator. Used to estimate how many ARSG are needed and how much they will be used.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>No, the operators need access to instructions throughout the workday</td>
<td>If ARSG need to be worn for the whole day, they can return their investment cost faster, for example, by saving time needed to check instructions. How instructions should be designed depends on whether they are needed for guidance or reference; with greater needs it’s more likely that guidance is needed, which can demand more extensive design work. Instruction needs can be very individual and ARSG have the potential to give dynamic and individually adapted instructions.</td>
<td>500</td>
</tr>
<tr>
<td>No, the operators have sporadic but frequent needs for instructions</td>
<td>How instructions should be designed depends on whether they are needed for guidance or reference; with needs for shorter periods, they are likely used more as a reference, which likely entails simpler design work. Even with needs for shorter periods, ARSG can support quality assurance, to ensure that standards are followed. Instruction needs can be very individual and ARSG have the potential to give dynamic and individually adapted instructions. If the need is great at a specific sequence, it can be considered whether ARSG should provide support there specifically.</td>
<td>400</td>
</tr>
<tr>
<td>No, the operators have sporadic and limited needs for instructions</td>
<td>Generates a follow-up question.</td>
<td>200</td>
</tr>
<tr>
<td>Yes, at most the operators need instructions for two hours at a time during a day</td>
<td>If the instruction need is plannable and limited in time, there can be an opportunity to save money with several operators sharing ARSG. And if there are needs for ARSG throughout the day, they can return their investment faster, for example, by saving time needed to check instructions. How instructions should be designed depends on whether they are needed for guidance or reference; with greater needs it’s more likely that guidance is needed, which can demand more extensive design work. Instruction needs can be very individual and ARSG have the potential to give dynamic and individually adapted instructions. If the need is great at a specific sequence, it can be considered whether ARSG should provide support there specifically.</td>
<td>200</td>
</tr>
<tr>
<td>Yes, at most the operators need instructions for four hours at a time during a day</td>
<td>If the instruction need is plannable and limited in time, there can be an opportunity to save money with several operators sharing ARSG. And if there are needs for ARSG throughout the day, they can return their investment faster, for example, by saving time needed to check instructions. How instructions should be designed depends on whether they are needed for guidance or reference; with greater needs it’s more likely that guidance is needed, which can demand more extensive design work. Instruction needs can be very individual and ARSG have the potential to give dynamic and individually adapted instructions. If the need is great at a specific sequence, it can be considered whether ARSG should provide support there specifically.</td>
<td>150</td>
</tr>
<tr>
<td>I don’t know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
<td>-</td>
</tr>
</tbody>
</table>

**FOLLOW-UP:** According to the last question, the operators only have sporadic and rare needs for instructions. How rare?

**Tooltip:** Further specifications of how many instructions are needed. Choose the option closest to the most common case.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A few seconds, a few times per day</td>
<td>With very short and rare needs it can be good to first consider more cost-effective alternatives such as TV screens and pick-by-light. If the spread among operators is large and, for instance, new operators need more help, one solution can be to support them specifically with ARSG. How instructions should be designed depends on whether they are needed for guidance or reference; with needs for short periods they are likely more for reference, which likely entails simpler design work. Even with needs for short periods, ARSG can support quality assurance, to ensure that standards are followed. Instruction needs can be very individual and ARSG have the potential to give dynamic and individually adapted instructions, but with needs for short periods, it’s less likely. If the need is great at a specific sequence, it can be considered whether ARSG should provide support there specifically.</td>
<td>250</td>
</tr>
<tr>
<td>A few seconds, several times per day</td>
<td>With very short and rare needs it can be good to first consider other alternatives such as TV screens and pick-by-light. If the spread among operators is large and, for instance, new operators need more help, one solution can be to support them specifically with ARSG. How instructions should be designed depends on whether they are needed for guidance or reference; with needs for short periods, they are more likely for reference, which likely entails simpler design work. Even with needs for short periods, ARSG can support quality assurance, to ensure that standards are followed. Instruction needs can be very individual and ARSG have the potential to give dynamic and individually adapted instructions, but with needs for short periods, it’s less likely. If the need is great at a specific sequence, it can be considered whether ARSG should provide support there specifically.</td>
<td>350</td>
</tr>
<tr>
<td>A few minutes at a time, a few times a day</td>
<td>If the instruction need is plannable and limited in time, there can be an opportunity to save money with several operators sharing ARSG. How instructions should be designed</td>
<td>350</td>
</tr>
</tbody>
</table>
A couple of hours at a time, a few times a month

If the instruction need is plannable and limited in time, there can be an opportunity to save money with several operators sharing ARSG. How instructions should be designed depends on whether they are needed for guidance or reference; with needs for longer periods, it’s more likely that guidance is needed, which can demand more extensive design work. Instruction needs can be very individual and ARSG have the potential to give dynamic and individually adapted instructions. If the need is great at a specific sequence, it can be considered whether ARSG should provide support there specifically. 100

A couple of days at a time, a few times a month

With very rare needs, it can be good to first consider other alternatives such as TV screens, pick-by-light, and expert guidance. If the instruction need is plannable and limited in time, there can be an opportunity to save money with several operators sharing ARSG. How instructions should be designed depends on whether they are needed for guidance or reference; with needs for longer periods, it’s more likely that guidance is needed, which can demand more extensive design work. Instruction needs can be very individual and ARSG have the potential to give dynamic and individually adapted instructions. If the need is great at a specific sequence, it can be considered whether ARSG should provide support there specifically. 100

I don’t know

This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation. -

7. How often do the operators make mistakes on average?

Tooltip: Only consider how often instructions are changes. Include all times that the operators need to perform a task in a new way regardless of how small the changes are.

1–3 times a day

It is more worthwhile investing in instruction support such as ARSG when there is a lot of change. But at the same time, this can mean that more time needs to be invested in instruction creation, so how easy it is to extract and transfer data to ARSG becomes very decisive. This is brought up in later questions. If ARSG instructions cannot be automated, it can become uneconomical to update them. Muscle memory can be hard to relearn and ARSG can provide good support through showing information in the field of view. 350

1–3 times a week

It is more worthwhile investing in instruction support such as ARSG when there is a lot of change. But at the same time, this can mean that more time needs to be invested in instruction creation, so how easy it is to extract and transfer data to ARSG becomes very decisive. This is brought up in later questions. If ARSG instructions cannot be automated, it can become uneconomical to update them. Muscle memory can be hard to relearn and ARSG can provide good support through showing information in the field of view. 400

1–3 times a month

ARSG as instruction support can mean that more time needs to be put into instruction creation. If ARSG instructions cannot be automated, it can become uneconomical to update them. Muscle memory can be hard to relearn and ARSG can provide good support through showing information in the field of view. 500

1–3 times per quarter

Generates a follow-up question. 450

1–3 times per year

Generates a follow-up question. 350

I don’t know

This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation. -

FOLLOW-UP. How comprehensive are the changes of information?

Tooltip: This question focuses on how big the changes are. This is to estimate how hard it is to learn them.

A total change of the tasks with little connection to the old tasks

It is more worthwhile investing in instruction support such as ARSG when there is a lot of change. If the changes do not happen often, it becomes less critical that the information can be automatically generated than when they happen often. Muscle memory can be hard to relearn and ARSG can provide good support through showing information in the field of view. 250

A total change of the tasks but with great similarities to the old tasks

It is more worthwhile investing in instruction support such as ARSG when there is a lot of change. If the changes do not happen often, it becomes less critical that the information can be automatically generated than when they happen often. Muscle memory can be hard to relearn and ARSG can provide good support through showing information in the field of view. 300

About half of the tasks are changed with little connection to the old tasks

It is more worthwhile investing in instruction support such as ARSG when there is a lot of change. If the changes do not happen often, it becomes less critical that the information can be automatically generated than when they happen often. Muscle memory can be hard to relearn and ARSG can provide good support through showing information in the field of view. 200

About half of the tasks are changed but with great similarities to the old tasks

If the changes are rare and relatively small, ARSG are less likely to add value in regard to relearning, but they can still be valuable for quality assurance. Muscle memory can be hard to relearn and ARSG can provide good support through showing information in the field of view. 250

Only small adjustments

If the changes are rare and relatively small, ARSG are less likely to add value in regard to relearning, but they can still be valuable for quality assurance. Muscle memory can be hard to relearn and ARSG can provide good support through showing information in the field of view. 250

I don’t know

This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation. -

8. How often do the operators make mistakes on needs with short periods, ARSG can support quality assurance, to ensure that standards are followed. Instruction needs can be very individual and ARSG have the potential to give dynamic and individually adapted instructions. If the need is great at a specific sequence it can be considered whether ARSG should provide support there specifically.

Very rarely

If mistakes happen very rarely, it can mean that it’s harder to justify the costs of ARSG. ARSG can help with both quality problems and tact. Also, ARSG can help with the assessment and categorization of errors. If there is a large spread of errors, for instance, 300
certain individual operators make mistakes more often, then a smaller number of ARSG used as needed can be an alternative.

Rarely

If mistakes happen rarely, it can mean that it’s harder to justify the costs of ARSG. ARSG can help with both quality problems and tact. Also, ARSG can help with the assessment and categorization of errors. If there is a large spread of errors, for instance, certain individual operators make mistakes more often, then a smaller number of ARSG used as needed can be an alternative.

Somewhat often

If mistakes happen somewhat often, it can mean that it’s easier to justify the costs of ARSG. ARSG can help with both quality problems and tact. Also, ARSG can help with the assessment and categorization of errors. If there is a large spread of errors, for instance, certain individual operators make mistakes more often, then a smaller number of ARSG used as needed can be an alternative.

Often

If mistakes happen often, it can mean that it’s easier to justify the costs of ARSG. ARSG can help with both quality problems and tact. Also, ARSG can help with the assessment and categorization of errors.

Very often

If mistakes happen very often, it can mean that it’s easier to justify the costs of ARSG. ARSG can help with both quality problems and tact. Also, ARSG can help with the assessment and categorization of errors.

I don’t know

This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.

9. How serious is it if there is a mistake?

**Tooltip:** To estimate the consequences of errors, take the most serious consequence that can happen due to assembly.

<table>
<thead>
<tr>
<th>Severity of Error</th>
<th>Consequence of Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible (no or hardly any cost to remedy)</td>
<td>The cost is driven by how early mistakes are found and ARSG can contribute to discovering errors earlier. But with negligible costs, it’s less likely that it’s worth the cost of investing in ARSG. ARSG can, however, also contribute to ensuring that tact and standards are followed. It’s important to ensure that there is a need for ARSG.</td>
</tr>
<tr>
<td>Less serious (acceptable cost to remedy)</td>
<td>The cost is driven by how early mistakes are found and ARSG can contribute to discovering errors earlier. But if the costs are acceptable, it’s less likely that it’s worth the cost of investing in ARSG. ARSG can, however, also contribute to ensuring that tact and standards are followed. It’s important to ensure that there is a need before investment.</td>
</tr>
<tr>
<td>Severe (expensive repairs or risk of losing customer)</td>
<td>The cost is driven by how early mistakes are found and ARSG can contribute to discovering errors earlier. With large costs, it’s more likely that it’s worth the cost of investing in ARSG, but this needs to be confirmed before investment. ARSG can also contribute to the documentation of critical steps for later control.</td>
</tr>
<tr>
<td>Very severe (risk of minor personal injury)</td>
<td>The cost is driven by how early mistakes are found and ARSG can contribute to discovering errors earlier. With large costs, it’s more likely that it’s worth the cost of investing in ARSG, but this needs to be confirmed before investment. ARSG can also contribute to the documentation of critical steps for later control.</td>
</tr>
<tr>
<td>Catastrophic (risk of severe personal injury or death)</td>
<td>The cost is driven by how early mistakes are found and ARSG can contribute to discovering errors earlier. With large costs, it’s more likely that it’s worth the cost of investing in ARSG, but this needs to be confirmed before investment. ARSG can also contribute to the documentation of critical steps for later control.</td>
</tr>
<tr>
<td>I don’t know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
</tr>
</tbody>
</table>

**Infrastructure**

1. All assembly instructions are stored in a digital format.

**Tooltip:** If the instructions exist in both a digital and a printed format, they are counted as digital.

| Strongly disagree | ARSG need access to digital instructions; if they are not already available, they become a hidden extra cost before ARSG implementation can start. One way of handling the cost can be to limit the first investment to certain stations or elements. The value of ARSG can be a way to justify digitalization; in one way this can be an advantage, as one is not bound to a previous digital infrastructure. As it can be hard to digitalize expert competency and experience, ARSG can be used for remote assistance, which does not demand digitalization. If the station cycles are long and the tasks complex, film sequences can be a cost-effective means of digitalization. |
| Somewhat disagree | ARSG need access to digital instructions; if they are not already available, or only available to a small extent, they become a hidden extra cost before ARSG implementation can start. One way of handling the cost can be to limit the first investment to certain stations or elements. The value of ARSG can be a way to justify digitalization; in one way this can be an advantage, as one is not bound to a previous digital infrastructure, depending on how far the digitalization has progressed. As it can be hard to digitalize expert competency and experience, ARSG can be used for remote assistance, which does not demand digitalization. If the station cycles are long and the tasks complex, film sequences can be a cost-effective means of digitalization. |
| Neutral | ARSG need access to digital instructions; if they are not already available, or only available to a small extent, they become a hidden extra cost before ARSG implementation can start. One way of handling the cost can be to limit the first investment to certain stations or elements. The value of ARSG can be a way to justify continued digitalization. As it can be hard to digitalize expert competency and experience, ARSG can be used for remote assistance, which does not demand digitalization. If the station cycles are long and the tasks complex, film sequences can be a cost-effective means of digitalization. |
| Somewhat agree | ARSG need access to digital instructions; if they are already available to some extent, the threshold to invest in ARSG is lower. However, some adaptation of the IT structure may be needed for it to be ARSG compatible. As it can be hard to digitalize expert competency and experience, ARSG can be used for remote assistance, which does not demand digitalization. If the station cycles are long and the tasks complex, film sequences can be a cost-effective means of digitalization. |
| Strongly agree | ARSG need access to digital instructions; if they are already available, the threshold to invest in ARSG is lower. However, some adaptation of the IT structure may be needed |
2. All assembly instructions follow a standardized format so that information can be automatically extracted.

**Tooltip:** Can, for instance, text, pictures, CAD data, and other relevant information be converted to other file formats with only a small amount of manual work?

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly disagree</td>
<td>This question can be hard to assess without IT knowledge, and the answer depends on what should be presented. In general, it becomes harder to keep instructions updated if extraction and transferring to ARSG is time-consuming. This is especially the case if changes happen often, according to an earlier question in the tool.</td>
<td>150</td>
</tr>
<tr>
<td>Somewhat disagree</td>
<td>This question can be hard to assess without IT knowledge, and the answer depends on what should be presented. In general, it becomes harder to keep instructions updated if extraction and transferring to ARSG are time-consuming. This is especially the case if changes happen often, according to an earlier question in the tool.</td>
<td>250</td>
</tr>
<tr>
<td>Neutral</td>
<td>This question can be hard to assess without IT knowledge, and the answer depends on what should be presented. In general, it becomes harder to keep instructions updated if extraction and transferring to ARSG are time-consuming. This is especially the case if changes happen often, according to an earlier question in the tool.</td>
<td>300</td>
</tr>
<tr>
<td>Somewhat agree</td>
<td>This question can be hard to assess without IT knowledge, and the answer depends on what should be presented. In general, it becomes harder to keep instructions updated if extraction and transferring to ARSG are time-consuming. This means that if changes happen often, according to an earlier question in the tool, this is a smaller concern.</td>
<td>450</td>
</tr>
<tr>
<td>Strongly agree</td>
<td>This question can be hard to assess without IT knowledge, and the answer depends on what should be presented. In general, it becomes harder to keep instructions updated if extraction and transferring to ARSG are time-consuming. This means that if changes happen often, according to an earlier question in the tool, this is a smaller concern.</td>
<td>450</td>
</tr>
<tr>
<td>I don't know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
<td>-</td>
</tr>
</tbody>
</table>

3. Wi-Fi or Bluetooth connection in the work area is:

**Tooltip:** AR smart glasses need wireless communication to keep themselves updated.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>There is no connection</td>
<td>ARSG work the best if they have a wireless connection during usage, and it's a requisite if they are to be integrated into a production system. If there is no infrastructure for connection, this becomes an extra cost to consider. The larger the distances the operators move within, as addressed in a previous question, the more expensive the connection becomes. It’s also important to ensure that the ARSG connection fulfills any security certificates.</td>
<td>350</td>
</tr>
<tr>
<td>The speed and coverage is not enough where the operators work</td>
<td>ARSG work the best if they have a wireless connection during usage, and it’s a requisite if they are to be integrated into a production system. If there is no infrastructure for connection, then the step up is smaller, even though upgrading it becomes an extra cost to consider. The greater the distances the operators move within, as addressed in a previous question, the more expensive the connection becomes. It’s also important to ensure that the ARSG connection fulfills any security certificates.</td>
<td>400</td>
</tr>
<tr>
<td>The speed or coverage is not enough where the operators work</td>
<td>ARSG work the best if they have a wireless connection during usage, and it’s a requisite if they are to be integrated into a production system. If there is no infrastructure for connection, then the step up is smaller, even though upgrading it becomes an extra cost to consider. The greater the distances the operators move within, as addressed in a previous question, the more expensive the connection becomes. It’s also important to ensure that the ARSG connection fulfills any security certificates.</td>
<td>450</td>
</tr>
<tr>
<td>The speed or coverage is good where the operators work</td>
<td>ARSG work the best if they have a wireless connection during usage, and it’s a requisite if they are to be integrated into a production system. If there is no infrastructure for connection, then the step up is smaller, even though upgrading it becomes an extra cost to consider. The greater the distances the operators move within, as addressed in a previous question, the more expensive the connection becomes. It’s also important to ensure that the ARSG connection fulfills any security certificates.</td>
<td>550</td>
</tr>
<tr>
<td>The speed or coverage is good where the operators work</td>
<td>ARSG work the best if they have a wireless connection during usage, and it’s a requisite if they are to be integrated into a production system. If there is no infrastructure for connection, then the step up is smaller, even though upgrading it becomes an extra cost to consider. The greater the distances the operators move within, as addressed in a previous question, the more expensive the connection becomes. It’s also important to ensure that the ARSG connection fulfills any security certificates.</td>
<td>550</td>
</tr>
<tr>
<td>I don't know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
<td>-</td>
</tr>
</tbody>
</table>

4. A lot of expensive equipment is currently needed to guide operators in assembly work.

**Tooltip:** An estimation to see whether any equipment can be replaced with ARSG and thereby save other costs and space.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly disagree</td>
<td>This poses no hindrance in itself, but it can be seen as an extra advantage if ARSG can enable savings by replacing other equipment.</td>
<td>300</td>
</tr>
<tr>
<td>Somewhat disagree</td>
<td>This poses no hindrance in itself, but it can be seen as an extra advantage if ARSG can enable savings by replacing other equipment.</td>
<td>350</td>
</tr>
<tr>
<td>Neutral</td>
<td>This is not a decisive question, but it can be seen as an extra advantage if ARSG can replace other equipment and thereby reduce costs.</td>
<td>450</td>
</tr>
<tr>
<td>Somewhat agree</td>
<td>This is not a decisive question, but it can be seen as an extra advantage if ARSG can replace other equipment and thereby reduce costs.</td>
<td>450</td>
</tr>
<tr>
<td>Strongly agree</td>
<td>This is not a decisive question, but it can be seen as an extra advantage if ARSG can replace other equipment and thereby reduce costs.</td>
<td>450</td>
</tr>
</tbody>
</table>
### CHAPTER 5 FRAMEWORK

<table>
<thead>
<tr>
<th>I don't know</th>
<th>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production</strong></td>
<td></td>
</tr>
<tr>
<td>1. Fitting assembly details is difficult.</td>
<td><strong>Tooltip:</strong> ARSG can show information in 3D. How great a value is there in guiding operators in how they should rotate and place parts?</td>
</tr>
<tr>
<td>Strongly disagree</td>
<td>If the fitting is not difficult, then complex animations such as 3D models in the operators’ field of view are probably not needed, which drastically simplifies the implementation of instructions. 200</td>
</tr>
<tr>
<td>Somewhat disagree</td>
<td>Generates a follow-up question. 250</td>
</tr>
<tr>
<td>Neutral</td>
<td>Generates a follow-up question. 350</td>
</tr>
<tr>
<td>Somewhat agree</td>
<td>Generates a follow-up question. 300</td>
</tr>
<tr>
<td>Strongly agree</td>
<td>Generates a follow-up question. 250</td>
</tr>
<tr>
<td>I don't know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
</tr>
<tr>
<td><strong>FOLLOW-UP.</strong> Based on your previous answer, it is likely that fitting information is important. Choose the most suitable alternative below.</td>
<td><strong>Assembly data contain 3D data in a format that can be extracted with ease</strong></td>
</tr>
<tr>
<td>Assembly data contain 3D data that is very hard to extract to other formats</td>
<td>If ARSG can support complex work tasks such as fitting, then this can add great value. If this also can be done without adding a lot of work in the transfer of information from the IT system to ARSG, this can be a great advantage. Access to these data may however, need to be revised, since they can contain sensitive information. This question becomes especially important if the information is changed often as addressed in an earlier question. If ARSG can support complex work tasks such as fitting, then this can add great value. If a lot of work is added in the transfer of information from the IT system to ARSG, this can be a great disadvantage, especially if the information is changed often, as addressed in an earlier question. The use of more cost-effective alternatives, such as pictures or, if the cycle times are not very short, movies, can then be considered. 400</td>
</tr>
<tr>
<td>Assembly data contain no digital 3D data</td>
<td>If ARSG can support complex work tasks such as fitting, then this can add great value. If 3D data exist but are not digitalized, this means a hidden cost of first digitalizing them. If a lot of work is added in the transfer of information from the IT system to ARSG, this can be a great disadvantage, especially if the information is changed often, as addressed in an earlier question. The use of more cost-effective alternatives, such as pictures or, if the cycle times are not very short, movies, can then be considered. 400</td>
</tr>
<tr>
<td>Assembly data contain no 3D data at all</td>
<td>If ARSG can support complex work tasks such as fitting, then this can add great value. If there currently are no 3D data, this can mean large hidden costs of both creating and digitalizing them. If a lot of work is added in the transfer of information from the IT system to ARSG, this can be a great disadvantage, especially if the information is changed often, as addressed in an earlier question. The use of more cost-effective alternatives, such as pictures or, if the cycle times are not very short, movies, can then be considered. 450</td>
</tr>
<tr>
<td>I don't know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
</tr>
<tr>
<td><strong>2. We would consider having more variants in production if operators could handle variants without making more errors.</strong></td>
<td><strong>Tooltip:</strong> ARSG can reduce the need for operators to learn work tasks by heart and thereby make it possible for them to handle more product variants than before.</td>
</tr>
<tr>
<td>Strongly disagree</td>
<td>If this is not the case it poses no hindrance; it should be seen as potential value added by the ARSG investment. 100</td>
</tr>
<tr>
<td>Somewhat disagree</td>
<td>If this is not the case it poses no hindrance; it should be seen as potential value added by the ARSG investment. 200</td>
</tr>
<tr>
<td>Neutral</td>
<td>If this is not the case it poses no hindrance; it should be seen as potential value added by the ARSG investment. 300</td>
</tr>
<tr>
<td>Somewhat agree</td>
<td>This can be seen as potential value added by the ARSG investment. 400</td>
</tr>
<tr>
<td>Strongly agree</td>
<td>This can be seen as potential value added by the ARSG investment. 350</td>
</tr>
<tr>
<td>I don't know</td>
<td>This question has been removed from the result. Kindly find a more suitable answer to receive a more precise evaluation.</td>
</tr>
</tbody>
</table>
DISCUSSION
CHAPTER 6
DISCUSSION

People think they think, but it’s not true. It’s mostly self-criticism that passes for thinking. True thinking is rare – just like true listening. Thinking is listening to yourself. It’s difficult. To think, you have to be at least two people at the same time. Then you have to let those people disagree. Thinking is an internal dialogue between two or more different views of the world. (Peterson, 2018, p. 241)

This chapter provides a discussion of the results presented in this thesis, with an emphasis on the underlying Ph.D. research project and the resulting framework.

6.1 THE PH.D. RESEARCH PROJECT

This section presents the Ph.D. research project of which this thesis represents the culmination. It gives some background to my previous work concerning the focus of this thesis and argues for the main strengths and challenges of the research project as a whole.

6.1.1 CONTRIBUTIONS FROM LOWER RELEVANCE PUBLICATIONS

The early research and ongoing work in the field have made it possible for the focus of my research to evolve as the field continued to mature. My first experience with AR as assembly operator support occurred during my bachelor thesis work in 2014, in which the virtual reality Oculus Rift headset was modified to work as a pair of tethered and video-based ARSG. The work continuing this resulted in two publications (Syberfeldt et al., 2014, Syberfeldt et al., 2015), paper I and II respectively. They both focused on the validity of ARSG and video-based AR. This progressed to exploring dynamic and individualized operator instructions (Syberfeldt et al., 2016a), paper III. We then investigated and analyzed how these and other findings fit into the maturing concept of the “future Swedish shop-floor operator” (Syberfeldt et al., 2016b), paper IV. This concept has similarities to the Operator 4.0 concept previously discussed in Chapter 2. Two publications addressing this concept explored operator support aspects at greater
depth. I also co-authored a deeper exploration of dynamic operator instructions (Holm et al., 2017), paper V. When the first commercially available ARSG had been on the market for a few years, we decided to map this emerging market and provide some guidance to industrial practitioners in how to navigate among the different specifications, with a focus on value-creation through operator support (Syberfeldt et al., 2017), paper VI. Then followed the main publications of this thesis, which have already been described.

6.1.2 MAIN STRENGTHS

VCC was already an active partner in the conceptual stage of the research project that led to the creation of this thesis. This dedication continued to the end and has meant that there has been a clear and consistent industrial perspective present in this thesis, expressed mainly by an industrial mentor who has been an active agent throughout the project. This mentor guided the project towards results closely connected to challenges faced within the manufacturing industry. The support from VCC has also been direct, in the form of providing resources such as staff and facilities, indicating that the research topic is seen as strategically valuable. The clear connection to the industrial perspective has served as a valuable counterbalance to the academic guidance provided by the supervisors from the University of Skövde.

As chapter 2 briefly showed, AR as a concept has existed at least since the experiments of Sutherland (1968), and the term AR is widely believed to have originated from Caudell and Mizell (1992).

This research project has allowed me to follow the development of the field of AR in industry from around the time that the first ARSG were commercially available, according to the findings summarized by Danielsson et al. (2020b). An informal indicator of the development of the field of ARSG is that as the years have passed, the need to explain what AR and ARSG are to visitors at fairs or workshops or to participants in experiments has diminished.

6.1.3 MAIN CHALLENGES

One great challenge, perhaps the greatest, has been the pace at which ARSG and AR have, generally developed. The summary of ARSG available on the market presented by Danielsson et al. (2020b) illustrates how many different ARSG are commercially available as well as how many are no longer available.

Another challenge was the decision to use the mixed methods approach. As described in Chapter 3, mixed methods allow for a broader perspective than using only one of the qualitative or quantitative paradigms, but this comes at the cost of an increased workload and more time needed to reach conclusive results. A strong argument can be made for choosing one of these two paradigms to better accommodate research depth in a field that is developing rapidly. However, given the emerging nature of the field of ARSG, there is high plasticity in the field, so a mixed methods approach is suitable through its multiple perspectives, allowing for adaptability in what is suitable in specific cases. The multidisciplinary nature of the research also contributes to the value of a mixed methods approach. Qualitative research was, for instance, seen as the most suitable option for gaining a deeper understanding of the two main perspectives, given the purpose of developing recommendations using the framework. Quantitative research was valuable mainly as verification, for instance, through the survey in paper 6, which ensured broad confirmation of the framework’s usefulness according to the surveyed industrial practitioners. This has helped mitigate the risk of the qualitative data not being representative of the field at large.
6.2 THE FRAMEWORK: DISCUSSION

This section presents a discussion of the framework that is the main result of this thesis.

6.2.1 MAIN STRENGTHS

The focus and scope of the framework have been developed through an iterative process. The idea that the Ph.D. research project should aim to provide a practical framework was established early on, first formally mentioned in the research proposal for this thesis in 2016. As can be seen in the above descriptions, my earlier works were already exploring some elements that eventually became parts of the framework. This means that the content and design of the framework developed over several years, facilitated by feedback from several academics and industrial practitioners. The framework has thus had as long to mature as there have been commercially available ARSG.

The close collaboration between academia and industry has meant that the content and focus of the framework have aimed to balance these two perspectives. The framework has aimed to be broad enough to encompass the diversity within manufacturing, specific enough to add value for industry and academia, and scaled in size in a way that allows industrial practitioners to adjust their time allocation to fit their need for the framework. The feedback received from evaluations and discussions indicates that the framework has achieved a suitable balance between these objectives.

6.2.2 MAIN CHALLENGES

Given that ARSG for industry still constitute an emerging field, with ARSG still at a low technological readiness level (Danielsson et al., 2020b), this has made work with the framework more uncertain than if there already were an established field with standards to apply. The motivation for conducting three literature reviews was to provide a solid basis in the literature and to identify previous works to better guide the work on developing the framework.

The numerical estimation of ARSG suitability for a specific case is based on the estimations of six persons with a mix of practical and academic experience of manufacturing engineering or AR, estimating each answer alternative on a scale of 0–7 with a lower score indicating less ARSG suitability and a higher score more suitability. The final score for each question was the median value of the result from this survey, multiplied by 100 for implementation purposes. This process was chosen to create a group estimation of the suitability of ARSG for specific cases, a method adapted to the available resources. The median was chosen due to there being a high standard deviation (the highest was 3.0). Some participants said that it was hard to give an estimate because doing so required very specific knowledge in many different areas. In future iterations of the framework, a strong case can be made for revising the estimations. If more persons with the right type of expertise could be recruited, it would likely increase the accuracy of the framework. Since the questions in the framework span many different knowledge domains, it might be most suitable to conduct the evaluation in smaller groups looking at subsets of the questions. Another alternative that could soon be more available would be to use actual industrial implementations of ARSG as an evaluation basis.

Another limitation of the current framework is that it is only available in Swedish. The first version of the framework was written in English to allow for broad dissemination. However, all participants in the developmental stage of the framework were native Swedish speakers, and there were several questions regarding industrial terms in English. It was therefore decided to translate the framework into Swedish to minimize the
risk of misunderstandings when using the framework, at the cost of narrowing the target audience.

### 6.2.3 OTHER FRAMEWORKS

Given the potential of AR in general and ARSG specifically to present information, several other works have examined AR use and related considerations. Fraga-Lamas et al. (2018) compared hard- and software solutions for their suitability in building an AR system for shipyard workers.

A design framework developed by Berkemeier et al. (2019) emphasized design principles and elements for privacy protection and the acceptance of ARSG in logistics. As in this thesis, they used literature reviews, expert interviews, focus groups, surveys, and prototypes to develop their framework. They additionally used the shadowing method, in which they observed workplaces to better document processes and actions. The main challenge that Berkemeier et al. (2019) found was to connect the business perspective and technical design. One limitation they identified in their framework was that the long-term deployment of ARSG systems was not referred to in their data. In contrast, the framework in this thesis has considered long-term deployment from the manufacturing engineering perspective.

A qualitative framework for AR adoption in the Australian construction industry was proposed by Wang et al. (2021). They used the Innovation Diffusion Theory (IDT) as a theoretical frame and four previously identified key factors affecting innovation adoption within construction firms as a structural basis for their study. They used a literature review to identify barriers to AR adoption, which were further explored through semi-structured interviews with managers from the Australian construction industry. Identified barriers included a lack of integration and interoperability with other management systems (Delgado et al., 2020) and both a lack of management understanding of new technology and a lack of cost/benefit analysis (Noghabaei et al., 2020). When comparing the present industrial assembly findings with the findings of Wang et al. (2021) regarding industrial construction, it seems that there are more barriers within the construction industry to adopting new technology. The Wang et al. (2021) framework differs from the one presented here in that their framework focuses on mapping and linking factors and barriers related to assisting the promotion of AR adoption. Despite some similarities, the framework in this thesis focuses instead on feasibility and practical considerations in the long-term integration of ARSG.

### 6.2.4 GENERALIZABILITY

The framework has been designed to evaluate one specific assembly station at a time. At the same time, it has also been designed so that a majority of possible assembly stations can be represented within the framework. It is inappropriate to claim that the framework covers all possible assembly station configurations without exhaustively mapping the framework to obtain a fully representative sample. However, steps have been taken not to exclude possible assembly station cases due to negligence. The literature reviews were conducted with no limitation on the types of industrial assembly other than what was covered in actual publications. For papers 6 and 7, efforts were taken to ensure a diverse representation of industrial experts. Available networks were used to include as many experts as possible and, during data collection, they were encouraged not to limit their discussions to their own production cases.

In paper 6, the strawman version started with 10 questions and five follow-up questions, and the final version had 15 questions and five follow-up questions. Table 6.1 gives an overview of the changes made in each iteration. The changes mainly concern differences between operator work situations, such as how far workers move when conducting assembly, cycle time, and the effects of mistakes on assembly. The changes were based on the group
discussions of how the questions could better accommodate more variants within industrial assembly.

Table 6.1: Added questions from all focus groups in paper 6.

| Added: The surface of each station where the operator works is: | After first focus group | No changes. | Added: How serious is it if mistakes are made? |
| Added: The cycle time for the operators is: | | | Added: A lot of expensive equipment is currently needed to guide operators in assembly work. |
| Rewording From: How often do assembly instructions change for the operators? To: How often does an operator need to relearn or learn a new work task on average? | | | |
| Added: Wi-Fi or Bluetooth connection in the work area is: | | | |

In paper 7 the focus groups consisted of participants from eight different companies and one university, providing a diverse representation of perspectives. Three companies were chosen for case studies, all working in different areas of production. These steps to provide a broad evaluation of the framework gave an indication that it is relevant to the assessed types of cases. That the cases differ from each other also makes it plausible that the framework will be generalizable to even more diverse assembly cases. Future work could further extend the generalizability of the framework. Further discussion of this matter is presented in papers 6 and 7.

6.2.5 FEEDBACK

Besides the formal results of the evaluations of the framework in its two iterations, described in Chapter 5 and papers 6 and 7, there have been different forms of informal feedback. For instance, one participant in focus group 3 of paper 7 said that the questions helped facilitate “aha understanding.”3 Case study group one noted that the detailed recommendations for their case were correct, helpful, and at just about the right level of detail to create a good understanding of how to proceed. There has also been some criticism: In paper 6, some survey participants said that the tool was not specific enough. A framework for a real-world phenomenon will always need to make some simplifications, so it is impossible to fully mitigate this criticism. There was also some criticism concerning how precisely to interpret some wordings in the questions, and a desire to have figures to help users better understand the questions.

6.2.6 FURTHER IMPROVEMENTS

The received criticism illuminates valuable perspectives on how to further improve the framework. The current framework design relies very much on text. Graphics and videos could both be valuable ways to facilitate interpretation of the questions and identification of the most accurate answer option for a case. Translating the framework into English would provide valuable opportunities to gather more data and further support the manufacturing industry as a whole. Implementation on a webpage would allow for effective dissemination, so attempts to improve the dissemination should focus on identifying relevant communication channels.

3 Transcribed excerpt from the focus group session: "Jag säger så här de här frågorna hjälper ju till att få ett litet aha tänk." (Approximate English translation: “I will say like this, these questions help prompt a little aha thinking”).
CONCLUSIONS AND FUTURE WORK
CHAPTER 7
CONCLUSIONS AND FUTURE WORK

This chapter presents conclusions regarding how the RQs in this thesis have been addressed. The first section summarizes the thesis and the second section summarizes how the RQs were answered. The third section outlines the main conclusions drawn from the thesis research. The fourth section outlines the scientific contribution of this thesis, while the fifth section suggests avenues for expanding on the work presented here.

7.1 THESIS SUMMARY

This thesis has presented three RQs that build on each other towards a framework supporting strategic and practical decisions regarding the integration of ARSG into an assembly production system as an operator support tool. This resulted in a framework\(^4\) that provides strategic and practical guidance in the integration of ARSG into production as an assembly operator support tool. The framework is integrated as a web tool and has been developed and tested in two main cycles in collaboration with the industrial partner VCC and with support from the broader industrial community. Evaluation and feedback indicate that the framework is accurate and relevant to the needs of the manufacturing industry to assess how and when ARSG can add value to production.

7.2 SUMMARIZED RQ ANSWERS

This section briefly summarizes how the prerequisite and the RQs were addressed. The prerequisite asks the following: Is the thesis relevant to industrial partners and novel for the scientific community?

\(^4\) The framework is presented in detail in Chapter 5.
A demonstrator allowed industrial representatives, early on, to assess the value of the work presented here. They found the topic of the thesis relevant to their future business strategy. The first literature review indicated that the combined focus on operators and manufacturing engineering had not been explored and would therefore be a novel contribution.

RQ 1 asks the following: What do operators require in an ARSG-based interface and system so that it supports them in industrial assembly?

In summary, operators want dynamic and individual instructions, while ergonomic factors such as weight distribution are also important. Safety concerns need to be considered and the information presented should be easy to understand.

RQ 2 asks the following: What do manufacturing engineers and technicians need in ARSG so that the technology can be integrated into, maintained, and updated in a production system?

The literature review for this RQ provided key insights into the technological maturity of ARSG and the current state of systems needed for the integration and updating of ARSG in production. During the creation of the framework, manufacturing engineers were interviewed about what aspects were important for them when considering investment in and the integration of ARSG. Regarding investment, it was important what added value ARSG could give compared with more cost-effective alternatives such as paper-based instructions or TV screens. The added cost and added value could sometimes be related, for instance, when it comes to spatial guidance. Compared with paper and TV instructions, ARSG can provide spatial assembly information. To do so, there must be 3D information available that can be integrated into the ARSG system cost effectively. The decision as to whether the cost is worth it depends on how much value such information adds to operators. This in turn depends on work complexity, such as cycle time, number of variants, and how critical errors are.

In summary, when considering integrating ARSG as an assembly support tool, one must recall that this requires having or creating digital infrastructure to be able to present instructions dynamically on ARSG. There are some tradeoffs to consider, for example, that using ARSG over large areas utilizes their mobility but also increases connectivity demands.

RQ 3 asks the following: When and how can both the operators’ and the manufacturing engineers’ and technicians’ needs for ARSG be met?

The framework asks a set of questions related to an assembly production case. It provides general recommendations for that case regarding whether ARSG are suitable and what one must practically consider if one wants to integrate ARSG in that particular case to support operators. By applying the framework to all considered cases, one can see when ARSG are suitable and what must be considered for ARSG to work from both perspectives. The framework provides numerical estimations of how likely it is that the needs of both perspectives can be met. Furthermore, the detailed recommendations provide guidance on how these needs can be met. By applying the framework in evaluating potential assembly cases in which ARSG are being considered, the framework can give a summary answer as to when and how ARSG can be implemented so that operators can use them and understand what needs to be considered to integrate ARSG into production.
7.3 CONCLUSIONS
During the iterative process of creating and evaluating the framework, it became clear that there is a wide diversity in the need for support in different industrial cases. The main conclusions that were drawn from are as follows:

- Complexity dependent on number of features
- Factory digitalization important
- Tradeoffs needed

The first point refers to that some ARSG features are harder to implement than others, and not all are relevant in all cases. For instance, in some cases it can be enough operator support to just show simple text, or to play a small video. This can be implemented with relative ease and work well most ARSG models. But in these cases, there could be more ergonomic or cost-effective solutions, such as a computer screen within the FOV of the work area. Some cases might require more advanced guidance, such as 3D visualizations of parts to assemble superimposed on the physical location, combined with instructional animations on how to perform the actual assembly. This type of guidance is harder to replace with alternative solutions such as screens or paper instructions. But they are also more complex to implement. Animations needs to be created and placed correctly in relation to the real world. Depending on the specific case, there could be fewer ARSG that have the capacity to present the information in a way that is clear to the operators due to, for instance, limitations in processing power and FOV.

The second point that became clear in the process was the importance to start the digitalization process. Participating companies varied in how far they had come in the digitalization process. Since ARSG presents all information in a digital format, digitalization of at least the information that is to be presented in the ARSG in necessary. One advantage identified if digitalization was not yet started was that the risk of incompatibility between ARSG and the chosen digitalization can be minimized. There can be needs to prioritize and one option could be to digitalize a subset of the production flow to allow for a holistic ARSG test before committing large resources.

The third point also serve as a general conclusion; that there is no silver bullet solution. All options are different forms of tradeoffs between aspects such as help and implementation complexity, demands on infrastructure, and operator safety. What the right tradeoff is in each industrial case is beyond the scope of the framework to answer. The framework instead provides an understanding at an overview level on what ARSG can do and at what cost.

7.4 SCIENTIFIC CONTRIBUTION
Like all other areas of technological and scientific development, the fields of AR in general and of the industrial use of ARSG in particular have undergone several major changes as they have matured. The research presented here has aimed to reflect this by evaluating and adapting the focus to ensure that the results are of value. That AR can be used as operator support was discussed early on by Caudell and Mizell (1992). As technology has progressed, more applications have become possible, first in concept and later in practice. The fast-moving nature of the field of AR is reflected in the varying focuses of the appended papers that constitute this thesis. As the fields of AR, and of ARSG in particular, are still emerging, the focuses of the papers in this thesis have continually changed to reflect this.
Paper 1 presented an HRC assembly demonstrator with an AR interface, haptic robot control, and voice-recognition commands. It mainly contributed by providing a proof of concept of how to combine AR, HRC, and voice control with the use of a demonstrator. The resulting design was validated in a user study with a SUS test.

Paper 2 observed and interviewed assembly operators regarding their views of how to improve their support and of ARSG as assembly support. At the time of publication (2018), there were, to the best of my knowledge, no examples of ARSG being used as assembly operator support in real production. Paper 2 contributed quantitative observations of what instructions assembly operators look at, to better identify the instructions that operators need the most, which can be useful information in interface design. The interviews in paper 2 provided quantitative data showing that the operators were overall positively inclined towards ARSG technology.

Papers 3–5 were literature reviews, so their scientific contribution lies in their analysis of previous work in light of the aim of this thesis, rather than in any new experiments or data. Paper 3 provided an overview of AR within manufacturing at a meta level. It identified the focuses of previous literature reviews and how well different topics had been covered. Regarding this thesis, it identified what categories were relevant to each perspective. It also, through a meta-analysis, justified the technological maturity perspective as a necessary interface between the two main perspectives of the thesis: operators and manufacturing engineering.

Paper 4 gave an overview of current knowledge and future challenges from the operator perspective. A full summary of the findings is found in Table 1 of paper 4 (Danielsson et al., 2020a). Some highlights are that operators want individual and dynamic instructions, but there is a general lack of standards for how to design instructions, even within the branches of one company. This makes the translation of instructions into a format suitable for ARSG more costly, especially considering that there is also a lack of digitalized instructions. Operators are also facing increasingly complex tasks, making it harder to reach routine proficiency. Input from the industrial mentor also identified that when tasks change often, unlearning old tasks can sometimes be harder than learning new ones. These findings give credence to the need for operator information support.

Paper 5 gave an overview of current knowledge and future challenges from the manufacturing engineering and technological maturity perspectives. A full summary of the findings is found in Tables 3 and 4, respectively, in paper 5 (Danielsson et al., 2020b). Some highlights from the manufacturing engineering perspective are that systematic and comparative testing of ARSG is still an emerging topic. Authoring tools for ARSG instructions have become more accessible for non-programmers, with some preliminary results concerning the automatic extraction of instructions from video. Regarding the technological maturity perspective, some highlights of the findings are that ARSG constitutes an emerging market with some strong actors taking the lead. There are several technologies that can be used for hybrid tracking, but not all are suitable for industrial environments. For instance, GPS and ultrasonic are not suitable for industrial environments, but Bluetooth and infrared are.

Papers 6 and 7 present the work involved in developing and evaluating the framework. Paper 6 iteratively developed the framework from a strawman basis using qualitative input from industrial experts. This input ensured that the questions and their answer alternatives were relevant from an industrial perspective. Validation from a separate group of industrial representatives confirmed the content and general design. The main test provided quantitative data indicating a slightly positive evaluation of the tool implementation of the framework, with some suggestions for further improvements. Paper 6 contributes a validated tool
implementation of the framework that can serve as a baseline for further improvements or as a preliminary design concept for frameworks in related fields such as maintenance.

Paper 7 further improved the tool implementation of the framework by providing practical guidance after a case had been evaluated. Focus groups were used to discuss the questions from the iteration in paper 6. The participants were from eight different companies within several markets and one university. No groups gave opposing recommendations and there was some overlap between the groups. The recommendations from the individual groups were synthesized to one general recommendation for each question. For instance, three groups mentioned that fluids can be harmful to ARSG, with one of the groups also mentioning particles. This was condensed to a warning against fluids and particles as part of the recommendations in response to question 3 in the operator section of the framework. The final result was then evaluated in three different case studies. The framework recommendations were thus both grounded in and evaluated against the experience of a diverse representation of industries, indicating their relevance to theory and practice.

Paper 7 also summarized an interview with a senior expert (with around 30 years of experience) in operator instructions who had a leading role in testing ARSG at several manufacturing facilities within a multinational manufacturing company. The insight from this expert confirmed several points described in this thesis. For example, the expert commonly observed that teams testing ARSG started with a sense of euphoria in their initial discussions. Once they realized that there was a need to integrate ARSG into the production system, however, their expectations were lowered. This can be seen as confirming the value of the manufacturing engineering perspective as related to the operator perspective. The expert said that it was important not to see ARSG as a solution to all problems, but rather as one of many tools. In the case of the expert’s company, they did not have a strong use case for ARSG in practice, mainly due to their weight and the annoyance of operators when given too much information. Regarding weight, the expert believed that it was important for the weight to be close to that of normal glasses, but short-term usage lessened the importance of this requirement. This gives support to the framework, which considers the frequency of instruction needs.

In summary, it is argued that the papers presented in this thesis have contributed to the bodies of both scientific and practical knowledge. As with all such contributions, they have some limitations, but within their respective scopes and to the best of the author’s knowledge, they have provided either new data or new interpretations of previous data.

7.5 FUTURE WORK

This thesis presents a framework supporting the manufacturing industry in making early strategic decisions about where and how to invest in ARSG as operator support in production. As presented in section 1.4, “Delimitations,” there are still relevant areas that merit further research. The framework evaluates, at the operator level, a specific production cell or set of similar cells. Industrial representatives expressed an interest in being able to evaluate ARSG suitability at the factory level as well as for machine operations rather than just assembly. The framework is currently only available in Swedish, and translation into English and other languages would provide a wider basis for testing. While the manufacturing industry as a whole is relatively standardized globally, there can be cultural variations meriting exploration that multilingual support would enable. To further improve usability, the framework design could be improved in terms of, for instance, formulations and visual guidance. As the market for ARSG continues to mature, it will become more feasible to run “full cycle” tests
encompassing using the framework, implementing the recommendations, and evaluating the empirical results in production. This maturation will also make it possible, even necessary, for industrial standardization of ARSG to allow for compatibility and even interchangeability between different suppliers of ARSG. This will push research endeavors to move from proof-of-concept work to longitudinal tests of robustness.
REFERENCES


BULLEIT, W. M. 2015. The engineering way of thinking: The idea. STRUCTURE, 58.


NELLES, J., KUZ, S., MERTENS, A. & SCHLICK, C. M. Human-centered design of assistance systems for production planning and control: The role of the human in Industry 4.0. 2016 IEEE International Conference on Industrial Technology (ICIT), 2016 Taipei. IEEE, 2099-2104.


UNIVERSITY OF SKÖVDE 2011. General curriculum for education at doctoral level in Information Technology. *In: UNIVERSITY OF SKÖVDE (ed.).*


VOLVO CARS MEDIA RELATIONS 2019. Volvo Cars and Varjo launch world-first mixed reality application for car development. *In: VOLVO CARS* (ed.).


7. **Danielsson, O.,** Evaluation Framework for Augmented Reality Smart Glasses as Assembly Operator Support: Case Study of Tool Implementation. IEEE Access. Reprinted under the CC BY 4.0 license. The publication is available at IEEE through https://doi.org/10.1109/ACCESS.2021.3096855
PAPER 1
The 50th CIRP Conference on Manufacturing Systems

Assessing Instructions in Augmented Reality for Human-Robot Collaborative Assembly by Using Demonstrators

Oscar Danielsson*, Anna Syberfeldt, Rodney Brewster, Lihui Wang

*University of Skövde, Kunskapsgrund 3A, Skövde 541 34, Sweden
^Volvo Car Corporation, Komponentvägen 2, Skövde 541 36, Sweden
^KTH Royal Institute of Technology, Kungliga Tekniska högskolan, Stockholm 100 44, Sweden

* Corresponding author. Tel.: +46-500-448-596; fax: +46-500-416-325. E-mail address: oscar.danielsson@his.se

Abstract

Robots are becoming more adaptive and aware of their surroundings. This has opened up the research area of tight human-robot collaboration, where humans and robots work directly interconnected rather than in separate cells. The manufacturing industry is in constant need of developing new products. This means that operators are in constant need of learning new ways of manufacturing. If instructions to operators and interaction between operators and robots can be virtualized this has the potential of being more modifiable and available to the operators. Augmented Reality has previously shown to be effective in giving operators instructions in assembly, but there are still knowledge gaps regarding evaluation and general design guidelines. This paper has two aims. Firstly it aims to assess if demonstrators can be used to simulate human-robot collaboration. Secondly it aims to assess if Augmented Reality-based interfaces can be used to guide test-persons through a previously unknown assembly procedure. The long-term goal of the demonstrator is to function as a test-module for how to efficiently instruct operators collaborating with a robot. Pilot-tests have shown that Augmented Reality instructions can give enough information for untrained workers to perform simple assembly-tasks where parts of the steps are done with direct collaboration with a robot. Misunderstandings of the instructions from the test-persons led to multiple errors during assembly so future research is needed in how to efficiently design instructions.

Keywords: Augmented Reality, Human Robot Collaboration, Assembly

1. Introduction

1.1. Current industrial challenges

Customers are becoming more and more individualistic, products are getting more variation and the global market drives for shorter lifecycles for products [1-4]. This puts a demand on the industry to deliver more variants on their products and to introduce new products more often. Robots are becoming more flexible but are currently not flexible enough to cost-effectively replace all human workers [5]. A limitation that currently exists for a large part of robotics implementations is safety-concerns for humans [6]. Robots have traditionally needed large areas to work to allow for safety precautions such as safety-fences [7] but are currently being taken out of the fences to interact with human workers.

If robots can become safe enough for humans to efficiently interact with them in the manufacturing industry, there are great advantages to be had with the flexibility, precision, and quality skills of humans and the endurance and strength of robots [8]. Robots can now work in collaboration with humans and currently there is a lot of research into making robot interaction more dynamic and efficient without creating risks for humans [9, 10].

The aforementioned demands from the market combined with future collaborative robots means that future human operators are likely to face an increase in product variation, shorter life-cycles of products (and thereby more relearning) and collaboration with robots. This puts an increased demand...
on workers to learn more operations simultaneously and learn new products more often. How can this be achieved without reducing quality and efficiency? This paper has two aims. Firstly it aims to assess if demonstrators can be used to simulate human-robot collaboration. Secondly it aims to assess if Augmented Reality-based interfaces can be used to guide test-persons through a previously unknown assembly procedure.

1.2. Augmented Reality

Augmented Reality (AR) makes it possible to present virtual information in a direct connection with objects in the real world [11]. AR works by connecting the real world with the virtual, for instance with specific patterns that are pre-known. When a camera captures and digitalizes what is seen in front of it software can recognize the pattern and it can use the information of where the pattern was recognized to superimpose digital information on top of the rendering from the camera, thereby creating a mix between virtual and real information. This means that AR can show digital information in a real setting and in a specific context, for instance by highlighting real objects. As a result there have been many studies on how to use AR to present assembly instructions that has shown positive results [12]. But although there are positive results there is still more studies needed regarding how the instructions should be presented and how to comparatively evaluate them [12].

2. Demonstrator

2.1. Demonstrator as test-bed

To our knowledge there is no factory that currently have implemented Human-Robot Collaboration combined with Augmented Reality in production. A demonstrator was therefore created where a person will collaborate with a Human-Robot Collaborative robot, a UR3 robot from Universal Robots. A simplified car-model that can be assembled and dis-assembled by hand was developed and can be seen in Fig. 1.

The greatest advantages of using a demonstrator in user-tests are the authenticity and the modularity. The demonstrator allows a test-person to interact directly with a real HRC-robot in an assembly-scenario and thereby simulates a real situation. It is not as believable as real industrial assembly but it does not need to disrupt any real industrial assembly either. The currently developed demonstrator is limited to one test-person and one workstation and is thereby limited in comparison to industrial assembly that is mostly done with close connectivity between workstations and operators. Since the demonstrator is fully developed for experimentation it is also modular and can be changed depending on what needs to be tested. Together these two advantages means that the demonstrator can put a test-person in a semi-authentic situation and, depending on complexity of needed modifications, it can also be modified depending on findings within minutes or hours.

In the first iteration, the car-model was created with wood and the pieces were held together with friction between the pieces. A drawback with this model was that test-persons only had to identify, orient and position the individual parts; there was no need to fasten any pieces with anything else but friction. To make the car-model similar to more generic assembly, a new model was created. The pieces were 3D-printed which allowed for more detailed parts to be created. The new car-model had increased complexity in that thumbscrews were now needed to fasten some parts.

2.2. Augmented Reality Interface

To present the instructions for the test-persons a spatial top-view Augmented Reality system was created. The platform for the system was the game-engine Unity-3D. In the first iteration AR was implemented with the help of the Vuforia AR-system for Unity. The AR-system was built for Android and launched on an Nvidia Shield Tablet that can be seen at the top of Fig. 1. This tablet was chosen since it has both a USB-connection and mini-HDMI connection which was necessary to both have communication between the AR-system and the Robot Control system and to be able to project the visual information on a screen for the test-person to see. Test-persons worked with the table seen in Fig. 1 in front of them. This set-up meant that they had the work area in front of them, pieces to assemble at their sides, a screen giving the test-persons AR-instructions and a UR3 robot to their left that they had to collaborate with to assemble the car.

2.3. Second iteration of interface

Two big drawbacks with the chosen version of the AR-system was the low battery-life of a tablet that has to continuously have an active camera and the mixing of two
platforms. The tablet runs on Android and the Robot Control System runs on Windows and communicates with TCP via USB. We therefore made a second iteration where the Vuforia AR-system was replaced with ARToolKit, which supports the Windows-platform.

The AR-tracking was using the inbuilt multimarker functionality of ARToolKit with 6 markers. There was a redundancy in the number of markers to allow test-persons and the robot to move freely in-between the camera and the markers.

![Image](image1.png)

**Fig. 2** Introduction screen of AR interface.

The interface was designed to guide the test-person with a combination of textual information and AR to highlight parts of specific interest in each step. Fig. 2 shows what the test-person would see on the screen in front of them when beginning their test. The text in the middle explain in general terms what they are to do. To the right they can see voice-commands that the system currently accepts. The interface needed a voice-recognition-security of at least 85 % in order to avoid false positives. Values between 60 % and 100 % were shown to the test-person, values between 60 % and 85 % were shown in red to indicate that the system had detected a possible command but was not sure enough. Values above 85 %, in Fig. 2 the value is 89 %, were shown in green to indicate a correctly recognized command.

Once the test-person gave a start-command the interface would remove the introduction text and present all textual information in the upper right corner of the screen so as to not cover the areas of the screen where the test-person would work. An example of the interface during assembly is seen in Fig. 3. The top part of the text-area contained specific instructions for the test-person on what they were to do. Just below this the test-person could see their overall progress through the construction. Below this recognized and available voice-commands would be seen as previously explained in connection to Fig. 2.

2.4. The car-assembly

In the first iteration of the demonstrator, the test-persons had to assemble the entire car. For the second iteration, we changed this so that the test-person only had to assemble parts of the car. The three reasons for this were that we had introduced more complex parts to assemble and did not want to increase overall effort for test-persons, that not all parts were of interest seen to Human-Robot Collaboration, and a minor reason was also that the most common situation is that assembly workers only build part of a product.

The second iteration had a total of 11 steps for a test-person to perform and is presented in Table 1. The level of Human-Robot Collaboration (HRC) is defined as direct, indirect or no HRC. Direct means there is direct interaction between the test-person and the robot, in these cases haptic control of the robot. Indirect means that the robot or human support each other but have no direct interaction, in these cases the robot holds the assembled car in a fixed position to ease assembly.

![Image](image2.png)

**Fig. 3** Step four, where test-person and robot collaborate.

<table>
<thead>
<tr>
<th>Text-instructions</th>
<th>HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead front and position according to marking.</td>
<td>Direct</td>
</tr>
<tr>
<td>Lift the robot-arm ca 1 decimeter.</td>
<td>Direct</td>
</tr>
<tr>
<td>Take left roof and fasten between front and back.</td>
<td>No</td>
</tr>
<tr>
<td>Lead left sub frame to marked position.</td>
<td>Direct</td>
</tr>
<tr>
<td>Lift the robot-arm ca 1 decimeter.</td>
<td>Direct</td>
</tr>
<tr>
<td>Take left door and fasten at marking.</td>
<td>No</td>
</tr>
<tr>
<td>Take two lock-rings and assemble one at each protruding assembly-pin.</td>
<td>No</td>
</tr>
<tr>
<td>Take two wheels and tread on the protruding assembly-pins.</td>
<td>No</td>
</tr>
<tr>
<td>Take five thumbscrews and assemble one at each assembly-pin.</td>
<td>No</td>
</tr>
<tr>
<td>Take two wheels and tread on the protruding assembly-pins.</td>
<td>Indirect</td>
</tr>
<tr>
<td>Take two thumbscrews and assemble at the wheels.</td>
<td>Indirect</td>
</tr>
</tbody>
</table>

Table 1 Car-assembly steps
3. Methodology

3.1. Tested software

A pilot-study was performed for the second iteration of the interface to test how intuitive the interface was for new test-persons. The main goals were to see if the assembly was complex enough to require instructions to finish and that the assembly was feasible to finish for a test-person without previous instructions. This was to evaluate whether the demonstrator needed any major revisions before more in-depth user tests.

To compare how different designs of the interface affect test-persons, two versions of the AR-interface was implemented. Both versions were identical apart from that in one version the parts where the test-person should initiate actions were blinking and in the other version they were not blinking.

As explained in section 2.3, the test-persons interacted with the interface with the help of voice-commands. In each step they could issue two voice-commands that both did the same thing. This was to allow an alternative if the test-person had problems to pronounce the command clear enough for the software to recognize. There were two different versions of the voice-commands. One word-versions, for instance “start/_begin” and multiple word-versions, for instance “start demonstrator/ begin building car”. All four possible combinations were connected and set up for the user-study. Program 1 had blinking and short commands, program 2 had no blinking and short commands, program 3 had blinking and long commands, and program 4 had no blinking and long commands.

3.2. Test-group, environment and test-layout

Four groups of high-school students from local technical schools were used as test-groups. The students were chosen since they are very likely to have a career within the manufacturing industry. This makes them representative of parts of the future workforce within the manufacturing industry and their attitude towards this solution is valuable in the context of future workforce employment. The ages were self-reported in the interval 15-17. Genders were also self-reported and are presented in table 2.

<table>
<thead>
<tr>
<th>Group</th>
<th>Program</th>
<th>Females</th>
<th>Males</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>7</td>
<td>17</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>7</td>
<td>19</td>
<td>1</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>7</td>
<td>18</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>4</td>
<td>14</td>
<td>3</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 2 Group composition

Each group partook separately from each other. In each group 3 volunteers were chosen to perform the assembly. Table 2 shows which group had which program and shows that group 3 mistakenly got the same program as group 2. Of those chosen to perform the assembly, one stayed in the room and used the demonstrator while the other two left the room to avoid learning-effects. The room layout was a lecture classroom with a pitched floor and it was well lit during the tests. The students were seated in the front three rows of the auditorium and the demonstrator was placed on the floor in front of them.

After the first test-person had performed the assembly it was led aside to a table to fill out a usability-questionnaire. Then the next test-person was brought in to perform the assembly and the observing students were given questionnaires. After the second test-person was finished it was also led to the table to fill out a usability-questionnaire and the third test-person was led in. Finally the third test-person was also led to the table to fill out the same usability-questionnaire as the other two.

During each assembly one test-assistant noted times the test-person asked for help and when they did not do as instructed by the AR-interface. The language used for the entire study was Swedish.

3.3. Questionnaire-design

Both questionnaires used a five-level Likert-scale. The test-persons filled in 10 questions regarding the interface and the questions were based on the SUS-test [13] but translated to Swedish. The observing students filled in a questionnaire with 6 questions regarding general interest and 5 questions regarding the information displayed on the screen for the test-person.

3.4. Error-sources

The students chosen for performing the assembly were those who raised their hands first when we asked for volunteers and are therefore likely to have a positive bias for trying new technology. While the groups were mixed, volunteers were all male. The remaining students observed the test-persons and could interact with them even though this was discouraged and thus influenced the test-persons behavior. Program 4 was not tested due to a miss during execution of the test.

We did not manage to create a perfect alignment between the virtual and real world, which could have reduced understand-ability with the test-persons. The questionnaire for the test-persons was translated from English to Swedish, which can have affected the outcome.

4. Preliminary results

The first iteration was primarily used as a proof of concept that the demonstrator was feasible and the general layout understandable by test-persons. It was tested with volunteers at two different exhibitions. The tests indicated that the system was intuitive enough and on a difficulty level that allowed for most of those testing to be able to complete the task. For this reason there was no major revision of the setup from the first to the second iteration of the demonstrator.

The first iteration was also specifically presented for industrial representatives from the car-manufacturing industry to assess future industrial relevance. The response we
received was that the concept was seen as relevant seen to
industrial challenges in the near future.

The data from the user-study is inconclusive. The SUS-
scores of the groups were 80.8, 75, 32.5 and 77.5. Due to all
the possible error-sources, there can be many different reasons
for the different outcomes between group 3 and the other
two groups. Group 1, 2 and 4 followed the same trend in the
SUS when broken down to individual questions as can be
seen in Fig. 4.

A summary from the test-protocol shows that of the 12
test-persons, all of them made errors in at least one of the
steps. Of the total of 144 assembly steps, 75 steps were
performed with at least one deviation from the given
instructions. In open discussions after the tests many of the
test-persons and students from the observing group pointed
out that it was unclear that they should read the instructions in
the upper right corner.

5. Summary

5.1. Conclusions

This paper has two aims: to assess if demonstrators can simulate human-robot collaboration and to assess if AR-based interfaces can guide test-persons through assembly.

Regarding the first aim, the paper has shown that demonstrators can be used to create a modular test-environment that allows a test-person to perform real assembly in collaboration with a robot. The results from the pilot-study were distorted since the test-persons had their peers behind them when working. Despite this they managed to go through all the steps of the instructions. Based on this it can be said that the demonstrator has reached a level of maturity that enable persons without prior assembly-experience to independently work through all the steps of the demonstrator. This answers the second aim of this paper. But the amount of errors when working independently is far too high to be acceptable. The amount of errors shows that the assembly is complex enough to require instructions. Therefore the task in the demonstrator is of a satisfying complexity but the instructions need to be clearer. The screen shows a top-view of the assembly-area and is thus limited in how instructions can be shown.

While the current results have not given specific insight in how different designs affect the performance of test-persons it has given validity to the method of using demonstrators to test assembly-instructions. Further validity of the method was given from the feedback from the industrial representatives.

5.2. Future work

The demonstrator will be tested in more in depth user tests. Future tests will also be performed in a more controlled environment to reduce error-sources. Test-persons will work alone and be recorded to allow for more detailed observation of types of errors and where they focus when they work. The demonstrator itself will also need revision and future work for it includes:

- Increasing Augmented Reality tracking accuracy.
- Changing or adding camera-angles from which the assembly area is displayed in the interface.
- Layout of the different parts of the interface needs to be revised and also how the different parts are presented to ensure that test-persons find them.
- The information design will be updated.
- Increased system functionality such as animation to provide opportunities to use the strengths of AR-technology more effectively.

References


PAPER 2
51st CIRP Conference on Manufacturing Systems

Operators perspective on augmented reality as a support tool in engine assembly

Oscar Danielsson\textsuperscript{a,}\textsuperscript{*}, Anna Syberfeldt\textsuperscript{a}, Magnus Holm\textsuperscript{a}, Lihui Wang\textsuperscript{b}

\textsuperscript{a}University of Skövde, PO Box 408, 541 28, Skövde, Sweden
\textsuperscript{b}KTH Royal Institute of Technology, 100 44, Stockholm, Sweden

\textsuperscript{*} Corresponding author. Tel.: +46-500-448596; fax: +46-500-416325. E-mail address: oscar.danielsson@his.se

Abstract

Augmented Reality (AR) has shown its potential in supporting operators in manufacturing. AR-glasses as a platform both in industrial use are emerging markets, thereby making portable and hands-free AR more and more feasible. An important aspect of integrating AR as a support tool for operators is their acceptance of the technology. This paper presents the results of interviewing operators regarding their view on AR technology in their field and observing them working in automotive engine assembly and how they interact with current instructions. The observations and follow-up questions identified three main aspects of the information that the operators looked at: validating screw torque, their current assembly time, and if something went wrong. The interviews showed that a large amount of the operators were positive towards using AR in assembly. This has given an insight in both the current information interaction the operators do and their view on the potential in using AR. Based on these insights we suggest a mock-up design of an AR-interface for engine assembly to serve as a base for future prototype designs.

© 2018 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the 51st CIRP Conference on Manufacturing Systems.

Keywords: augmented reality; engine assembly; operator

Nomenclature

AGV Automated Guided Vehicle
AR Augmented Reality
ARSG Augmented Reality Smart Glasses
HRC Human Robot Collaboration

1. Introduction

The fourth industrial revolution will stand to change how we manufacture products. It will allow more dynamic flows of information and thereby enable swifter changes in production [1]. This will change the work tasks for operators drastically, who will have to handle more product variants and more frequent updates of work tasks. Industry 4.0 will also likely lead to larger responsibilities for operators. One solution to handle this is to implement information systems that can give operators needed information. Augmented Reality is one type of technology that might be used to support future operators [2]. AR is defined by Azuma et. al. to have the following characteristics: combining real and virtual objects in a real environment, running interactively and in real time, and aligning real and virtual objects with each other [3]. According to Azuma et. al. [3], AR can potentially apply to all senses and in this paper the focus is on visual AR specifically. AR has been shown to be able to increase efficiency in assembly tasks by giving information in context, thereby simplifying interpretation of data and reducing time and errors in doing so [4]. Implementations of AR can be categorized into three categories: head-attached, hand-held and spatial [5]. Rapid advances within head-attached solutions, specifically regarding Augmented Reality Smart Glasses, ARSG, has made this type of implementation a suitable platform for assembly support [6].

Therefore this paper limits itself to ARSG and when AR is mentioned in the rest of this paper in regards to the study and conclusions it implies ARSG.
While AR has made much progress in different fields, it is still struggling to reach the factory floors [7]. Handheld devices limit operators' effectiveness, head-worn displays are heavy and limited in focal depth and resolution, and large screens take up space [7]. Smart glasses are however becoming increasingly lighter and getting better technical functionality [6]. Wang et al. found that there are limitations in current AR systems in regards to assisting complex assembly processes [4]. One of the issues they identified as currently limited was intuitive user interfaces.

This paper focuses on the operators' perspective on using AR to support assembly tasks. The aim of this focus is to gain a better understanding of industrial operators as interface users to facilitate more intuitive user interfaces in the future. The operators' perspective is analyzed through observations of interaction in actual assembly to get a better understanding of the current situation. It is also analyzed through interviews that both complement the observations by giving the operators a chance to give a deeper explanation of their view. The interviews also give an insight in how much the operators trust AR technology. This is relevant since user trust of an information system will affect the user's efficiency when working with it [8, 9].

This paper is a continuation of our previous work within assembly support for operators, which has focused on evaluating different AR support systems from an operators perspective and the technology's suitability for guiding operators through HRC assembly [6, 10, 11]. This paper focuses directly on operators themselves to observe their behavior and interview them regarding their views.

2. Case study

This section describes the layout of the factory and the operators' assembly tasks, how data was collected, how the operator observations were setup, how the operator interviews were setup, ethical considerations, and possible error-sources and how they were remedied.

2.1. Layout and assembly tasks

The interviewed and observed operators are all from one section of engine outer assembly of the Volvo Car Corporation engine factory in Skövde. There are four assembly lines, each with eight sequential stations placed in a U-formation. The engines are transported on Automated Guided Vehicles, AGVs, from station to station and stops at a specific point at each station. Each operator follows one engine from the first to the last station. After the last station they move to the first station where a new engine waits for them. Figure 1 gives an overview of one such U-formation with 8 stations.

Fig. 1. Overview of an assembly line.

Each station is equipped with a monitor displaying station specific information. The monitors are all mounted above the engine at its fixed position. The most common information displayed is feedback on which screws and bolts to use and the results from the screwing machine whether the screwing process was of sufficient force or not. Figure 2 shows a detailed view of the instructions available for the operators. The left-most instruction contains detailed instructions for each step, the middle instruction shows possible specific details to check, and the right-most instruction is a digital screen that gives feedback on the operator’s progress based on data from the production system. The screen shows the operator available time left on the current assembly cycle and how many screws that had been fastened with the right torque for instance. If the operator went beyond available time or if incorrect torque was used on a screw, the system gave this feedback to the operator.

Fig. 2. Close-up of instructions available for the operators.

2.2. Data collection

Two data collection strategies were used, observing the operators while performing their assembly tasks and interviews. One researcher performed all observations and interviews.
2.3. Observation setup

The goal of the observation was to gather quantitative data about how the operators interacted with current information systems. It was executed by following an operator during one lap of assembly. One lap consisted of 8 stations from 1 to 8 as in figure 1. Operators were asked to consent to the observation before proceeding and none declined. The observer placed himself as to avoid being in the way for the operator while still being able to see where the operator was looking. For each station the number of times the operator looked at the monitor or other information systems was counted by subjective observation of the operators gaze. When the operator looked for approximately half a second or more in the direction of an instruction (a computer screen, lit lamp, or a piece of paper with instructions) or interacting with another person directly connected to work performance and when the gaze was roughly half a second or more it was counted as an observation. Time spent looking was not recorded or measured.

After following an operator for one lap, and if it did not disturb production, he or she was informed about what had been observed and were asked if he or she generally looked often on instructions and what things he or she looked on.

2.4. Interview setup

The goal of the interviews was to gather a deeper understanding of the operators’ views on the need for information in their current work environment as well as their views on other information systems.

The interviews were semi-structural and individual. Each participant filled in a consent-form that informed them of the general goal of the data-collection: to gain knowledge in how operators view instructions in their work and how they currently interact with them. The extended purpose of creating a more efficient learning of new instructions and allowing for a more dynamic production was also explained. They were also given the option to provide an e-mail address if they wanted to know more about the results of this study. All interviews were audio-recorded to facilitate deeper analysis afterwards.

The interview questions were: age, how many years they have worked with assembly in a factory, how many years they have worked at their current position, how often there are changes in their tasks in production, how the company informs about the new tasks, if the operator complements the information in any way, how often they check up things in documentation (with the follow up questions: what they check then, how easy it is to understand, if it is easy to find), the operator’s view on being able to do personal adjustments, how the operator would design the information flow if he or she had free hands, and if they had any other ideas or thoughts based on what had been brought up in the interview.

2.5. Ethical considerations

Operators’ work in assembly is stressful [12]. Each operator has an individual RFID-tag that the use to login to each station. Any errors in assembly can therefore be tracked down to individual level. While this means operators are used to being monitored this can also be a source of stress due to constant observation and measurement of performance. It was therefore emphasized by the data collector to the operators that the purpose of the data collection was for research of new technologies to display instructions and that the data would not be connected on an individual level.

During the observations they were not told what was being observed until afterwards when the purpose of the observation and what was being observed was revealed. No operator declined being observed which greatly simplified data collection.

All interviews started with the person being interviewed being presented a consent-form that informed about the purpose of the study, that the interview would be recorded and they had the right to abort the interview at any time with no motivation needed. Who had access to the recording was stated as very limited university staff. This was not more precisely specified since who would analyze the data was not determined at the time of the interviews.

2.6. Potential error sources

The observer made sure to place himself as to be out of the way for the operator while maintaining a good field of view of the operator’s work. This meant moving in an assembly line while simultaneously making observations. This combination of structured subjective measurements and an active environment can have had a negative effect on the accuracy of the data. Video-recording the operators in production was not deemed feasible due to permissions needed and integrity. This was in part remedied by having one data collector and following an observation protocol, thereby reducing the risk of inter-measure discrepancy. The observer has also previously worked with industrial assembly for one year and was thereby used to this form of environment. The observation data from the first day was used to learn what could be feasibly observed and was not used in analysis.

3. Results

This section summarizes the results from the observations, summarizes the results from the interviews, and presents an AR-design based on the previously mentioned results.

3.1. Observation

A total of 35 observations were done. 19 observations were done on males and 16 on females. Two observations (one male and one female) were incomplete since there was a break before completing a full lap and one observation (female) was incomplete because of the shift ending. Of the 35 observations, 24 gave comments after the observation about what they look at when looking at the instructions in general in their daily work. The most common (10 operators looked at this) was checking the torque on screwing stations. The second most common (9 operators looked at this) was assembly time, and the third most common (8 operators looked at of this) was checking when something goes wrong. A full list of the

observation and measurement of performance. It was therefore emphasized by the data collector to the operators that the purpose of the data collection was for research of new technologies to display instructions and that the data would not be connected on an individual level.

During the observations they were not told what was being observed until afterwards when the purpose of the observation and what was being observed was revealed. No operator declined being observed which greatly simplified data collection.

All interviews started with the person being interviewed being presented a consent-form that informed about the purpose of the study, that the interview would be recorded and they had the right to abort the interview at any time with no motivation needed. Who had access to the recording was stated as very limited university staff. This was not more precisely specified since who would analyze the data was not determined at the time of the interviews.

2.6. Potential error sources

The observer made sure to place himself as to be out of the way for the operator while maintaining a good field of view of the operator’s work. This meant moving in an assembly line while simultaneously making observations. This combination of structured subjective measurements and an active environment can have had a negative effect on the accuracy of the data. Video-recording the operators in production was not deemed feasible due to permissions needed and integrity. This was in part remedied by having one data collector and following an observation protocol, thereby reducing the risk of inter-measure discrepancy. The observer has also previously worked with industrial assembly for one year and was thereby used to this form of environment. The observation data from the first day was used to learn what could be feasibly observed and was not used in analysis.

3. Results

This section summarizes the results from the observations, summarizes the results from the interviews, and presents an AR-design based on the previously mentioned results.

3.1. Observation

A total of 35 observations were done. 19 observations were done on males and 16 on females. Two observations (one male and one female) were incomplete since there was a break before completing a full lap and one observation (female) was incomplete because of the shift ending. Of the 35 observations, 24 gave comments after the observation about what they look at when looking at the instructions in general in their daily work. The most common (10 operators looked at this) was checking the torque on screwing stations. The second most common (9 operators looked at this) was assembly time, and the third most common (8 operators looked at of this) was checking when something goes wrong. A full list of the

observation and measurement of performance. It was therefore emphasized by the data collector to the operators that the purpose of the data collection was for research of new technologies to display instructions and that the data would not be connected on an individual level.

During the observations they were not told what was being observed until afterwards when the purpose of the observation and what was being observed was revealed. No operator declined being observed which greatly simplified data collection.

All interviews started with the person being interviewed being presented a consent-form that informed about the purpose of the study, that the interview would be recorded and they had the right to abort the interview at any time with no motivation needed. Who had access to the recording was stated as very limited university staff. This was not more precisely specified since who would analyze the data was not determined at the time of the interviews.

2.6. Potential error sources

The observer made sure to place himself as to be out of the way for the operator while maintaining a good field of view of the operator’s work. This meant moving in an assembly line while simultaneously making observations. This combination of structured subjective measurements and an active environment can have had a negative effect on the accuracy of the data. Video-recording the operators in production was not deemed feasible due to permissions needed and integrity. This was in part remedied by having one data collector and following an observation protocol, thereby reducing the risk of inter-measure discrepancy. The observer has also previously worked with industrial assembly for one year and was thereby used to this form of environment. The observation data from the first day was used to learn what could be feasibly observed and was not used in analysis.

3. Results

This section summarizes the results from the observations, summarizes the results from the interviews, and presents an AR-design based on the previously mentioned results.

3.1. Observation

A total of 35 observations were done. 19 observations were done on males and 16 on females. Two observations (one male and one female) were incomplete since there was a break before completing a full lap and one observation (female) was incomplete because of the shift ending. Of the 35 observations, 24 gave comments after the observation about what they look at when looking at the instructions in general in their daily work. The most common (10 operators looked at this) was checking the torque on screwing stations. The second most common (9 operators looked at this) was assembly time, and the third most common (8 operators looked at of this) was checking when something goes wrong. A full list of the
operators’ self-reported reasons for looking at the instructions are shown in table 1.

Only two observations were done of an operator interacting with another operator related to their task. In one instance a colleague showed that an assembly piece had been moved to a more efficient position. In the other instance the operator wanted to verify with a colleague that a certain assembly piece were to be used. Social interaction was frequent but not measured. Interaction with signs was in the form of “pick-by-light”, a system where a lamp would light up to indicate which detail to assemble at a specific product. The light would switch off when an RFID-tag held at the operator’s wrist came close to the light.

No statistically significant patterns could be observed based on gender or experience regarding how often operators looked at instructions.

Table 1. Operator observations (self-reported)

<table>
<thead>
<tr>
<th>View on AR</th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque of screwing machine</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Assembly time</td>
<td>4</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Something goes wrong</td>
<td>2</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Learning new steps</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Must look at 240</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Deviations from normal</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Forget themselves</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>“When it’s needed”</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>When production stops</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>If RFID tag does not react</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>More when interrupted</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Automatically check in beginning or end</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

3.2. Interviews

A total of 28 interviews were held. The interviewed operators were chosen from the same group as the observed operators and some operators were chosen for both observation and interview. The first five interviews had a different set of questions and was used mainly as a test of the questions. The remaining 23 interviews had a modified set of questions based of the result from the first five. In the first group, 3 of the operators were male and 2 were female. In the second group 13 were male and 10 were female.

At the end of each interview the purpose of the study and the technologies involved was explained. Each participant was asked if they knew of the term “augmented reality” and it was known by 6 of the operators. Based on their reactions when the technology was explained and how it could affect their future work a large amount in both groups, 4 of 5 and 17 of 23, audibly exclaimed positive interest. Examples that was interpreted as positive are (translated from Swedish) “It sounds very interesting, of course I would like to see how this goes.”, “Shit, how cool!” and “That would have been something.” Two of the operators showed positive interest in the technology but expressed concerns that they did not think the management of the company would like to spend the resources to invest it. But since they showed positive feelings regarding the technology in itself they were counted as positive.

Of the remaining operators, 6 showed no clear reaction to the possibilities of the technology and one operator expressed concern. The concern was (translated from Swedish) “God how creepy.”. She expressed this when augmented reality was explained by using the example of a digital green arrow following a pen in its movements. The results can be seen summarized in table 2.

Table 2. AR acceptence.

<table>
<thead>
<tr>
<th>View on AR</th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>12</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>Neutral</td>
<td>4</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Negative</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

3.3. AR-design

Since the operators showed a clear interest in using AR and since AR can simplify distribution and presentation of assembly instructions it is of value to further investigate how AR can be used as support for the operators in their work. The current design is limited in that the screens are mounted in a specific position which limits from which angles the operators can see the screens. This has been solved in the current layout but is a limiting factor in where tasks and information regarding tasks can be placed. Based on the presented observation and interview data we have created a design suggestion for how an AR interface could present information to the operators.

Figure 3 shows an engine from an operator’s point of view. The results can be seen summarized in table 2.

Figure 3 shows how instructions could be shown to an operator in one assembly step. The operator is to place the detail that is marked blue in the position that it is seen on figure 4. Then two screws are to be fastened with the correct torque. The blue marking in the middle highlights the current detail to assemble. Two bolts have been attempted to be fastened in this example where the first one (top right corner of the blue marking in the middle) is highlighted green, indicating a correct torque. The second bolt is marked red, indicating incorrect torque. In the current system, operators can see correct torque via a green/red lamp on the screwing machine or alternatively how many.

Checking torque of screws was the most common reason for the Operators to check instructions according to their own view. The red highlighting also shows an example of how an error can be displayed to the operator. Checking if something went wrong was one of the second most common reasons to check instructions. The other second most common reason to check instructions was time, how much time the Operator had left on the current cycle. This AR-design presents information that the operators state is the most important to check and it is presented in similar colors and design as the current information systems that they use. It is possible that this design will not be effective in actual assembly but these two factors makes this design a good basis for future empirical studies.
4. Conclusions

A high number of the interviewed operators showed positive reactions to augmented reality in connection to providing support in their work, indicating a high acceptability among the Operators regarding the technology.

Observations done showed that operators look on instructions mainly to check screwing torque, assembly time and if something went wrong. The suggested AR-design uses this as a base as to what operators find as important information to display.

The local managers for this section of production were pleased with the results and insights from this evaluation. The data helps the managers what positive values the operators see and which threats they see. What is mainly lacking from their perspective is comparative data that can be gained from tests on a prototype to show more concrete increases in efficiency.

The analysis of the observations done indicate better understanding of how create intuitive user interfaces for operators and how to assess operator acceptance of AR. Furthermore, the operators view on AR as an information platform can support when estimating operator readiness and willingness to adapt when using this technology and thereby help in strategical decisions regarding further use of AR.

4.1. Future work

Although the gathered data is comprehensive it is limited to one factory so it would be useful to extend this data in the future to more factories to account for possible differences in cultures between companies and factories. The suggested layout of information, while relevant to the operators according to their answers and from the data gathered from observations, is just a mockup. The gathered data is based on self-reported acceptability however and needs to be validated further in a more concrete setting. To fully validate its usefulness for the operators a functioning interface needs to be developed. It is unlikely to get permission to test such an interface in real production, at least in earlier stages of testing. A testing environment with similar tasks being performed could provide a suitable test-case and would further validate such an interface design. While actual production would be an ideal environment to prove that the technology is ready, it might be less optimal for first tests. The first iterations are likely to disrupt production too much. More suitable would be to have a test-environment with similar tasks but with less critical cycle-times.

Acknowledgements

The authors would like to thank the operators and management at the assembly line in the Volvo Car factory in Skövde for their immense help in gathering this data.

References


Augmented Reality Smart Glasses for Industrial Assembly Operators: A Meta-Analysis and Categorization

Oscar DANIELSSON\textsuperscript{a,1}, Magnus HOLM\textsuperscript{a}, and Anna SYBERFELDT\textsuperscript{a}

\textit{University of Skövde, Department of Engineering Science, Högskolevägen, Skövde 541 28, Sweden}

Abstract. Augmented reality smart glasses (ARSG) are an emerging technology that has the potential to revolutionize how operators interact with information in cyber-physical systems. However, augmented reality is currently not widespread in industrial assembly. The aim of this paper is to investigate and map ARSG in manufacturing from the perspectives of the operator, of manufacturing engineering, and of its technological maturity. This mapping provides an overview of topics relevant to enabling the implementation of ARSG in a manufacturing system, thus facilitating future exploration of the three perspectives. This investigation was done using a meta-analysis of literature reviews of applications of augmented reality in industrial manufacturing. The meta-analysis categorized previously identified topics within augmented reality in industrial manufacturing and mapped those to the scope of the three perspectives.

Keywords. Augmented Reality, Literature Review, Assembly, Assembly Operators

1. Introduction

A competitive and fast-growing market is pushing manufacturers to become more efficient and productive, as well as more agile, responsive, and customized [1]. Customers are increasingly asking for individual products, pushing the change from mass customization to mass personalization [2]. Increased product variation and an increasingly complex shop floor environment are putting more pressure on assembly workers to handle more information. Despite technological advances, these assembly workers are still likely to continue to be an important part of manufacturing [3]. So the future information-intensive shop floor environment requires operators to be able to handle and process a dynamically changing environment [4]. One possible way of supporting them in this is through digitalizing information using augmented reality (AR) [5].

Augmented reality smart glasses (ARSG) can potentially be of great support to operators in industrial assembly by providing contextual, interactive, and digital information in the operators’ field of view (FOV). However, there are only a few examples of their actual implementation in industry [6]. The aim of this paper is to investigate what previous research has been done in relation to industrial implementation,
application, and long-term maintenance of ARSG for operators. The added value of this mapping is that it facilitates more in-depth research by providing an overview of relevant topics.

2. Methodology

The methodology used for this paper is based on [7]. To improve understanding of the existing literature, a scoping review was made of literature reviews of AR in industry. On the basis of these reviews, the following databases were chosen: IEEE Xplore, ScienceDirect, Scopus, and Google Scholar [6]. Table 1 shows the search phrases.

<table>
<thead>
<tr>
<th>Database</th>
<th>Search phrase</th>
<th>Limitations</th>
<th>Matches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Google Scholar</td>
<td>allintitle: “augmented reality” (survey OR review) (industry OR manufacture OR assembly OR maintenance)</td>
<td>Since 2015, no patents, no quotes</td>
<td>7</td>
</tr>
<tr>
<td>IEEE Xplore</td>
<td>(“Publication Title”: (“augmented reality” (survey OR review) (indust* OR manufact* OR assemb* OR maint*))</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>ScienceDirect</td>
<td>Title: “augmented reality” (survey OR review) (industry OR manufacture OR assembly OR maintenance)</td>
<td>Since 2015, review articles, research articles, book chapters, conference abstracts, replication studies</td>
<td>2</td>
</tr>
<tr>
<td>Scopus</td>
<td>TITLE (“augmented reality” (survey OR review) (industry OR manufacture OR assembly OR maintenance)) AND PUBYEAR &gt; 2014</td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

After filtering for unique hits, a total of seven matches were found [5, 6, 8-12]. These reviews and studies were then analyzed to obtain an overview of relevant topics to explore. The analysis was done by examining the review papers and identifying categorizations of AR used in industrial assembly applications. Categorizations outside of scope were not considered. Through a meta-analysis, these categorizations within scope were grouped into three different perspectives: operators (Perspective 1 in Figure 1), manufacturing engineering (Perspective 2), and technological maturity (Perspective 3). The term “operators” is defined in this context as humans working on an assembly line and performing assembly tasks. The term “manufacturing engineering” is defined as the planning, preparation, integration, and maintenance of ARSG in an assembly line. These perspectives were chosen to cover aspects needed to enable the use of ARSG in industrial assembly. The operator perspective takes the end user into account. The manufacturing engineering perspective takes the surrounding infrastructure and administrative staff, such as maintenance and integration staff, into account. The final perspective takes technical feasibility into account. Together, these perspectives give a holistic understanding of what is needed to bring ARSG into practical use in production.

3. Results and Discussion

This section begins with the analysis of each literature review and then presents the synthesis into the three perspectives. For each literature review, a table presents the identified themes, keywords, and topics. Each entry in these tables that is within the
scope of this paper is accompanied by a set of numbers, representing the category and subcategory they fall into in Figure 1.

Paper 1, *Augmented and virtual reality applications in industrial systems: A qualitative review toward the industry 4.0 era*, identified nine key technologies, which are presented in Table 2 [11].

<table>
<thead>
<tr>
<th>Key technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis on three dimension space</td>
</tr>
<tr>
<td>Calibration</td>
</tr>
<tr>
<td>Collision detection</td>
</tr>
<tr>
<td>Display interaction technology</td>
</tr>
<tr>
<td>Human-computer interaction</td>
</tr>
<tr>
<td>Object detection and recognition technology</td>
</tr>
<tr>
<td>System modeling technology on space and geographic environment</td>
</tr>
<tr>
<td>Tracking, positioning and registration technology</td>
</tr>
</tbody>
</table>

Table 2. Paper 1: The nine identified key technologies listed by [11], in alphabetical order.

Paper 2, *A systematic review of augmented reality content-related techniques for knowledge transfer in maintenance applications*, analyzed the state of the art in authoring, context awareness, and interaction analysis in the context of maintenance applications [10]. The results from the studies reviewed can only be validated for AR fields in maintenance, but the approach can be used as a basis for understanding other areas. The paper is a qualitative analysis that used thematic categorization to organize the data into the categories presented in Table 3.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>Design</td>
<td>Monitoring</td>
<td>Procedural</td>
<td>Users</td>
<td>Contexts</td>
<td>Data</td>
</tr>
<tr>
<td>Medium</td>
<td>Assembly</td>
<td>Guidance</td>
<td>Declarative</td>
<td>Rules</td>
<td>Rules</td>
<td>Automation</td>
</tr>
<tr>
<td>Large</td>
<td>Diagnosis</td>
<td>Collaboration</td>
<td>Automation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Repair</td>
<td>Simulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Training</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Management</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Paper 2: Themes defined by [10].

Paper 3, *A review on industrial augmented reality systems for the Industry 4.0 shipyard*, identified the most relevant industrial tasks and sectors where AR can add value to the Industry 4.0 shipyard [9]. Table 4 presents its findings.

<table>
<thead>
<tr>
<th>Service</th>
<th>Manufacturing</th>
<th>Sales &amp; marketing</th>
<th>Design</th>
<th>1.1 Operations</th>
<th>1.5 Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuals &amp; instructions</td>
<td>2.1 Quality assurance</td>
<td>Product displays &amp; demos</td>
<td>Collaborative engineering</td>
<td>Heads-up displays</td>
<td>Job-specific training</td>
</tr>
<tr>
<td>Service inspections &amp; verifications</td>
<td>Maintenance work instructions</td>
<td>Logistics, retail space optimization</td>
<td>Inspection of digital prototypes</td>
<td>Digital product controls</td>
<td>Safety &amp; security training</td>
</tr>
<tr>
<td>Remote expert guidance</td>
<td>2.1 Performance dashboards</td>
<td>Augmented brand experience</td>
<td>1.3 Augmented interface</td>
<td>1.4 Augmented operator manuals</td>
<td>1.5 Expert coaching</td>
</tr>
<tr>
<td>Improved service and self-service</td>
<td>1.1 Assembly work instructions</td>
<td>Augmented advertisement</td>
<td>2.1 Error diagnosis</td>
<td>Augmented interface</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Paper 3: Value of AR across Industry 4.0 according to [9].

Paper 4, *A systematic review of augmented reality applications in maintenance*, investigated the state of the art of AR applications in maintenance for operator support, and future developments of AR in maintenance [6]. Table 5 presents the categories derived from the data extraction from the selected papers in the review.
Table 5. Paper 4: Comprehensive categories derived from article data extraction [6].

<table>
<thead>
<tr>
<th>Field of application</th>
<th>Maintenance operations</th>
<th>Hardware</th>
<th>Development platform</th>
<th>Tracking method</th>
<th>Interaction method</th>
<th>Authoring solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation industry</td>
<td>Dis/Assembly</td>
<td>HMD</td>
<td>2.1 Mid/Low-level</td>
<td>1.3 Text</td>
<td>2.1 Manual</td>
<td></td>
</tr>
<tr>
<td>Plant maintenance</td>
<td>Repair</td>
<td>Hand held display (HHD)</td>
<td>2.2 Libraries of functions</td>
<td>1.3 Audio</td>
<td>2.1 By annotations</td>
<td></td>
</tr>
<tr>
<td>Mechanical diagnosis</td>
<td>Diagnosis</td>
<td>Desktop PC</td>
<td>2.1 Software development kit (SDK)</td>
<td>1.3 Static 2D/3D</td>
<td>2.1 By “boxes”</td>
<td></td>
</tr>
<tr>
<td>Consumer technology</td>
<td>Training</td>
<td>Projector</td>
<td>2.1 Game Engine</td>
<td>1.3 Dynamic 2D/3D</td>
<td>2.1 Automated</td>
<td></td>
</tr>
<tr>
<td>Nuclear industry</td>
<td>Haptic</td>
<td></td>
<td>2.1 3D modeling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remote applications</td>
<td></td>
<td></td>
<td>3.1 Sensors</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Paper 5, Literature review of augmented reality application in the architecture, engineering, and construction industry with relation to building information, presented a subset of the findings of [13], in four phases to develop a complete AR application [8]. The related technologies according to [8] are presented in Table 6.

Table 6. Paper 5: Architecture of AR application in four phases, modified by [8] from [13].

<table>
<thead>
<tr>
<th>Data phase</th>
<th>Computing phase</th>
<th>Tangible phase</th>
<th>Presentation phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud computing environment</td>
<td>Localization technologies</td>
<td>Portable devices</td>
<td>Natural user interface</td>
</tr>
<tr>
<td>BIM</td>
<td>GPS</td>
<td>Cheap</td>
<td>Gesture</td>
</tr>
<tr>
<td>Internet</td>
<td>RFID</td>
<td>Light</td>
<td>Motion capture</td>
</tr>
<tr>
<td></td>
<td>Barcode</td>
<td>Wearable</td>
<td></td>
</tr>
</tbody>
</table>

Paper 6, A comprehensive survey of augmented reality assembly research, grouped AR assembly research into three main categories and twelve subcategories, presented in Table 7 [5].

Table 7. Paper 6: Main categories and subcategories identified by [5].

<table>
<thead>
<tr>
<th>1.5 AR assembly guidance</th>
<th>1.6 AR assembly training</th>
<th>AR assembly design, simulation and planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4 Interactive instructions</td>
<td>1.6 Assembly training for procedural tasks</td>
<td>1.7 Human computer interaction</td>
</tr>
<tr>
<td>1.3 Multimedia-instructions</td>
<td>1.3 Feedback for user’s action</td>
<td>Assembly design and planning</td>
</tr>
<tr>
<td>1.2 Context-awareness</td>
<td>1.3 Design guidelines</td>
<td>Assembly simulation</td>
</tr>
<tr>
<td>2.4 Usability evaluation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Paper 7, Augmented reality technology in the manufacturing industry: A review of the last decade, reviewed journal publications on AR technology in the manufacturing industry between 2006 and 2017 and found 69 technical papers and 70 application papers [12]. By analyzing and grouping the keywords into thematic fields, the authors of that paper identified a total of 69 unique thematic fields in the two categories technical and application papers, merged and presented in table 8.
3.1. Meta-analysis

The identified themes, keywords, and topics in the reviewed papers were categorized into the three chosen perspectives. They were also subdivided into more specific topics under the perspectives, as shown in Figure 1. This was done by interpreting the meaning of each theme/keyword/topic, sorting them one by one, and grouping them into categories. If it was unclear how to interpret a term, the description provided in the literature was used. If this was not sufficient to fully understand the term, the source(s) cited was used. The categories for each perspective were also related to each other based on their contents and internal role within the perspective.

Perspective 1, operators, has the following categories and interrelations: *Assembly instructions* is the category that is the main purpose of ARSG for operators, that is, enhancing their capability to quickly understand complex assembly instructions. The category *Human factors* is on the same level and relates to aspects needed to support the operators in regard to safety and ergonomics. *Design* is the category pertaining to how to design an interface that gives effective assembly instructions while not hampering the human factors of the operators. *Validation* is the category of ensuring that the design does what is intended. Finally, there are the two categories of support and training. *Support* relates to being able to support operators in full production. *Training* relates to training operators on more complex tasks outside of full production. Validation also needs to take these separate purposes into account.
Perspective 2, manufacturing engineering, has the following categories and interrelations. **Authoring** is the category of how to create content using authoring tools for the designed interface of ARSG for assembly instructions. **Infrastructure** is the category of specific limitations and possibilities that manufacturing puts on ARSG, which affects what is possible in regards to authoring tools. **Validation** is the category of ensuring that the contents created by the authoring tools are compatible with the remainder of the infrastructure in the factory.

Perspective 3, technological maturity, has the following categories and interrelations. **Enabling technology** is the category of specific technologies that makes ARSG and useful interfaces possible. **Technological demands** is the category of the general developmental level of ARSG-related technologies and how well they meet market demands such as price and weight. **HMD** (head-mounted display) is the category within which ARSG are located. **Tracking** is the category related to the system’s ability to identify AR content in the real world.

4. Conclusions and Future Work

This paper performed a meta-analysis of literature reviews related to the scope of implementing ARSG for industrial assembly and mapped the identified themes, keywords, and topics to three perspectives: the operator, manufacturing engineering, and technological maturity perspectives. The results summarized in Figure 1 show how the perspectives can be further divided into interrelated subcategories. There is a general
consistency when comparing the categories across the different papers, indicating that the categories and perspectives are suitable and that the field in general is well mapped.

The scope of this paper was to provide a brief overview of the relevant literature on ARSG. Future work is needed to more thoroughly investigate the chosen perspectives. The categories and their relationships also need to be validated.

References


Augmented reality smart glasses for operators in production: Survey of relevant categories for supporting operators

Oscar Danielsson*, Magnus Holm, Anna Syberfeldt

*University of Skövde, PO Box 408, 54128, Skövde, Sweden

Abstract

The aim of this paper is to give an overview of the current knowledge and future challenges of augmented reality smart glasses (ARSG) for use by industrial operators. This is accomplished through a survey of the operator perspective of ARSG for industrial application, aiming for faster implementation of ARSG for operators in manufacturing. The survey considers the categories assembly instructions, human factors, design, support, and training from the operator perspective to provide insights for efficient use of ARSG in production. The main findings include a lack of standards in the design of assembly instructions, the field of view of ARSG are limited, and the guidelines for designing instructions focus on presenting context-relevant information and limiting the disturbance of reality. Furthermore, operator task routine is becoming more difficult to achieve and testing has mainly been with non-operator testers and overly simplified tasks. Future challenges identified from the review include: longitudinal user-tests of ARSG, a deeper evaluation of how to distribute the weight of ARSG, further improvement of the sensors and visual recognition to facilitate better interaction, and task complexity is likely to increase.

© 2020 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)

Peer-review under responsibility of the scientific committee of the 53rd CIRP Conference on Manufacturing Systems

Keywords: augmented reality; assembly operator; literature survey; augmented reality smart glasses

1. Introduction

Industry 4.0 is one of a number of initiatives that have been undertaken to improve manufacturing, mainly by enabling more customizable production through the use of Information and Communications Technologies (ICT) [1]. However, while technology such as robotics are being used to a greater extent, assembly workers are still likely to have a central role in manufacturing operations [2]. An increased need for flexibility and adaptability in future production systems is likely to lead to a demand for cognitive aids such as augmented reality (AR) [3]. Production managers and HR managers have previously predicted that support tools on the shop-floor will become increasingly important and several of them mention AR as a probable technology to be integrated [4]. This can now be seen in that while adoption levels of AR are still low in industry in general, there are already examples of AR being used in manufacturing operations [5].

This aim of this paper is to explore the operator perspective of using AR smart glasses (ARSG) in assembly. This will contribute to a better understanding of the current status and future challenges of ARSG in relation to assembly operators and thereby help facilitate a faster application of ARSG in assembly. The paper will achieve this aim by reviewing categories that are relevant for the operator perspective. A previous scoping review of ARSG for industrial assembly operators identified six categories covering an operators perspective: assembly instructions, human factors, design, validation, support, and training (as seen in Figure 1) [6].

The connection between the categories in Figure 1 that was established by [6] can be described as follows: The two main perspectives of ARSG for operators are assembly instructions and human factors. Assembly instructions are the main purpose for operators to use ARSG but human factors is also critical to ensure operator safety. Both of these categories needs to be considered in ARSG design. The design needs to be validated...
and validation in turn depends on how the ARSG are to be used, as a live support in production or as a separate training tool. Based on these connections the categories assembly instructions, human factors, design, support, and training are explored in this paper.

2. Background

There are generally three ways through which a user can experience AR: worn on the user’s head (head-mounted), held in the user’s hand (handheld), or through equipment placed in the user’s environment (spatial) [7, 8]. Handheld solutions are generally unsuitable for operators since they need both hands for assembly tasks. With a spatial solution the operator does not need to wear any extra equipment, but it limits where AR can be displayed to only close to the equipment. It is also limited as it can only display 2D objects on physical surfaces [9].

Head-worn AR can be further categorized into, for instance, contact lenses, helmets, and headsets (smart-glasses) [8]. This paper defines ARSG as a wearable device with one or two screens in front of the user’s eyes that can merge virtual information with physical information in the user’s field of view (FOV). The definition is similar to that used by [10] but broader. The motivation for this is that as ARSG continues to improve it is a reasonable assumption that all head-worn AR will be light and small enough to be considered as smart-glasses. The main advantages of ARSG are that the display is in the operator’s FOV, can display information in full 3D, and is hands-free. The main disadvantages are that ARSG currently have a more limited battery-life and FOV compared to spatial and handheld solutions.

Four ways to implement AR in ARSG is projection based, eye multiplexed, optical see-through, and video see-through [11]. Retinal projection (1 in fig.2) is a fifth way, where thin parallel light beams are focused into the user’s eyes [12]. Projection based AR (2 in fig.2) is implemented with projectors worn on the user’s head and retroreflective materials placed in the environment [13]. Eye multiplexed AR (3 in fig.2) is a virtual scene registered to the physical environment but not composited with the real world view. Video see-through (4 in fig.2) combines virtual content with a real-time video stream of reality and presents the result on a screen in front of the user [14]. Optical see-through (5 in fig.2) creates AR in the user’s FOV, usually by directing the light of the virtual scene through half mirrors or prisms [11]. Optical see-through is currently the most common solution used in commercial ARSG [15]. ARSG displays can be monocular (one eye views a screen, A in fig.2), binocular (both eyes view the same screen, B in fig.2), or dichoptic (each eye views different screens, enabling depth perception, C in fig.2) [16]. Dichoptic is preferable for ARSG if spatially sensitive information should be displayed.

3. Assembly instructions

Assembly operators need instructions on how to perform his/her assembly tasks, and more instructions are needed the more complex the task is [17]. Since products are updated and replaced regularly, operators need updated instructions to perform the correct assembly. Operators and white-collar workers at three different plants within the same global production network where interviewed by [17] in regards to areas of improvement within assembly instructions. Some problems they identified were slow updating processes (it could take three weeks for instructions to be updated at one plant), a technical language that was hard to understand, irrelevant information, a lack of feedback on errors made, and a large variation in teaching quality due to operators learning from each other. Limits on teaching quality have been identified in other reviews as well [18]. Operators also wanted more individualized and dynamic instructions and which problems that occurred, and their prevalence, varied between the plants [17]. In another case it was found that instructions should focus on clearly marked pictures and be as simple as possible with minimal text [19]. But according to [20] written text should not be removed completely. They found that users using multimedia instructions (both text and pictures) had less errors, faster learning times and were less affected by secondary tasks compared to single media instructions (only text or only picture).

Task complexity also has an influence on how to best design instructions. By dividing users into three experience levels, [21] adapted the instructions to show the right amount of information for each operator. This was implemented in a multi-modal system where the operators used ARSG.

One case study that observed and interviewed operators in an engine assembly factory found no gender or experience differences in how often operators needed to look at assembly instructions [22]. It was further found that the main reasons operators gave for looking at instructions were for checking the torque of the screwing machine, assembly time, and if something goes wrong. In general, the reasons for operators to look at instructions were for things that needed to be checked.
(such as the torque of the screwing machine), deviations from normal (if something goes wrong for instance), or things that varies (like assembly time). The operators were also interviewed about their opinions of ARSG and expressed clear positive reactions towards the possibilities of more dynamic and individual instructions.

To summarize, the current status in industry is that there is a lack of standards in regards to development and distribution of assembly instructions. Assembly workers have expressed interest in individual and dynamic instructions. Cognitive research has found multimedia instructions to be less mentally demanding, leading to less learning time and fewer errors. Digitizing assembly instructions would enable individual and dynamic instructions. However, it is important to recognize that standardizing the format and handling of instructions is necessary to facilitate digitization.

4. Human factors

Equipment that humans are to interact with and use needs to take ergonomic aspects into consideration and this is even more important for equipment used within assembly since it is usually used with a high frequency or for extended periods of time. Ergonomic issues within AR have so far, according to the findings of [23], mostly been tested in laboratory settings within the scientific literature.

An ARSG solution means that some form of equipment will be worn by the operator on his/her head. One important aspect from an ergonomic perspective is the weight of the ARSG. Night vision goggles are another type of head-mounted equipment and [24] found that reducing the length of the protruding part of night vision goggles had little effect on reducing neck muscular strain. The main issue they identified was instead how much weight was placed off from the center of the user’s skull. However, [25] tested different weights and centers of mass for one pair of experimental HMD with different poses. They found that which center of mass (COM) to use varied depending on the pose; if the user was in a neutral position it was best to keep COM around the top center of the head, if the user looked up the COM should be placed forward, and if the user looked down the COM should be placed backward, as illustrated in Fig. 3. They also found that a lower mass reduced the neck joint torque ratio, a measure used as an indicator of physical workload. Evaluation of fatigue from extended usage was an aspect identified as valuable future work and [25] further hypothesized that intended duration will determine the recommended upper mass limit due to the strong correlation between duration and load.

Fig. 3. Shifting of COM depending on head-pose (adopted from [25])

Using a video-based HMD can affect users’ efficiency. When comparing movements and time to finish identification tasks between using and not using an HMD, [26] found that when participants used a HMD to perform a simple object location targeting task they needed more time and made larger movements, implying that using a HMD hinders performance, possibly due to time delays in feedback. The HMD used in the experiment was a form of video-based AR. They also found that the larger movements could affect users’ sickness levels negatively. Areas they identified as interesting for future studies were more extensive studies with more participants and longer exposure time, analyzing simulator sickness and its relationship between posture and performance, as well as if HMDs affect the transfer of training. Similarly, [16] found that video-based HMDs cause significantly more visual discomfort, such as visually induced motion sickness, compared to traditional displays such as TV-screens. Video-based HMD also has an added safety-risk in case of power-failure. Motion sickness in optical see-through HMDs is still an understudied subject according to [27], but they found that participants experienced insignificant motion sickness when using Microsoft Hololens, an optical see-through HMD. This could indicate that an optical see-through HMD would be more suitable in regards to preventing visual motion sickness.

In summary, both the weight and the displacement of the weight of ARSG are important ergonomic factors for operators. The COM should be positioned close to the center of the skull when working in neutral positions, and towards the front or back respectively when looking up or down. Video-based displays can cause significant motion sickness. Microsoft Hololens, an optical see-through HMD, caused insignificant motion sickness which could indicate that optical see-through HMDs cause less motion sickness but further studies are needed.

5. Design

Designing for AR introduces novel challenges and possibilities compared to traditional screen-based interfaces. It is therefore important to know what is known regarding designing for AR in general, and for ARSG in particular.

Designing interfaces for mobile AR requires its own set of design principles compared to general AR and mobile systems in general, so [28] proposed a set of interaction design principles for development of mobile AR applications. The principles were:

1. Use the context for providing content
2. Deliver relevant-to-the-task content
3. Inform about content privacy
4. Provide feedback about the infrastructure’s behavior
5. Support procedural and semantic memory

The principles were based on mobile AR and the limitations of smartphones but they may still be relevant to ARSG. Using the context for providing content is important since interaction is bound to the physical environment, but this is most important when the physical environment changes. The second principle is to minimize cognitive overhead from interacting with both the system and the real world by minimizing content. Since assembly operators have a high workload this principle is likely to be very relevant. The third principle is probably of lesser relevance in an industrial setting than for private usage, but it
can still be relevant to let operators know what activities are logged. Providing feedback about the infrastructure’s behavior is important since users still interact with real world objects and might depend on external service providers. Applications should therefore be able to adapt to different availability. This principle is of lesser relevance in an industrial setting where all objects the user interacts with can be assumed to be a part of the same infrastructure. The last principle is to support procedural and semantic memory by making the interface and interactions easy to understand which is highly relevant.

A more general set of guidelines, including both AR and VR, and applied to both assembly and maintenance training is proposed by [29]. The first guideline is to start the training with an observation of the task to create a mental model of the assembly. The second is to combine physical and cognitive fidelity since they have complementary advantages. The third is to have the right amount of guidance aids since too much reduces learning. The final guideline is to provide enriched information about the task to promote deep learning. There are however indications that AR will only help an operator if the task is difficult [30].

The operator perspective is also an important aspect of the design. A minimal viable solution for an ARSG-based training system was found based on an engine assembly case [31]. The following features were identified as the most important:

1. The HMD shows the assembly procedure.
2. The HMD shows the relevant parts to pick.
3. The HMD is always available as a training support.
4. The HMD solution works as a “training island” and works separately from the line.

Spatial navigation in an AR interface compared to a traditional screen interface differs in that there is no clear limitation; with a screen a user knows where to look for information but in an AR setting the information could be behind them. A proposed solution to this is a virtual funnel leading the user to the target, a solution that reduced the time needed to find objects and perceived cognitive load for users [32]. This concept has been further explored with different variations such as different forms of the funnel (circular or square) for instance [33]. After six test iterations they arrived at a solution that could guide the user with different visual cues depending on how big the angle was between the user and the intended target. AR might also be used to help operators navigate team tasks by increasing their ambient awareness and by guiding their visual attention [34].

Interaction in the interface will likely differ in an AR implementation compared to a screen-based implementation since the user has a higher degree of mobility and probably do not have a mouse and keyboard in front of them. To make navigation more intuitive, [35] comparatively evaluated a mixed reality (MR) prototype that used a ‘tangible interface’. A physical cube that was tracked by the system allowed the user to navigate in the interface. At the time tracking technology was limited and fiducial markers were used on the cube to allow for it to be accurately tracked. Microsoft Hololens allows for gesture recognition, allowing the user to interact in a similar manner but without an intermediary artifact. Sometimes operators make mistakes and an ARSG system needs to detect these mistakes to allow for correct interaction. Force sensors can detect that parts are picked and placed at the correct position but not that they have the correct orientation, but by combining force sensors with an AR-system more errors can be detected and presented in an ARSG-system [36].

In summary, designing ARSG-interfaces means different challenges compared to a completely digital screen-based interface. AR means placing digital information in the real world and when presented in ARSG this gives the user a hands-free interaction with a bigger environment than a traditional screen-based interface. Design guidelines suggest in general to minimize information in any given context to what is needed in those contexts and to help orient the user to the correct physical location. When interacting in a completely digital world the developer can be seen as omniscient in where all things the user interacts with are. But in AR the world needs to be digitized if the results of interaction are to be interpreted in an ARSG system.

Future challenges lie in improving sensors and visual recognition of parts to allow for more accurate digitizing of the real world. Since ARSG have not been available for a long time or to a wide array of people, guidelines will need to be further tested to ensure their robustness.

6. Support

The role of assembly operators has become increasingly complex, from almost being seen as a machine to now having an increasing number of tasks and responsibilities [4]. Global competition has diversified manufacturing companies’ product range, leading to an increased complexity for assembly workers that in turn affects quality. This can be somewhat alleviated by simplifying the assembly tasks [37]. But due to an increased number of variants and shorter life-cycles of products it is more difficult for assembly operators to achieve task familiarity and routine [38]. While some assembly operator stations currently contain routine work that the operators learn fast there are already stations that require frequent relearning, for instance single inspection point (SIP) stations. Here operators need to inspect different details of products depending on what is currently having quality issues and this can vary from day to day. According to R Lindgren Brewster (personal communication, February 13, 2019), Industrial Business Optimization Manager at Volvo Car Corporation, SIP-stations are complex for operators to learn. The main problem is not to learn new things to inspect, but to stop inspecting things that are no longer a quality issue, leading to waste.

To summarize, some operator tasks are already so complex that learning new tasks, and unlearning old tasks, could benefit from information support through ARSG. Given the shortening of life-cycles of products as well as more simultaneous products it is a likely scenario that task complexity will continue to increase in the future, creating more operator tasks that have a need for increased information support.
7. Training

Training a new operator using on-the-job training (OJT) is one common method of training new operators [39]. Instructions can however be hard to understand for novice operators, who require adequate training before working on the assembly line [40]. This leads to a loss in efficiency that ARSG could help to improve by allowing operators to become independent and efficient workers faster.

AR research for industrial applications has been a research topic since the 1990’s, but there are still severe limitations in that most test-participants are students and assembly tasks are often simplified, many times using LEGO models [41]. AR based training is also mostly compared to paper- or video-based instructions rather than face-to-face training and most measurements are on time rather than quality and training transfer rates [41]. And also, in most studies monitors or handheld devices has been used [41].

Research on training transfer rates from using AR in industrial environments is still very limited. In an effort to close this gap, [42] performed an evaluation of slightly different AR headset interfaces. They found that errors can be reduced by adding a quiz on a task an operator has just been trained on. Most AR training systems are not intelligent but adding intelligent support can significantly improve training results [14]. This seems to support the wish from operators to have dynamic support, found by [17].

In summary, most research regarding AR training for operators has been done using simplified tasks and other equipment than ARSG and it has been done by non-operators outside an industrial environment. Adding intelligent support and quizzes to the training can improve the training results.

8. Conclusions

This paper has investigated ARSG for industrial assembly from an operator perspective. Table 1 presents a summary of the findings.

Table 1. Summary of current status and future challenges per category.

<table>
<thead>
<tr>
<th>Category</th>
<th>Current status</th>
<th>Future challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly instructions</td>
<td>Lack of standards</td>
<td>Digitization</td>
</tr>
<tr>
<td></td>
<td>Worker interest in individual and dynamic instructions</td>
<td>Standardization</td>
</tr>
<tr>
<td>Human factors</td>
<td>Video-based ARSG can cause efficiency losses</td>
<td>Deeper evaluation of COM on ARSG</td>
</tr>
<tr>
<td></td>
<td>Limited FOV in current ARSG</td>
<td>Longitudinal tests of ARSG</td>
</tr>
<tr>
<td></td>
<td>Interface potential safety risk</td>
<td>Expansion of FOV</td>
</tr>
<tr>
<td></td>
<td>Weight of ARSG should be kept a minimum</td>
<td></td>
</tr>
<tr>
<td>Design</td>
<td>Guidelines exists, focuses on presenting context-relevant information and limit disturbance of reality</td>
<td>Sensors and visual recognition needs further improvements</td>
</tr>
<tr>
<td></td>
<td>Sensors and visual recognition allows ARSG to interact with real world objects</td>
<td>More verification and iteration of guidelines</td>
</tr>
</tbody>
</table>

It shows that there is currently a lack of standards in design of assembly instructions. Operators have also expressed interest in more customized and dynamic instructions as well as in using ARSG, and the increased complexity and updates leads to a need for dynamic instructions. The main future challenges regarding assembly instructions lie in improving standardization and digitization to enable ARSG compatibility.

In the human factors category it was found that video-based ARSG can cause efficiency losses and that there is a general limit of ARSG FOV. There are potential safety risks and the weight should be kept at a minimum, but the placement of the weight is also important. Future challenges identified are that weight and COM should be further evaluated and improved on, that more longitudinal user tests with ARSG are needed and that FOV in general needs to be expanded.

The current status in the design category is that available design guidelines focus on presenting context-relevant information and to limit disturbance of reality. Improvements in sensors and visual recognition has opened up more design alternatives by making it possible for ARSG to interact with real world objects. But future challenges lie in improving sensors and visual recognition. Current guidelines also needs to be further improved on and adapted to industrial settings.

In the support category the current status is that operators face complex and often changing tasks and that task routine is increasingly difficult to achieve. Future challenges lie in that this complexity is likely to increase in the future.

The current status in the training category is that many tests are simplified and not performed by operators. Few of the AR-studies has been done with ARSG and there has been few quality and training transfer measurements. Future challenges lie in performing more studies, mainly longitudinal ones.

The main contribution of this paper lies in that it gives a synthesized overview of what has been achieved and what still needs to be achieved when it comes to ARSG for operators within previously identified relevant categories. This overview will help to give an overall understanding of the current potential of ARSG as well as guide further improvements of ARSG for the use of industrial operators.

Future works include considering other relevant perspectives such as manufacturing engineering and technological maturity, further described in [6]. A more exhaustive review of the categories explored in this paper could also be beneficial, particularly validation which was only indirectly explored in this paper through the support and training categories.
References


Augmented reality smart glasses in industrial assembly: Current status and future challenges

Oscar Danielsson*, Magnus Holm, Anna Syberfeldt
Production and Automation Engineering, University of Skövde, Kanikegränd 3A, Skövde, Sweden

ARTICLE INFO

Keywords:
Augmented reality
Smart glasses
Industry 4.0
Literature survey

ABSTRACT

This article aims to provide a better understanding of Augmented Reality Smart Glasses (ARSG) for assembly operators from two perspectives, namely, manufacturing engineering and technological maturity. A literature survey considers both these perspectives of ARSG. The article’s contribution is an investigation of the current status as well as challenges for future development of ARSG regarding usage in the manufacturing industry in relation to the two perspectives. This survey thereby facilitate a better future integration of ARSG in manufacturing. Findings include that commercially available ARSG differ considerably in their hardware specifications. The Technological Readiness Level (TRL) of some of the components of ARSG is still low, with displays having a TRL of 7 and tracking a TRL of 5. A mapping of tracking technologies and their suitability for industrial ARSG was done and identified Bluetooth, micro-electro mechanical sensors (MEMS) and infrared sensors as potentially suitable technologies to improve tracking. Future work identified is to also explore the operator perspective of ARSG in manufacturing.

1. Introduction

The role of industrial operators has seen several changes, from being seen almost as a machine in the 1920’s, to currently having an increasing range of responsibilities and tasks, and to the prediction that future operators will be expected to interpret information and act accordingly [1,2]. The fast and profound changes that have impacted manufacturing industry have of course also affected manufacturing personnel. In particular, operators on the industrial shop floor there are less margins for error, changing work methods, and new technologies. This has led to both new demands but also new possibilities. Presently there is no indication that this process will slow down. The predictions of what industry 4.0 can bring rather indicates the opposite will be the trend and change will accelerate.

In this technology driven scenario it is important that the operators’ work and working conditions are considered as a part of the general development of future manufacturing. As the available production data and product variations increases on the industrial shop floor, the pressure on assembly operators to handle this vast information flow increases as well, surpassing what is humanly possible. Assembly operators therefore need decision support that simplify this information. Augmented reality (AR) can provide effective support for assembly operators to help them visualize information and to place it in its context.

There has been a notable move within manufacturing from mass production to mass customization, brought about by ever increasing customer demands [3]. Industrial management representatives predict increasing importance of decision support tools for operators, AR being one such technology mentioned by managers interviewed by [1]. One of the trends within cyber-physical based manufacturing systems in recent years is smart manufacturing based on AR [4]. The AR market was predicted to grow substantially in the coming years to more than a billion users by 2020 [5]. One type of AR that shows good potential for industrial applications are AR smart glasses (ARSG) [2,6].

The aim of this article is to review the current status of ARSG from an industrial perspective and identify what challenges remain before successful implementation on the shop floor becomes viable. Even though many see the potential for AR in industry, companies are largely still performing ‘proofs of concept’ and the enabling technologies for AR (eyewear and headsets) are not yet sufficiently robust for continuous use in harsh working environments [7]. Quandt, Knoke, Gorldt, Freitag and
Thoben [8] found that industrial AR has specific constraints compared to other application areas that can lead to application barriers. Aspects they found to be particularly lacking were reliability, work safety fulfillment, and overlay accuracy.

Fig. 1 presents two relevant perspectives to consider regarding ARSG as operator assembly support that have been identified [9]. This article explores these perspectives: the technological maturity of ARSG related technology and the manufacturing engineering perspective of ARSG. The main contribution of this paper is to determine the current status of ARSG within research and commercially available technology and to compare this with the needs of the manufacturing industry to see what future challenges needs to be addressed before ARSG can be integrated into production to a greater extent. Thus the paper will contribute a technical foundation for better uptake and integration of ARSG’s into manufacturing assembly.

Manufacturing engineering is a very broad area and within this paper the scope is limited to the aspects of integrating, maintaining and updating ARSG as a support tool for operators in assembly lines. This definition is also connected to the production preparation process.

Shook and Marchwinski [10] describes production preparation process (3P) as: “A disciplined method for designing a lean production process for a new product or for fundamentally redesigning the production process for an existing product when the design or customer demand change substantially. A cross-functional 3P team examines the total production process, developing a number of alternatives for each process step and evaluating these against lean criteria. Using simple materials, the team then mocks up the process to test assumptions before equipment is ordered or installed in the final configuration.” [10 p. 65]

Three questions were identified as important to seek answers for in this survey:

Q 1: What previous works has been done in regards to integration, maintenance, and updating of ARSG interfaces for operators into a production system? The answer to this question provides better understanding of the current state of research and development of ARSG.

Q 2: What is the technical development level of ARSG in regards to usage as assembly support? This question puts the general technological maturity of ARSG into the perspective of usage as an operator support tool.

Q 3: What needs do manufacturing engineers and technicians have in using ARSG and their interface from a manufacturing engineering perspective? The focus of this question is on the administrative personnel and their needs in regards to implementing and maintaining ARSG in a production system.

Section 1 has developed the aims and motivation for this article. This is followed with some background to ARSG in industry in Section 2. Section 3 then explains the structure of the literature survey. The first perspective explored is manufacturing engineering presented in Section 4 and the second perspective, technological maturity is given in Section 5. Discussion of the findings are presented in Section 6 and finally Section 7 presents the conclusions drawn.

2. Background

As the technological base for AR has improved there has been a rapid growth of the field of AR [5]. Bottani and Vignali [11] found that more than half of all journal papers with an AR focus in manufacturing industry featured only five countries: Singapore, Germany, Italy, USA, and China, and many countries only had two published journal papers. They believe this indicates that AR in manufacturing is still in its infancy. They also noted that most implementations in current literature has so far been carried out in laboratory settings.

The technology to display AR can generally be classified in three areas: on the user’s head (head-mounted), in the user’s hand (headheld), or installed in the environment (spatial) [12,13]. A handheld solution limits the user’s efficiency by tying up at least one hand. With a spatial solution the user does not need to wear any equipment, but it limits workstation design by requiring equipment to be installed in the environment. A spatial solution is also limited to displaying virtual information on surfaces, and cannot visualize mid-air objects [14].

Head-worn AR can be categorized and implemented in different ways depending on their size and placement, for instance contact lenses, helmets, and headsets (smart-glasses) [13]. This article uses a more simplified categorization in that all forms of head-worn AR system are referred to as ARSG. Rauschnabel, Brem and Ro [15] defines ARSG as: “Augmented Reality Smart Glasses are defined as wearable Augmented Reality (AR) devices that are worn like regular glasses and merge virtual information with physical information in a user’s view field.” [15 p. 6]. A similar definition is given by [16]. This article broadens their definition by including all forms of head-worn devices in the category ARSG. This is motivated by the assumption that processing power and batteries will improve over time to a point where all the necessary performance for most uses can fit in a device that can be worn like regular glasses, at which point there would be no added value in increasing the size of a pair of ARSG.

Billinghurst, Clark and Lee [5] describes four possible ways to implement AR in head mounted displays (HMD’s): projection based, eye multiplexed, optical see-through and video see-through. A fifth way of implementing AR in HMD’s is retinal projection, which works by focusing thin parallel light beams into the user’s eyes [17]. Projection based AR uses projectors worn on the head combined with retroreflective material in the environment [18]. Westerfield, Mitrovic and Billinghurst [19] describes eye multiplexed AR as a virtual scene registered to the physical environment but not composited with the real world view. Advantages they see is less demands for accuracy but with less intuitiveness than other implementations. They further describe video see-through as a system that uses a camera to capture the real world of a user, then adds virtual content to create AR, and then presents this to the
user on a screen. Optical see-through creates AR by combining a view of the real world with virtual images, usually achieved through directing the light of the virtual images through half mirrors or prisms [5]. This allows the user to continue to see the real world in real time while seeing AR content. Optical see-through is the most common solution currently for commercially available ARSG [6]. Regarding displays in HMD’s there are three possible choices: monocular (one eye views a screen), binocular (both eyes view the same screen), or dichoptic (each eye views a different screen, enabling depth perception) [20].

3. Structure of the literature survey

As previously described, Fig. 1 presents the results of a scoping review of ARSG for industrial assembly operators [9]. The perspectives of manufacturing engineering and technological maturity are explored in this article. The definition of these perspectives and their sub-topics are based on those of [9].

The manufacturing engineering perspective is defined by the topics: authoring, infrastructure, and validation. The authoring topic explores how authoring tools can be improved to allow developers to create operator instructions in ARSG more efficiently. The infrastructure topic explores how ARSG can be integrated into a production system, which information that can be provided to the ARSG interface and what limitations an industrial environment places on ARSG. The validation topic explores how authoring tools, their created content, and ARSG can be validated to be compatible with a production system.

The technological maturity perspective is divided into the topics: ARSG, enabling technology, technological demands, and tracking. The topic ARSG is named differently from that used in [9] due to the definition of ARSG used in this paper. This paper specifically explores currently available ARSG, their specifications, and the trends of the ARSG market. Enabling technology is the topic that explores technologies that enable ARSG to be used in practice. Technological demand is the topic that explores the limitations that are put on ARSG when being used for industrial assembly. Tracking explores further which types of sensors can be used for achieving AR and their suitability for industrial environments.

4. Manufacturing engineering perspective

The manufacturing engineering perspective explores the topics of authoring, infrastructure, and validation, as described in Section 3.

4.1. Authoring

Global competition drives a constant need for the manufacturing industry to seek ways to optimize their production. Therefore if ARSG are to be used to present assembly instructions, the process of updating the instructions or creating new ones entirely needs to be simple enough that it can be done as a regular part of current continual improvement. Bocevska and Kotevski [21] suggest an approach to author AR content that does not require programming skills or expertise in computer science. Similarly, Erkoyuncu, del Amo, Dalle Mura, Roy and Dini [22] show that maintenance personnel with limited prior AR experience can create AR content to be used in maintenance. Authored content was also compared by tests with paper-based instructions and the authored content led to participants performing the maintenance tasks at around half the time of that of those using the paper-based instructions [22]. Pham and Xiao [23] instead presents preliminary results from a system that can automatically analyze video of mechanical assembly and extract tasks from it. The system still needs to be improved in its accuracy of object and hand gesture recognition. Gimeno, Tena, Orduna and Fernández [24] developed an authoring tool that allowed non-programmers to develop prototypes faster than programmers using traditional tools. Kinect cameras were used to create a depth map to provide occlusion capability [24]. Another possible support in creating content is algorithmic analysis of CAD-data that supports detection of axis and direction for each part in an assembly/disassembly task, thus allowing faster manual creation of instructions [25]. Kaipa, Morato, Liu and Gupta [26] presented a design framework for automatically generating instructions for operators. The framework can generate and order tasks from high-level assembly tasks that have previously been generated from assembly planning. [27] have created a concept for a learning design for both students and industrial stakeholders to implement automated reconfigurable digital assistance systems. This system would have an interaction device and among the systems they identified ARSG were mentioned. They planned to implement, test, and evaluate this concept in the TU Wien Pilot Factory Industry 4.0 for industrial use cases.

In the commercial market there is now specialization towards specific markets rather than just providing general AR authoring. An example of AR authoring aimed towards industrial applications is the company FTC’s industrial AR platform [28]. This AR platform has already been implemented into production in some manufacturing companies and it is predicted that many more will do this within a year [29].

In summary, there currently exists authoring tools for AR that are specific for industrial production. Support for automated assembly instruction generation has been investigated that includes depth recognition for correct AR occlusion and improved interfaces have helped simplify the authoring process in general. Future challenges include improving automated instruction generation to further reduce lead times for assembly instruction generation.

4.2. Infrastructure

For ARSG to be able to present dynamic instructions it is desirable that they are connected, directly or indirectly, to the surrounding production system. In this way feedback from tools, for instance if the torque was correct when tightening a screw, can be integrated into the interface and the instructions can be made relevant when errors are detected.

General requirements for AR applications in the industrial sector are summarized by Quandt, Knoke, Gorldt, Freitag and Thoben [8] and validated through two case studies, one within maintenance and one within weld fabrication training. They identified three categories of requirements, the first being requirements during development and integration, consisting of cost-effectiveness, data security, and applicable regulations. The second requirement being during set-up, consisting of set-up time and system reliability. The final requirement type was operational, consisting of accuracy of presentation, real-time capability, and ergonomics.

If each product can store its own assembly process on an individual RFID then this would enable decentralization of production information which could be used for easier access for an ARSG interface [30]. Another way of supporting ARSG by enhancing the surrounding environment is presented by Yew, Ong and Nee [31]. They describe a manufacturing system that has a digital coordinate system that corresponds to the real world. Natural visual landmarks in the environment are used to help viewing devices navigate where they are to present AR content in the correct positions. Manufacturing resources within this landscape can then interact using customizable interfaces [31]. Connectivity is also an important issue and AR has been identified to need a high data rate of around 25 Mbps as well as a very low latency of around 1 ms [32].

Investment in the infrastructure of a production line requires insight into the costs and benefits in relation to specific needs of each production line. To choose an appropriate ARSG for a specific infrastructure a company management can use a step by step evaluation of available ARSG’s to compare which ARSG are the most suitable for their specific needs [6]. Another form of evaluation is proposed by Palmarini, Erkoyuncu and Roy [33] who, on the basis of a literature review,
developed a set of questionnaires to evaluate a maintenance task to determine if AR could improve operator performance and which combination of AR hardware, development platform and visualization method to use, if any. Future work pointed out by the authors are validating the process and extending the process with ergonomic and economic aspects.

To summarize, surrounding infrastructure can provide ARSG’s with feedback, through product-integrated status and visual landmarks in the production facility, to allow for more accurate and dynamic interaction, both for navigation and for determining product status. Guidelines for making strategic decisions regarding ARSG for assembly exists but are still in need of validation and do not take economic aspects into account.

4.3. Validation

A holistic view on how to implement and validate AR in an assembly task is proposed by Chimienti, Iliano, Bassisti, Dini and Failli [34], starting with a preliminary analysis of the assembly procedure and through the use of intermediary to improve the adaptability of test-down to assembly instructions. Once you have a set of detailed assembly instructions you select which AR hardware to use, define a user interface, implement the software and validate the design [34]. A current limitation is that: “Published evaluation and test results often cover out-of-date hardware or prototype systems.” [35, p.26]. To mitigate this, Paelda, Röcker and Bulk [35] developed a test platform with test applications to systematically evaluate ARSG in industrial settings. The test platform evaluates hardware through sensors and assesses usability, comfort, and ergonomics through user tests. The test platform is also compact and flexible to allow easy setup in different locations, including a real factory environment. Future work identified including extending the framework with a more customizable questionnaire and a wider set of visualization options to enable usability tests of visualization.

AR can also help in testing in learning factories [36]. It can be used both for enhancing learning by for instance visualizing steps such as painting and pollution that learning factories cannot feasibly have or through presenting data, such as power flow, visually. A learning factory can also be used to test out new technology in a relevant environment before implementation in a real setting [36]. This can allow for more complex tests of ARSG in a relevant industrial setting. Hennig, Reisinger, Trautner, Hold, Gerhard and Mazak [37] presents the TU Wien Pilot Factory, which they define as a combined demonstration, pilot, and learning factory. In their definition, a demonstration factory allows for better dissemination of new technology to the general public. A pilot factory instead focuses on having a protected environment for companies to jointly develop, implement, and evaluate prototypes as well as to train employees without disrupting production. They finally describe a learning factory as a way to experience theoretically learned subject matter in a real environment. In the cases of both [36] and [37] purpose-made factories can be used to validate new designs in an accurate and fast way without disturbing current production facilities.

In summary, testing ARSG in a systematic and comparative way is still an emerging topic, where there are needs to further extend aspects that can be evaluated to improve the adaptability of test-designs. Learning factories can also prove to be useful settings to test ARSG with less restrictions than real industrial settings.

5. Technological maturity perspective

The perspective of technological maturity is explored in this section by first looking at the technological demands that are put on ARSG for them to be of use for operators on the shop floor as well as the general technological readiness level (TRL) of ARSG in general and as individual components of ARSG. It is then followed by a closer look at specific technologies that are crucial for enabling ARSG’s as a stable platform for assembly operators. The last sub-section provides an overview of the ARSG commercial market from 2013 to the present.

5.1. Technological demands

This section presents previously identified areas that are in need of improvements regarding ARSG for operators from a technological perspective. In general there is a lack of standards for AR regarding vertical industry application in industrial scenarios according to [38]. They more specifically identify a lack of human-machine interaction standards and unified norms, high construction cost, and a lack of references for enterprises to the deployment of AR. Syberfeld et al. point out some areas in need of further development to allow ARSG to be successfully integrated into the industrial shop floor [6]. These areas are: extending the field of view (FOV), making the glasses wearable, developing guidelines for user interface design, enabling benchmark evaluation, and improving voice-based interaction in noisy environments. Of these areas FOV is within the scope of this survey. Other limitations in current AR systems in general are intuitive user interfaces, integrating the systems with enterprise data and time-consuming authoring procedures [39], the latter two having been discussed in the previous chapter. And there are as yet no long term studies regarding the use of AR hardware, which relates to Section 4.3 [40]. Given that ARSG are mobile devices there is a need for more powerful batteries [41]. Internet connectivity will also put a strain on batteries and a challenge for future 5G development is to develop low energy solutions [32]. Given that AR in general and ARSG specifically is just on the verge of being broadly implemented in industrial shop floors [29], it is possible that more technological demands will become apparent in the future that have not been possible to predict before ARSG becomes more widespread in manufacturing industry.

In summary, there is currently a need for improved battery technology and extending the FOV. But more demands, that have not yet been predicted, could become apparent as ARSGs are implemented at a broader scale.

5.2. Enabling technology

To implement a pair of ARSG there are a multitude of technologies needed and it is beyond the scope of this survey to present an exhaustive analysis of them all. This section instead presents the current status and possible future developments in some specific areas that have been identified as important for future developments of ARSG in the context of operator support. The areas are: batteries [41], and FOV [6].

An important aspect of investing in ARSG as assembly instruction support is the technological level of ARSG. AR is a fairly new technology without widespread adoption in the industry and it has not yet reached maturity, except in some areas such as picking [42]. While smart glasses (SG) in themselves have been found to have a TRL of 9, AR technologies are at a lower level [43]. For industrial use, ‘Augmented Reality Tracking Techniques’, ‘Interaction Techniques and User Interfaces’, and ‘Augmented Reality SDK’s’ all have a TRL of 5 and ‘Augmented Reality Display Technologies’ have a TRL of 7 according to [43]. It was similarly found by [44] that AR has a TRL between 6 and 7. The TRL of AR has been found to be between 5 and 6 for military use [45]. In medicine AR TRL follows a rough bell curve from 4 to 7 [46]. However, even though there are many ARSG available for consumers (see Table 1 and Fig. 2), a reason for them not previously having been in industrial use is because of restrictions within shop floor usage [43]. More recent developments have seen some use of AR on the industrial shop floor, although ARSG are still not a common technology [29]. Regarding connectivity, an identified future evolution scenario of 5G is Enhanced Mobile Broadband (eMBB) which could potentially support AR [4].

Another area of interest is the extension of battery life through improved energy efficiency [47] or better battery technology [6, 41]. Um et al. also tested a solution of transmitting captured images from ARSG to a server for processing and re-transmitting the results, thus reducing the strain on the batteries [48]. The servers were placed in the architecture in the form of edge computing. This solution would also
have the added advantage of being less dependent on specific ARSG interface designs. The results did not show an improvement in time with current wireless technology \[48\]. Szajna et al. also proposes a setup using edge computing but uses it to monitor the production line rather than visualization \[49\].

A person that has a normal eye vision has a FOV of about 150° with one eye and about 180° with two eyes \[50\]. It is however inaccurate to compare this FOV directly with a mechanical camera system since, for instance, visual acuity in the human eye is not evenly distributed and individuals can have various visual limitations \[51\]. There is currently no video-based or optical see-through HMD that can provide AR with the same FOV as that of a human. An experimental setup makes it possible to achieve a FOV of 100° diagonally \[52\].

To summarize, while ARSG have been found to have a high technological maturity with a TRL of 9 for SG, however, there are still limitations in individual components and in regards to industrial adaptation. Current battery-technology or techniques to minimize battery drain do not allow full usage of ARSG through a normal workday and even experimental setups cannot reach the FOV of the human eye.

5.3. ARSG

This topic explores the general development of the emerging ARSG market. Previous publications have mapped ARSG, for instance \[6, 53\]. Table 1 presents some ARSG that have been released or scheduled for release since 2013 until the present, sorted by year and name. Since ARSG is an emerging market there are some ARSG that are no longer available. Some companies have since the release of their ARSG discontinued or exited the ARSG market altogether, been incorporated into other companies, or declared bankrupt. This is indicated in Table 1 with italic text.

To make comparisons of battery capacity more accurate both estimated hours of usage and battery size in mAh are declared when data has been available. What many of the companies specify on their websites is that battery life greatly depends on features in usage, which might partly explain the wide span of estimated battery life. Other aspects that affect this are the battery size and hardware such as processors and sensors.

When comparing the specifications of ARSG it can be seen that there is a substantial variation between them. Weight varies between 69 and 579 g. The FOV ranges from 15 to 90° diagonally and the battery capacity varies between 1 and 12 h. Within the timeframe of 2013–2019 there are several examples of companies that have exited the ARSG market, indicating some volatility. The general market for ARSG is however growing and there are manufacturing companies investing resources into researching the use of ARSG in assembly operations. The latest generation of ARSG, for example Microsoft Hololens 2 and Magic Leap One creator edition has achieved a FOV of 52 and 50° respectively.

For the Hololens 2 this is an improvement of about 50% in three years. To summarize, the authors believe that in the last six years there has been an emerging ARSG market that is now starting to stabilize with strong actors making fast progress. Some of the future challenges the authors see is improving battery life, reducing prices, and ergonomic strain. Batteries need to be improved at least to the point where full AR functionality can be used for one work shift, alternatively easily exchangeable external batteries can allow an undisrupted work flow. While prices for high end ARSG are affordable for most manufacturing companies, if they were to be introduced on a broad scale on the shop
floor it would in total constitute a large expenditure. This expenditure would replace current operator support which is usually paper instructions or computer screens and would therefore be both a big and a new expenditure. The current tradeoff that can be seen in Fig. 2 is that in general the higher the FOV the heavier the weight, which can be a big challenge if assembly operators are to use ARSG during their entire work shift.

5.4. Tracking

Tracking is the topic of how an AR-system can track its position in relation to the real world. Without tracking there can be no AR and as such it is a critical technology for ARSG. A widespread definition of AR is that it should fulfill three requirements [55]:

1. Combine reality and virtuality
2. Real time interactivity
3. Registered in 3D

As Billinghurst, Clark and Lee [5] describes it, tracking is related to the third criteria, enabling an AR-system to keep track of the real world to be able to correctly place digital content in relation to the real world. Their use of the term tracking refers to the combination of two phases. The first is the registration phase, which determines the pose of the viewer in relation to the anchor in the real world. The second is the tracking phase, which updates the viewer compared to the previously known pose. Table 2 presents a combined list of tracking technologies identified by [56–58]. Different tracking methods have different strengths and weaknesses and one way to compensate for this is to use a hybrid approach where different technologies are used in combination [56].

Bluetooth is a widely supported technology that can be used for indoor positioning [59]. Bluetooth-based beacons using Bluetooth low energy (BLE) can be used to estimate the general position of the user and in a hybrid tracking combined with vision-based AR to give feedback to the user [60]. A further advantage of using BLE beacons for general position tracking is that they are likely to be a key enabling technology for the Internet of things (IoT) [61]. Jeon, She, Soonsawad and Ng [61] give a thorough summary of the current state-of-the-art of BLE beacons. Since GPS-based solutions only work outdoors [56,62], they are not further considered in this survey.

Infrared (IR) light emitting diode (LED) markers can be used for tracking the position and orientation of objects and thereby enabling AR [63]. The IR markers prototyped by Urtans and Nikitenko [63] worked up to 1.5 m from the camera with comparable fiducial markers working up to 3 m away. Similarly they found that marker identification time was 290 ms, three times slower than with IR markers, mostly limited by the frame-rate of the IR camera, although this was still fast enough for real-time applications. A general drawback with marker solutions is that it requires placement of markers on objects that are to be tracked. Usage of infrared cameras in industrial environments is currently limited due in part to a lack of interfaces, but recent advances in smart infrared cameras may open up more widespread use [64].

Radio frequency identification (RFID) is implemented by placing a tag on the object to track which can be identified through a reader equipped with an antenna that can read the tag remotely [65]. By combining RFID tags with depth cameras, Sun, Xie, Cai, Wang, Wu and Lu [66] managed to identify and distinguish up to 15 tags simultaneously with an average match ratio of 91%. RFID tags can be used to identify products in both assembly and disassembly for AR guidance [67].

Ultra-wideband (UWB) can detect the user position through sending a signal from the user and then using triangulation of the signal to 3–4 base stations around the user [68]. The signals are affected negatively by metal however and the equipment should be placed as far away as possible from metallic objects [68]. This limits its usability in industrial settings.

Lu and Song [69] note that since Wi-Fi signals are widespread in most buildings today and since they do not require sophisticated devices to track they are an interesting tracking technology. However, they also further note that there are several drawbacks to using Wi-Fi for tracking. For instance the accuracy is usually only within several meters and layout changes will affect the signals. Wi-Fi is also limited to 3 degrees of freedom. They do however see a value in using Wi-Fi and image-based localization together for hybrid tracking, with Wi-Fi providing a rough position of the user to limit the queries of the image-based localization. Wi-Fi can also be used to compensate for drift in an inertial measuring unit consisting of an accelerometer and gyroscope as proposed by [70]. Their solution works without first having to perform fingerprinting of the area, a common technique for Wi-Fi tracking where the signal strength of an area is mapped beforehand. This contributes to their solution being more resilient to changes in the environment such as moving objects and makes it more suitable for an industrial environment.

Micro-electro-mechanical systems (MEMS) have enabled miniaturization of a number of sensing components, including triaxial accelerometers, triaxial gyroscopes, and triaxial magnetometers, which have made it possible to include them in most smartphones [71]. But their small size causes their readings to drift [72]. Besides drift, noise and magnetic interference also affect the sensors readings [73].

Accelerometers measures how much a mass is deflected from its starting position when being affected by a force, and by combining three perpendicular accelerometers it is possible to measure all components of vector acceleration for an object [74, 75]. One proposed improvement for accelerometer-based positioning is to try to estimate the accelerometer drift based on outdoor GPS drift data and using this to reduce drift errors [72].

Gyroscopes measures angular velocity and a MEMS gyroscope can measure the rate of rotation around three axis [76]. These types of MEMS gyroscopes are widely available in for instance smartphones, drones, and IoT devices [76].

Magnetometers measures the strength and direction of the magnetic field around it [77]. One MEMS magnetometer implementation used in smartphones is the Hall effect method [78], which is currently one of the dominant technologies in consumer electronic devices [79]. A Hall effect sensor is implemented by sending a current through a thin metal plate, and when magnetic field hits the plate perpendicularly it will generate a voltage that can be measured [80]. But a drawback of Hall effect sensors is that they have a limited range [81]. Magnetic sensing on large range motions can suffer from significant errors in position estimation due to magnetic disturbances [81]. Many industrial environments contain strong low-frequency magnetic disturbances such as AC

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group</strong></td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Electromagnetic</td>
</tr>
<tr>
<td>Differential GPS</td>
</tr>
<tr>
<td>GPS</td>
</tr>
<tr>
<td>Infrared</td>
</tr>
<tr>
<td>Real-time kinematic (RTK)</td>
</tr>
<tr>
<td>GPS</td>
</tr>
<tr>
<td>RFID</td>
</tr>
<tr>
<td>UWB</td>
</tr>
<tr>
<td>Wi-Fi</td>
</tr>
<tr>
<td>Inertial</td>
</tr>
<tr>
<td>Gyroscopes</td>
</tr>
<tr>
<td>Magnetic</td>
</tr>
<tr>
<td>Magnetic beacons</td>
</tr>
<tr>
<td>Ultrasonic</td>
</tr>
<tr>
<td>Vision</td>
</tr>
<tr>
<td>Nature feature</td>
</tr>
</tbody>
</table>
noise from power-lines, fork-lifts, machinery, and tools [82]. Based on this the industrial suitability of magnetometers on their own currently has clear limitations.

By combining data from a gyroscope and accelerometer it is possible to track the pose, speed and position of a pair of ARSG which thereby provides inertial navigation [54]. [54] uses these inertial measurements in combination with visual tracking which are run in parallel and filtered through an extended Kalman filter. Another similar hybrid solution proposed by [73] uses a Kalman filter to complement image processing techniques with sensor array measurements from three different types of sensors: magnetometer, gyroscope, and accelerometer.

Magnetic beacons can be used as a low-cost navigation solution according to [83]. Their proposed solution requires the installation of magnetic beacons at intervals of 4–6 m but does not require recalibration after installation and a low resolution magnetometer like those in a smartphone or tablet can be used as receiver. Another advantage they described was that the method utilized low frequency magnetic fields that have a high penetration ability and is less contaminated by high magnetic background compared to direct current (DC) fields. They did not test it for industrial environments.

One hybrid tracking solution proposed by Alahmadi and Yang [84] was to use a smartphone’s accelerometer and magnetometer to extract directional data. This data was then used to remove candidates from a list of possible targets that had different directional readings, thereby reducing the search space.

Ultrasonic tracking can achieve high tracking accuracy but are at the same time sensitive to temperature, occlusion and ambient noise [56]. Ultrasonic background noise can easily interfere in industrial use cases [85]. It is therefore not explored further in this survey.

Vision based tracking methods using an ordinary camera is the most common technique for linking the real and the virtual spaces [86]. There are some different ways to categorize vision based tracking. The categorization by [86], summarized in Fig. 2, defines two main categories of methods: 3D model based techniques and Coplanar based techniques. A broader categorization that also includes categories that are not widely used presently is made by [5] and summarized in Fig. 3.

Visual tracking methods can be based on feature tracking or model tracking, the difference being that in feature-based tracking the system detects salient features in the images and in model-tracking the system has a model of the scene that it tries to detect from the images [87]. Siltanen further states that visual tracking methods can also be divided into those that require a priori knowledge (for example model-based tracking) and those that use ad-hoc methods (for example feature tracking).

Based on Siltanen, Palmarini et al. AR-tracking can be divided into the following categories: Model-based, Features-based, Marker-based, and Others [88]. The first three categories are a-priori vision-based tracking techniques and 90% of the articles of AR studied in maintenance used this technique, with marker-based tracking being the most common (52%). Wang, Ong and Nee [39] found marker-based tracking to be the most common within AR in assembly. Markerless AR is the more flexible alternative since it does not require markers to be placed in the environment [89].

In summary, there are many possible solutions for achieving a connection between the real and the virtual. Table 2 presents a summary list of which technologies are most suited for industrial uses. Bluetooth and RFID are two technologies that can give a good estimated position of objects and they also have further uses besides AR tracking for assembly instructions, which means that the cost of implementing these trackers can be divided between more gains. Combining visual tracking with inertial measurement units (IMU) such as gyroscopes, accelerometers, and magnetometers can provide extra stability in the tracking results.

6. Discussion

Two perspectives of ARSG for industrial assembly have been explored within this literature survey. A summary of the findings are presented in Tables 3 and 4, one for each perspective.

The manufacturing engineering perspective is shortly summarized in Table 3. Authoring is currently a work intensive procedure but preliminary results show that content can be automatically extracted from

<table>
<thead>
<tr>
<th>Topic</th>
<th>Current status</th>
<th>Future challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authoring</td>
<td>• Support for non-programmers</td>
<td>• Improve automated instruction generation</td>
</tr>
<tr>
<td></td>
<td>• Preliminary automatic extraction from video</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Occlusion through video-depth</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Part-orientation through CAD-data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Some adaptation in production lines</td>
<td></td>
</tr>
<tr>
<td>Infrastructure</td>
<td>• Product-integrated sensors for decentralized input</td>
<td>• Further develop and use sensors for ARSG</td>
</tr>
<tr>
<td></td>
<td>• Visual AR landmarks for ARSG navigation</td>
<td>• Validate and broaden guidelines for ARSG investment</td>
</tr>
<tr>
<td></td>
<td>• Guidelines for evaluating/buying ARSG for assembly</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Systematic and comparative tests are emerging topics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Learning and prototype factories useful test-environments</td>
<td></td>
</tr>
<tr>
<td>Validation</td>
<td>• More adaptable test platforms</td>
<td>• Usability tests of visualization</td>
</tr>
<tr>
<td></td>
<td>• Improved automated instruction generation</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Vision based tracking categorization made by [5].

Table 3 Summary of findings in the manufacturing engineering perspective.
video-recording of assembly steps and support for non-programmers can make it possible to reduce the required skills for content creation. The technologies for automatic content creation are however still not robust enough to reliably create instructions in the general case and need to be further improved. Digitalization of factories has made it possible to decentralize product data so that production status is more readily available. Sensors can support ARSG by linking the digital and real world through other ways than optical recognition although there needs to be further improvement of sensor capabilities. There are guidelines available to help industrial managers in making strategic decisions regarding ARSG but these guidelines need to be validated and broadened to give a more complete picture. Systematic and comparative testing of ARSG is still an emerging topic and test platforms need to be further developed to take more aspects into account.

The manufacturing engineering perspective can thus be summarized that tools and guidelines exists but are still in an early stage of development. There is a need to further study the manufacturing engineering perspective to identify relevant parameters for ARSG as assembly operator support and how this can be practically achieved and maintained over time. The early adopters within the manufacturing industry can provide good test cases to further improve the advances already made.

The technological maturity perspective is summarized in Table 4. Despite current applications mostly being experimental prototypes, AR systems are showing great potential in a wide range of industrial areas and are expected to become even more widespread in the near future [11]. There are still some technical limitations in regards to hardware for broad usage, but research has shown AR to be feasible for manual assembly assistance [90]. To some extent AR is already used in production practice within the areas of visualization of production systems and the picking process [91] as well as in production to a limited extent [29]. ARSG is likely to be more prevalent once battery technology and FOV has been improved further. Commercial ARSG manufacturers are making fast improvements in terms of battery, FOV, and other hardware as well as general hardware and software design. Visual tracking has been greatly improved and MEMS sensors are also being improved, allowing hybrid tracking methods that can further improve tracking accuracy which will allow more possible uses of ARSG as operator support.

The technological maturity perspective can thus be summarized that while ARSG are currently not suitable for being used through an entire workday for operators, they are being improved on at a rapid pace, driven by a growing commercial market. There is now both research and practical implementation of ARSG taking place at an ever increasing pace and tracking technologies are getting closer to a seamless integration of the real and the virtual.

7. Conclusions

This literature survey had the aim to identify what still needs to be solved before ARSG implementation on the shop floor is possible by surveying the current status of ARSG from an industrial perspective. Two perspectives with accompanying sub-topics were explored with the summary results presented in Tables 3 and 4. Three questions of supplementary interest were also asked. The following section presents the answers this survey has identified.

Q 1: What previous work has been done in regards to integration, maintenance, and updating of ARSG interfaces for operators into a production system?

A 1: AR interfaces have been investigated for a long time but as technology has matured it has been possible to focus more specifically on ARSG adapted software. Updating ARSG interfaces has mostly been explored through improving authoring tools. Integration depends in part on standardized communication between different components in production systems to enable interface feedback to assembly operators. This is something that Industry 4.0 aims to provide, but a development of increased standardization is not dependent on Industry 4.0 and likely to continue regardless. Maintenance of ARSG software as a topic is less explored, possibly due to the early stages of adaptation in the manufacturing industry.

Q 2: What is the technical development level of ARSG in regards to usage as assembly support?

A 2: While the general TRL of SG is 9, the individual parts needed to improve SG into ARSG are still at a lower TRL. AR displays are at TRL 7 and tracking, interaction, and UI at TRL 5, both central for creating ARSG. In general terms the development level of ARSG is currently at such a level that it can be used in actual production in a limited capacity but is still at an early stage of implementation and as such still needs further development before large scale adoption can readily take place.

Q 3: What needs do manufacturing engineers and technicians have in ARSG and their interface from a manufacturing engineering perspective?

A 3: Manufacturing engineers and technicians primarily need to know how to integrate the ARSG in the production line, maintain, and replace them when they become outdated. This requires that ARSG follows standards that makes them compatible with the surrounding infrastructure. A challenge in the current ARSG market is the great diversity in hardware specifications, with large variance of weight, FOV, and battery time it can be a challenge to handle the differences. If multiple types of ARSG are bought there could be a significant variance in their capabilities that needs to be considered.

This survey presents current research and market data regarding ARSG and relates the findings to industrial application. The contribution this can lead to is both a deep and broad understanding of the current state as well as future challenges for ARSG implementation into the industrial shop floor as an operator support tool.

This survey has focused on the technical and manufacturing engineering perspective of ARSG as support for operators in the industrial shop floor. The operators’ perspective with aspects such as ergonomics is an important perspective that is connected to the two perspectives explored in this survey, as described in [9] but have been left out due to the scope of this particular survey. A survey or literature review exploring that perspective is a suggested future work.
PAPER 6
Integration of augmented reality smart glasses as assembly support: a framework implementation in a quick evaluation tool

Oscar Danielsson*, Anna Syberfeldt, Magnus Holm and Peter Thorvald

School of Engineering Science,
University of Skövde,
Skövde, Sweden
Email: oscar.danielsson@his.se
*Corresponding author

Abstract: Augmented reality smart glasses (ARSG) have been successfully used as operator support in production. However, their use is not yet widespread, likely in part due to a lack of knowledge about how to integrate ARSG into production. This lack of knowledge can also make it hard to estimate whether this is a worthwhile investment. Our solution is to provide an online evaluation tool to help production planners estimate the likelihood that ARSG will be worth the investment cost in specific production cases. Based on a strawman design, multiple design iterations were followed by a pilot test performed by participants from different manufacturing companies involved in planning production for operators. A Likert scale survey was used to evaluate the tool. The results show a slightly positive evaluation of the tool with suggestions for improvement, including widening the scope and granularity of the tool. Future works include further iterations and case studies.

Keywords: augmented reality; AR; augmented reality smart glasses; ARSG; assembly operator; framework; evaluation tool; focus groups.


Biographical notes: Oscar Danielsson received his BS in Computer Science, MS in Automation Engineering and the Lic. in Informatics from the University of Skövde, Sweden, in 2014, 2015, and 2020, respectively. He is currently pursuing his PhD in Informatics at the University of Skövde. From 2013 to 2015, he was a Research Assistant with the Department of Engineering Science, University of Skövde, Sweden. His research interests include operator support systems, augmented reality, and industrial informatics.

Anna Syberfeldt is a Full Professor in Engineering Science at the University of Skövde in Sweden. She received her PhD from the De Montfort University, UK, in 2009. Her research interests include production development, virtual engineering, operator support systems, and advanced ICT solutions. She has published over 120 scientific articles and is the leader of the Production & Automation Engineering research group at the University of Skövde.
Introduction

The term augmented reality (AR) is generally believed to have first been used in Caudell and Mizell (1992) to describe the concept of a head-mounted device that can provide dynamic information in an operator’s field of view (FOV). The authors predicted that providing manufacturing workers with direct access to computer aided design (CAD) data when performing manufacturing or assembly could eliminate several expenses and sources of error (Caudell and Mizell, 1992). Within Industry 4.0, AR has been identified as a central technology (Oztemel and Gursev, 2020), and the highest adopters of AR are currently industrial enterprises (Campbell et al., 2019).

AR can be implemented in various ways. A device may be worn on the user’s head, held in the user’s hand, or placed in the user’s environment (Bimber and Raskar, 2006; Peddie, 2017). However, the implementation that has been found suitable for operators is a head-worn implementation in the form of augmented reality smart glasses (ARSG) (Syberfeldt et al., 2017). These allow operators to have their hands free while seeing information in their FOV (Fraga-Lamas et al., 2018; Pierdicca et al., 2020). In this study, we have focused on head-worn AR in the form of ARSG, which is defined as “a wearable device with one or two screens in front of the user’s eyes that can merge virtual information with physical information in the user’s field of view” [Danielsson et al., (2020a), p.1299]. The reason for focusing on ARSG is that a head-worn implementation of AR provides mobility and is hands-free. ARSG also makes it possible for different operators to see other instructions at the same physical location. These characteristics are advantageous for operators in general. It is estimated that between 2019 and 2026, the ARSG market will have a compound annual growth rate of 36%, and Industry 4.0 applications that incorporate AR are expected to be a powerful catalyst for adoption (Inside Market Reports, 2020).

But even though ARSG is becoming more widespread, the adoption level of AR is still low within the industry, according to Masood and Egger (2020). They conclude that the central concern for the industry is not technological challenges but software ecosystems and organisational integration. Further, they hypothesise that companies need more knowledge of AR for the industry when deciding whether to adopt it and argue that it could be relevant to build the necessary knowledge base with external support. There are likely several reasons for companies’ lack of knowledge, including the availability of more cost-effective alternatives and a lack of resources to investigate ARSG. But since
ARSG are still not as widely known and used as, say, smartphones, it could sometimes simply be because of a lack of knowledge of the capabilities of ARSG and how it can support operators. If those who develop and improve assembly stations for operators had access to an effective way to evaluate their production cases concerning using ARSG, this could lead to broader implementation of ARSG in assembly lines and improved operator efficiency.

2 Aims and objectives

This paper aims to create a framework for production engineers and others in similar work roles who develop and improve assembly stations for operators. This framework is meant to help in the initial stage when alternative ways of enhancing the operators’ efficiency are considered. It consists of a set of questions about the use case, support for assembly operators, and the structural needs for integration. A grading system is used to evaluate the answers to the questions and generate a recommendation on how to proceed. By using the framework, one can decide at an early stage whether to allocate more resources to investigating ARSG as a way to improve assembly efficiency or whether other, more cost-effective solutions should be prioritised. The framework does not provide specific guidance on which ARSG to implement or how to implement it. Instead, it helps in the early decision stage. Is it worth considering ARSG at all?

To make the framework accessible and easy to use for industrial decision makers, a tool implementation of the framework was developed. The tool presents the framework in an online format and automatically generates a recommendation based on user input. Besides creating a practical tool to help in the decision process, this project will contribute to identifying which aspects need to be considered before choosing to incorporate ARSG in an assembly line.

The short-term gain of developing this framework is that it will accelerate the integration of ARSG into assembly lines and thereby increase efficiency. The long-term gains will be that the evaluation tool will provide a better understanding of the strengths and weaknesses of ARSG in general, which will make it possible to plan for ARSG use at an earlier stage. It can also help to identify areas that need improvement in regards to ARSG for assembly operators.

The following research objectives were therefore set:

- identify relevant aspects for integrating ARSG as an operator support tool in assembly
- develop and evaluate a framework-based web evaluation tool that can evaluate the relevant aspects and generate a recommendation for specific cases.

3 Related work

In the 1980’s it was believed that automation, through the introduction of robotics, would end the need for human manual workers in industry (Gilchrist, 2016). But Industry 4.0 can instead be seen as a digital transformation of the manufacturing industry, where physical and digital worlds merge, which will not always mean downsizing (Gilchrist,
2016). So despite improved automation and robotics, human demands should still be considered in regards to improvement in production (Szajna et al., 2020). The Operator 4.0 concept represents a new design and engineering philosophy where automation is seen as an enhancement of humans’ physical, sensorial, and cognitive capabilities in the form of human cyber-physical system integration (Romero et al., 2016). And AR is one cognitive aid that can support operators in increasingly dynamic working environments (Romero et al., 2016).

3.1 ARSG for operators

As a tool for operators, it is important to evaluate how ARSG fulfils the operators’ needs regarding cognitive support and ergonomics. In one experiment, it was found that operators, in regards to cognition, can adapt to ARSG and that the cognitive load is lower with ARSG than without (Atici-Ulusu et al., 2021). Regarding ergonomics, there have been reports of minor inconveniences to eyesight when using ARSG (Szajna et al., 2020). Another essential ergonomic factor is motion-sickness. When the ARSG Hololens from Microsoft was tested for this, only negligible symptoms were found (Vovk et al., 2018).

Another aspect of ARSG as a tool for operators is if and how it increases efficiency. Regarding the design of ARSG instructions, it has been found that 3D in-situ design is more efficient than side-by-side design, where the instructions show how to assemble next to the work object rather than correctly translated onto the object (Blattgerste et al., 2018). FOV of the ARSG and what type of gesture interactions that are used will influence task performance (Kim et al., 2019).

3.2 Previous frameworks

To enable the use of ARSG as assembly operator support, there needs to be support for how to choose, integrate, and maintain them as any other production equipment. A process for selecting an AR system for maintenance operations was proposed by Palmarini et al. (2017). It was based on a literature study, grey documents, and expert interviews and assessed AR feasibility, hardware, development platforms, and visualisation methods. It proposed that suitable validation processes could be surveys and questionnaires and recommended case studies comparing experts’ choices with those of non-experts using the developed process. A recent framework for developing ‘extended reality’ (XR), of which AR is a part, was proposed by Gong et al. (2021). The framework is based on six case studies of different XR systems. There are five sequential steps: understanding requirements, solution selection, data preparation, system implementation, and system evaluation. The steps in the framework serve as a general guide that provides an overall picture of the XR system development; details can be gained by complementing with other established methods. The framework presented in this paper serves as a support in the first step, understanding. More specifically, it gives a support in making the precursory decision if ARSG is a viable alternative at all.

An AR maturity model was proposed by Atheer (2019) to show how enterprises can have a return of investment (ROI) through four distinct stages: exploring, deploying, connecting, and leading. The exploring stage is described as the initial stage when AR is first considered. In this stage, ARSG usage is mainly in the form of “solutions looking for problems” [Atheer, (2019), p.7], which can lead to using ARSG where other alternatives might be more suitable. One activity at this stage is to explore single-use cases. The
proposed framework could help identify appropriate use cases at this stage by guiding the process when experience is still lacking in the company.

4 Methodology

Lings and Lundell (2004) introduced three perspectives on a method, conceptualised as a ‘method triangle’ by Thorvald et al. (2019). These perspectives are method-in-tool, method-in-concept, and method-in-action (see Figure 1).

Figure 1 The ‘method triangle’ as visualised by Thorvald et al. (2019)

A method-in-concept is described as a method as the stakeholders understand it, that is, as a social construct (Lings and Lundell, 2004). The method-in-tool is the realisation of the method-in-concept. Method-in-action is the use of different method-in-tools in particular contexts. Transforming a method-in-concept into a method-in-action (Lings and Lundell, 2004) requires that both social and technical issues be addressed. This classification of different instantiations of a method highlights the fact that a method can and should be seen through different lenses depending on where it is in the development and application phase. The concept, the tool, and the application do not always fully overlap.

Blandford and Green (2008) presented a general method development process consisting of five iterative steps in a life cycle approach. Thorvald et al. (2019) argued that this development process could be viewed through the lens of the method triangle to clarify method development steps. Thus, the first step can be seen as focusing on the method-in-concept, and steps two to four represent the process from method-in-concept to method-in-tool. The last step represents the method-in-action (see Figure 2).

The method used in this paper is based on the development process of the cognitive load assessment for manufacturing (CLAM) method developed by Thorvald et al. (2019) and presented in Figure 2. The goal of the CLAM method is to assess the cognitive load for assembly operators. The authors used a method-in-tool developed as an online web tool for this purpose. Similarly, this project aims to support the planning of support tools for assembly operators, with method-in-tool also being an online web tool.
4.1 Iterative design

Iteration is essential when many solutions are possible, and creativity is important (Wynn and Eckert, 2017). Different forms of iterations can be performed. Based on the taxonomy created by Wynn and Eckert (2017), the iterative stereotype used in this research is the convergence stereotype, a subset of the progressive iteration function. This method focuses on optimising details point-by-point after the main form of the design has been decided upon (Wynn and Eckert, 2017).

4.2 Evaluation

The tool was evaluated using three forms of evaluation: discussion, a usability test, and a survey. During the iterative design cycles, the contents of the tool were discussed in two focus group sessions and one interview. After the insights gained through this process were integrated into the tool, an observed usability test was performed. The main evaluation of the final version of the tool was done with a Likert scale survey that participants were linked to as the last step in using the tool.

4.2.1 Focus groups and interview

Focus group interviews have been described as having five characteristics: “(1) a small group of people, who (2) possess certain characteristics, (3) provide qualitative data (4) in a focused discussion (5) to help understand the topic of interest.” [Krueger and Casey, (2014), p.6]. The typical size for a focus group is five to eight people, but it can range from 4 to 12 (Krueger and Casey, 2014). In this research, the lower size range was used. The first focus group consisted of four participants and the second of three.
The first focus group consisted of three people with a mainly academic background but some industrial experience. The fourth person had a senior management role at an international engine manufacturer. One of the manager’s previous roles was evaluating early tests of using ARSG in production.

In the second focus group, two of the participants had senior management roles at another international engine manufacturer. The third person was a participant from the first focus group iteration with a mainly academic background.

One person who could not participate at the same time as the second focus group was interviewed separately. The interview followed the same format as the focus group sessions.

4.2.2 Usability test – pilot test

After the strawman design and the subsequent improvement iterations through the focus groups and interview, the tool was given a final pilot test before broad distribution to test participants. Representatives of the target users were invited to do a supervised and recorded run-through of the tool. The test was done online in a video session with two persons: the person performing the test and the test supervisor. The test supervisor was the same person in all tests and was also the person who had led the focus groups and the interview.

The person doing the test was given a short and scripted introduction in which consent for recording the session was requested. They were then prompted to use the tool. They were free to ask questions, but the test supervisor did not initiate communication at this stage. After the test, the person was debriefed to obtain their feedback on the test contents, focusing on their interpretation and understanding of the questions asked. The sessions were recorded to facilitate the correct interpretation of the test person’s feedback.

4.2.3 Survey

To evaluate the value of the tool, a survey followed the test. The statements in the survey and their motivations are presented in Table 1. The overall motivation can be summarised as assessing the reliability and validity of the tool. The scale used was a Likert scale from 1 to 5, with 1 being ‘I disagree’ and 5 being ‘I agree’. There was also an option for ‘I do not know’. It was chosen to have a midpoint value (3) in the survey questions. Some drawbacks to having a midpoint can be that respondents misuse it if they lack knowledge of the content, are ambivalent about it, do not care about it, think the answer depends on other factors, or they want to provide more socially acceptable answers (Chyung et al., 2017). In contrast, omitting a midpoint risks producing partial data by forcing respondents to choose a side (Chyung et al., 2017). Since the respondents reach the survey after having used the tool, it is likely that they know enough to answer the questions. If they have reached the survey, they have successfully used the tool and are thereby likely enough interested to not be considered ambivalent about the topic. If they think the answer depends on other factors, they can use the ‘I do not know’ option and leave comments in the free text section. And since the topic of the survey is of a technical nature the risk of respondents adjusting their answers for social factors was deemed as low.
Table 1 Survey questions and their motivation

<table>
<thead>
<tr>
<th>Statement</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I believe the questions were relevant for the evaluation of ARSG</td>
<td>The questions constitute the main data from which the result is generated, so it is vital that the target user finds them suitable.</td>
</tr>
<tr>
<td>The tool guided me to make a decision</td>
<td>The purpose of using the tool is to assist decision-making.</td>
</tr>
<tr>
<td>I think the tool recommendation is reliable</td>
<td>To evaluate the generated result of using the tool.</td>
</tr>
<tr>
<td>I would consider using this tool as part of my work</td>
<td>To determine whether test participants could envision practical use of the tool in their routine work.</td>
</tr>
<tr>
<td>The tool is good overall</td>
<td>To estimate general satisfaction with the tool.</td>
</tr>
</tbody>
</table>

Below the statements, there was room to add comments. Only five questions were asked on the assumption that since the tool also involved multiple-choice options, there was a risk of severely limiting the response rate if there were too many statements to consider.

5 Implementation

The following section shows how the different stages of the method-in-tool were implemented. The tool is available at https://www.arsg-quick-evaluation-tool.se (Figure 3). However, it has been updated since the tests described in this paper were performed.

Figure 3 Partial view of the final version of the tool (translated from Swedish) (see online version for colours)

Notes: The first section shows metadata from the test participant, followed by a sliding estimation preceding the test and the first two questions. The black box shows the tooltip on question 1.
5.1 Overview

Figure 4 presents an overview of the methods used in the implementation of the framework as a tool. Each step is described in detail in the following sections. To summarise, literature reviews and experience in this research area were used to create the first design for a web tool, a strawman. This tool was then iteratively refined with the support of external experts. After three iterations, a pilot test was done to ensure that the tool worked as intended. A final design was locked in based on the pilot test, and the main test was performed. The test group consisted of a varied group of end-users who were instructed to test the tool on real production cases from their fields. Using the tool provided insight into the usability of ARSG for each test user’s applications, and by filling out the survey, they generated evaluation data of the tool itself.

5.2 Strawman base

The initial design was based on three literature reviews in the area of the use of ARSG as operator support in assembly. The first review was a meta-analysis of ARSG that analysed previous literature reviews regarding AR in manufacturing, assembly, and maintenance. It provided an overview of relevant perspectives and their sub-topics for long-term ARSG integration as operator support (Danielsson et al., 2019). The findings were categorised into the operator, manufacturing engineering, and technological maturity perspectives. A second literature review provided insight into the operator perspective (Danielsson et al., 2020a). The third review provided insight into the manufacturing engineering and technological maturity perspectives (Danielsson et al., 2020b). As a whole, the literature reviews gave theoretical overviews of the current status and future challenges of ARSG as operator support in terms of the needs of the operators as end-users. They also discussed the requirements for manufacturing engineers as the
integrators and maintainers. These aspects served as a theoretical basis for a framework for enabling industrial integration of ARSG as assembly operator support.

The first tool was designed based on this theoretical framework. The overall design of the tool was that of an interactive questionnaire with weighted questions. It was intended to lead the user through a set of analytical questions regarding a specific production case. The different answers available were given a hidden numerical score depending on the suitability of ARSG. If an answer indicated that a critical issue might exist, a follow-up question was presented, also with multiple choices. After having answered all statements and possible follow-up questions, the result of the evaluation was presented. The first result was a list of potential critical issues. The list showed the questions where the answer indicated a critical issue, what the person answered, the follow-up question, and its solution. Finally, the system issued a recommendation on how to mitigate the critical issue based on these answers. The second part of the result was a numerical estimation, normalised between 0–100, of how suitable ARSG would be. This estimation score resulted in one of four possible recommendations, depending on the quartile in which the score landed. The final step was an evaluation of the tool itself through a Likert scale evaluation.

The questions for the first iteration were divided into three categories: Operators, Infrastructure, and Production. The categories were chosen to fit the perspective of the end-users of the tool. The operator category had a total of six questions, of which four had follow-up questions. The infrastructure category had a total of three questions with one follow-up question. The production category had only one question without any follow-up questions.

5.3 Refinement

The previously described strawman version was then used in the first iteration as a basis for discussion. The questions and their alternatives were walked through in the first focus group, and points for discussion were raised wherever necessary. The meeting was recorded and analysed afterward. Several shortcomings were identified in the first design, such as assumptions about regular production cycles that can vary from minutes to months depending on the industry. The feedback was analysed and partly incorporated in a new iteration of the questions for the second group, where the process was repeated. Only one participant could attend the third focus group meeting, and it was thus turned into a semi-structured interview. After the third review, a total of three gradual improvements of the tool from the strawman version had been done. No conflicting advice was given by the participants in this process, such as one group giving opposite advice to another group.

After these three iterative refinements of the tool based on expert input, the questions and answer options were locked from further change, and a weight survey was sent to the participating experts, asking them to assign numerical weights to the different answer options. Six of the experts answered by visiting a temporary webpage and filling in values for each answer option. They were instructed on the webpage that the scale went from 0–7, with 0 meaning no suitability and 7 meaning entirely suitable. The average weight of each answer option was then used in the tool. For instance, for question five, ‘What headgear do operators need to wear?’, values for each respective answer option was: 4.5, 3.2, 2.5, and 2.8. Thereby suitability was the highest for ‘No headgear is needed’. The final set of questions and answer options are presented in Tables 2(a)–2(c).
Integration of augmented reality smart glasses as assembly support

The tooltip mentioned becomes visible when hovering over the question and explains the question.

Table 2(a)  A final operator questions in the tool, tooltip, and answer options, translated from Swedish

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer options</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 The surface for each station where the operator works is:</td>
<td>0–2 metres</td>
</tr>
<tr>
<td>Tooltip: The surface is per station. Do not count areas where the operator just repositions.</td>
<td>3–5 metres</td>
</tr>
<tr>
<td></td>
<td>6–10 metres</td>
</tr>
<tr>
<td></td>
<td>More than 11 metres</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>2 The cycle time for the operators is:</td>
<td>Less than 2 minutes</td>
</tr>
<tr>
<td>Tooltip: The question is posed to estimate how much repetition training the operators receive.</td>
<td>Up to an hour</td>
</tr>
<tr>
<td></td>
<td>Several hours</td>
</tr>
<tr>
<td></td>
<td>Several days</td>
</tr>
<tr>
<td></td>
<td>None (craftsmanship)</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>3 The work environment requires safety glasses.</td>
<td>Never</td>
</tr>
<tr>
<td>Tooltip: Some smart AR glasses are classed as safety glasses, but the selection becomes smaller.</td>
<td>For some stations</td>
</tr>
<tr>
<td></td>
<td>For most stations</td>
</tr>
<tr>
<td></td>
<td>Always</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>4 The operators share workspace with moving vehicles during assembly work.</td>
<td>Never</td>
</tr>
<tr>
<td>Tooltip: Only count vehicles where the operators risk collision and injury, for example bicycles, trucks and similar.</td>
<td>Only for some stations</td>
</tr>
<tr>
<td></td>
<td>It varies</td>
</tr>
<tr>
<td></td>
<td>A few times per day</td>
</tr>
<tr>
<td></td>
<td>All the time</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>FOLLOW UP. Your latest answer mean that operators risk moving in traffic with smart AR glasses. Expand on how the operators come in contact with traffic.</td>
<td>The operators come in direct contact with vehicles within their work area</td>
</tr>
<tr>
<td>Tooltip: The purpose of this question is to estimate how to best adjust the usage of smart AR glasses to the traffic situation.</td>
<td>The operators need to move through trafficked areas for some tasks</td>
</tr>
<tr>
<td></td>
<td>The operators need to move through trafficked areas to get to and from their work stations</td>
</tr>
<tr>
<td></td>
<td>There is traffic directly next to the work environment but it is clearly delimited from the operators</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
</tbody>
</table>

...
Table 2(a)  A final operator questions in the tool, tooltip, and answer options, translated from Swedish (continued)

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer options</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>What do the operators need to wear on their heads?</td>
</tr>
<tr>
<td></td>
<td>Nothing</td>
</tr>
<tr>
<td></td>
<td>Helmets to protect the skull</td>
</tr>
<tr>
<td></td>
<td>Welding helmet or similar that covers the face</td>
</tr>
<tr>
<td></td>
<td>Helmet that completely encloses the head</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td></td>
<td>The equipment sits so tightly that there is only space for regular glasses</td>
</tr>
<tr>
<td>FOLLOW UP. Choose the alternative that best describes the operator’s equipment on the head:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>There is room for smart AR glasses as big as safety glasses, but the operator’s ears are covered</td>
</tr>
<tr>
<td></td>
<td>There is room for smart AR glasses as big as safety glasses and the operator’s ears are not covered</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>6</td>
<td>The operators’ need for instructions can be limited to specific and connected times.</td>
</tr>
<tr>
<td></td>
<td>No, the operators need access to instructions during the whole workday</td>
</tr>
<tr>
<td></td>
<td>No, the operators have sporadic but often occurring needs for instructions</td>
</tr>
<tr>
<td></td>
<td>No, the operators have sporadic and limited need for instructions</td>
</tr>
<tr>
<td></td>
<td>Yes, at the most the operators need instructions 2 hours at a time during a day</td>
</tr>
<tr>
<td></td>
<td>Yes, the operators need at the most instructions 4 hours at a time during a day</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>FOLLOW UP. According to the last question the operators only have sporadic and rare need for instructions. How rare?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A few seconds, some times per day</td>
</tr>
<tr>
<td></td>
<td>A few seconds, several times per day</td>
</tr>
<tr>
<td></td>
<td>A few minutes at a time, a few times a day</td>
</tr>
<tr>
<td></td>
<td>A couple of hours a time, a few times a month</td>
</tr>
<tr>
<td></td>
<td>A couple of days a few times a month</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>7</td>
<td>How often do the operators need to relearn or learn a new task, on average?</td>
</tr>
<tr>
<td></td>
<td>1–3 times a day</td>
</tr>
<tr>
<td></td>
<td>1–3 times a week</td>
</tr>
<tr>
<td></td>
<td>1–3 times a month</td>
</tr>
<tr>
<td></td>
<td>1–3 times per quarter</td>
</tr>
<tr>
<td></td>
<td>1–3 times per year</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>FOLLOW UP. How comprehensive are the changes of information?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total change of the tasks with little connection to the old tasks</td>
</tr>
</tbody>
</table>
Table 2(a) A final operator questions in the tool, tooltip, and answer options, translated from Swedish (continued)

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooltip: This question focuses on how small the changes are. This is to estimate how hard it is to learn them.</td>
<td>Total change of the tasks but with large similarities to the old tasks</td>
</tr>
<tr>
<td></td>
<td>About half of the tasks are changed with little connection to the old tasks</td>
</tr>
<tr>
<td></td>
<td>About half of the tasks are changed but with large similarities with the old tasks</td>
</tr>
<tr>
<td></td>
<td>Only small adjustments</td>
</tr>
<tr>
<td>8 How often do the operators make mistakes on average?</td>
<td>Very rarely</td>
</tr>
<tr>
<td></td>
<td>Rarely</td>
</tr>
<tr>
<td>Tooltip: To estimate how often quality will be affected. Take an average for all operators that will use smart AR glasses.</td>
<td>Somewhat rare</td>
</tr>
<tr>
<td></td>
<td>Often</td>
</tr>
<tr>
<td></td>
<td>Very often</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>9 How serious is it if there is a mistake?</td>
<td>Negligible (no or hardly any cost to remedy)</td>
</tr>
<tr>
<td>Tooltip: To estimate the consequences of errors. Choose the most severe risk that can occur.</td>
<td>Less serious (acceptable cost to remedy)</td>
</tr>
<tr>
<td></td>
<td>Severe (expensive repairs or risk of losing customer)</td>
</tr>
<tr>
<td></td>
<td>Very severe (risk for smaller personal injury)</td>
</tr>
<tr>
<td></td>
<td>Catastrophic (risk for severe personal injury or death)</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
</tbody>
</table>

Table 2(b) Final infrastructure questions in the tool, tooltip, and answer options, translated from Swedish

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer options</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 All assembly instructions are stored in a digital format.</td>
<td>Strongly disagree</td>
</tr>
<tr>
<td>Tooltip: If the instructions exist both digitally and printed, it counts as digital.</td>
<td>Somewhat disagree</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
</tr>
<tr>
<td></td>
<td>Somewhat agree</td>
</tr>
<tr>
<td></td>
<td>Strongly agree</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>2 All assembly instructions follow a standardised format so that information can be automatically extracted</td>
<td>Strongly disagree</td>
</tr>
<tr>
<td>Tooltip: Can for instance text, pictures, CAD data, and other relevant information be converted to other file formats with only small amounts of manual work?</td>
<td>Somewhat disagree</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
</tr>
<tr>
<td></td>
<td>Somewhat agree</td>
</tr>
<tr>
<td></td>
<td>Strongly agree</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
</tbody>
</table>
Table 2(b)  Final infrastructure questions in the tool, tooltip, and answer options, translated from Swedish (continued)

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer options</th>
</tr>
</thead>
<tbody>
<tr>
<td>3  Wi-Fi or Bluetooth connection in the work area is:</td>
<td>There is no connection</td>
</tr>
<tr>
<td><em>Tooltip: Smart AR glasses need wireless communication to keep themselves updated.</em></td>
<td>The speed or coverage is not enough where the operators work</td>
</tr>
<tr>
<td></td>
<td>The speed or coverage is good where the operators work</td>
</tr>
<tr>
<td></td>
<td>The speed and coverage is good where the operators work</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>4  A lot of expensive equipment is currently needed to guide operators in assembly work</td>
<td>Strongly disagree</td>
</tr>
<tr>
<td><em>Tooltip: An estimation to see whether any equipment can be replaced with smart AR glasses and thereby reduce cost and needed space.</em></td>
<td>Somewhat disagree</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
</tr>
<tr>
<td></td>
<td>Somewhat agree</td>
</tr>
<tr>
<td></td>
<td>Strongly agree</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
</tbody>
</table>

Table 2(c)  Final production questions in the tool, tooltip, and answer options, translated from Swedish

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer options</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Fitting of assembly details is difficult.</td>
<td>Strongly disagree</td>
</tr>
<tr>
<td><em>Tooltip: Smart AR glasses can show instructions in 3D. How much benefit is there for guiding operators in how they should rotate and place details?</em></td>
<td>Somewhat disagree</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
</tr>
<tr>
<td></td>
<td>Somewhat agree</td>
</tr>
<tr>
<td></td>
<td>Strongly agree</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>BIG FOLLOW UP. Based on your previous answer it is likely that fitting information is important. Choose the most suitable alternative below.</td>
<td>Assembly data contains 3D data in a format that can be extracted with ease</td>
</tr>
<tr>
<td><em>Tooltip: Is there 3D data (such as CAD data)? Can it easily be transmitted to other platforms, such as for instance smart AR glasses?</em></td>
<td>Assembly data contains 3D data in a format that is very hard to extract to other formats</td>
</tr>
<tr>
<td></td>
<td>Assembly data contains no digital 3D data</td>
</tr>
<tr>
<td></td>
<td>Assembly data contains no 3D data at all</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
<tr>
<td>2  We would consider having more variants in production if operators could handle variants without making more errors.</td>
<td>Strongly disagree</td>
</tr>
<tr>
<td><em>Tooltip: Smart AR glasses can reduce the need for operators to learn work tasks by heart, and thus makes it possible to have more product variants than before.</em></td>
<td>Somewhat disagree</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
</tr>
<tr>
<td></td>
<td>Somewhat agree</td>
</tr>
<tr>
<td></td>
<td>Strongly agree</td>
</tr>
<tr>
<td></td>
<td>I do not know</td>
</tr>
</tbody>
</table>
5.4 Pilot test

The pilot test was performed with seven test participants and was setup in seven individual online meetings lasting approximately 30 minutes. The participants were recruited through the help of senior managers at industrial companies. They were actively encouraged to participate through the senior manager but had a voluntary choice in their participation. The tests were done as part of their working hours, and no other forms of compensation were given. Participants one to five works within the automotive sector and the remaining two within grain handling equipment manufacturing. To reduce differences in conditions, all seven tests were led by the same person who followed a script introducing the test and giving instructions on how to complete it. All meetings started by asking for consent to record the session to allow for accurate analysis afterward. Participants were instructed to work through the tool questions and to voice their opinions and questions while using the tool. After completing the questionnaire, they were guided to the results, and their meaning was explained. In the final step, they filled out a survey of the tool.

Feedback was collected informally by identifying the questions the participants needed help with and formally through the debriefing after using and evaluating the tool. Part of the feedback provided indicated that the language was hard to understand. All the participants were native Swedish speakers, but the tool was in English.

6 Results

This section presents the results of the first pilot test and the main test. The primary purpose of the pilot study was to provide feedback for further improvement of the tool and final validation before performing the main test with a more extensive test group.

6.1 Pilot test

There were seven test participants in the pilot test. Their work roles and experience are presented in Table 3, which also shows their estimation of ARSG suitability for their case at the start of the test and the actual result. As shown in Table 3, five of the seven participants overestimated the suitability of ARSG compared to the tool.

<table>
<thead>
<tr>
<th>Role</th>
<th>Experience</th>
<th>Self-estimation</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production engineer</td>
<td>0–1 years</td>
<td>72</td>
<td>61</td>
</tr>
<tr>
<td>Production engineer</td>
<td>2–4 years</td>
<td>100</td>
<td>61</td>
</tr>
<tr>
<td>Production engineer</td>
<td>5 or more years</td>
<td>100</td>
<td>64</td>
</tr>
<tr>
<td>Manager</td>
<td>5 or more years</td>
<td>63</td>
<td>74</td>
</tr>
<tr>
<td>Production engineer</td>
<td>0–1 years</td>
<td>56</td>
<td>48</td>
</tr>
<tr>
<td>Process engineer</td>
<td>5 or more years</td>
<td>50</td>
<td>52</td>
</tr>
<tr>
<td>Manager</td>
<td>5 or more years</td>
<td>62</td>
<td>52</td>
</tr>
</tbody>
</table>

The feedback from the pilot test was used in the final iteration of the tool design. The main criticisms of the tool related to understanding the questions, understanding technical
terms in English, and understanding the concept behind some questions. Therefore, the main focus of the final iteration was on simplifying the language by translating the questions from English to Swedish and replacing complex words with more commonly understood synonyms. A tooltip was added to each question as well, where the test participants could see a textbox with a short explanation of the question when hovering over it.

6.2 Summary of results from the pilot test

A total of seven test persons used the tool and performed the following evaluation of the tool. Figure 5 shows the average answers from the test persons as well as each test persons’ answer. The result was interpreted as being generally positive by the pilot test group. The questions with the most considerable deviations are questions 2 and 4, with question 2 containing the only ‘I do not know’ option (chosen by test person 5). Overall, the test persons gave positive answers (4 or 5 on the five-point scale) to most questions. Questions 1, 3, and 5 had no negative answers (1 or 2 on the five-point scale). Thus, the basic design of the tool was validated by the pilot test, and no significant redesign was needed.

![Figure 5](image)

6.3 Main test

The main test was performed through a website. The link to the tool was distributed to managers at several manufacturing companies with different branches and of varying sizes. The managers were asked to identify suitable test persons such as production engineers and technicians and forward the invitation to these individuals. Appropriate test persons were described as personnel involved in building, updating, or maintaining production systems that involved assembly operators.
6.4 Results

A total of 22 test persons used the tool and took part in the survey – seven of these left comments in the comment box. One person did not indicate their job title and years of experience, and another chose a custom job title, ‘retired’. The one case in which the tool was used by a group was analysed separately.

Table 4 summarises the comments received. The comments on the lack of granularity were related to the jump from ‘under 2 minutes’ to ‘up to an hour’ for question 2 (operator cycle time). This broad range can be related to the discussion following the first iteration, where the range of the answer options was described as too limiting if looking at assembly as a whole. Thus, this comment relates to a known trade-off in the current design. The comment about only focusing on assembly may be related to a communication failure, as the participant possibly assumed that the tool had a more broad application area. The absence of questions about ergonomics was intentional as factors such as the weight of specific ARSG designs were out of scope.

Table 4 Summary of comments from test persons

<table>
<thead>
<tr>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of granularity in answer options (1)</td>
</tr>
<tr>
<td>Quick and easy to use (1)</td>
</tr>
<tr>
<td>Picture/movie of an operator with ARSG could have been useful (2)</td>
</tr>
<tr>
<td>Lack of ergonomics in wearing ARSG (1)</td>
</tr>
<tr>
<td>Only focused on assembly, not machining (1)</td>
</tr>
<tr>
<td>Case-specific feedback on AR usage (2)</td>
</tr>
</tbody>
</table>

Note: The numbers indicate the number of answers.

The group described the tool as a little ‘dull’, which was interpreted as indicating that the tool lacked depth regarding its scope and the number of results available. Their answers to the survey review questions (Figure 6) R1–R5 were: 3, 2, 2, 2, and 3, respectively.

Figure 6 Results of the 22 answers in the main test (see online version for colours)

Notes: For each question (R1-R5), the width of each bar indicates the number of replies and the height means which answer (0 = do not know to 5 = completely agree). The dashed lines show the averages for the main test and pilot test, respectively.
Figure 6 gives an overview of the results from the review questions, which were the same as in the pilot test. For each question, the number of answers for each category is indicated by the width of the corresponding bar.

As Figure 6 shows, questions 1, 2, 3, and 5 all had a lower average (densely dashed line) in the main test compared to the average from the pilot test (spaced dashed line). The approximate averages for each question are R1: 3.9, R2: 3.1, R3: 3.5, R4: 3.8, and R5: 3.6. These averages indicate somewhere between neutral and agree for all questions, which can be interpreted as a slightly positive result. Taken together with the comments received, the results suggest that the tool concept was viewed as having potential, but the tool needs improvement in its design, scope, and granularity.

7 Discussion

In this section, the results and their validity are discussed in more detail.

7.1 Validity of results

The tool is available online through a URL link. The webpage was not visible to search engines in order to reduce the risk of uncontrolled access. The address was instead distributed directly to the target audience through a closed network of production technicians and by e-mailing participants personally. Using the tool, the test person provides information about their occupation and years of experience, thereby limiting the risk of invalid data entries.

The risk of errors caused by misinterpretation of the questions was addressed through the multiple pre-evaluations in the iterative design described above. However, there could still be errors due to test persons misinterpreting the questions since they took the test alone and online. To minimise this risk, each question had a short helper-text (or tooltip) when hovering over the question with a mouse or when selecting the question if doing the test on a smartphone. There was also an ‘I do not know’ option for each question. An e-mail address and a mobile telephone number were provided to the test persons if they had any questions, but no questions regarding the tool were received.

7.2 Validity of method

The chosen method, based on the development process developed by Thorvald et al. (2019), is a form of design science. Design science is implemented through building and evaluating artefacts that are designed to solve specific business needs (Hevner et al., 2004). It is complemented by behavioural science research. Whereas the goal of behavioural science is truth, the goal of design science is utility. Not all design activity is considered design science. To help in differentiating design science from routine design, (Hevner et al., 2004) provide seven guidelines to evaluate whether a project is design science or not. Table 5 presents the guidelines and indicates how this research project adheres to the guidelines. The table shows that this research project has followed all seven guidelines and was thus an appropriate and valid method.
Table 5  Project adherence to design science guidelines as described by Hevner et al. (2004)

<table>
<thead>
<tr>
<th>Guideline</th>
<th>Adherence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Design as an artefact</td>
<td>An online evaluation tool is a viable artefact created for this project.</td>
</tr>
<tr>
<td>2  Problem relevance</td>
<td>The spread of ARSG in assembly is a current and relevant challenge in the manufacturing industry.</td>
</tr>
<tr>
<td>3  Design evaluation</td>
<td>The evaluation of the tool is done through a survey after the tool's usage by the target user group.</td>
</tr>
<tr>
<td>4  Research contributions</td>
<td>As explained in the introduction, ARSG is still not widely adopted. This research paper provides a tool to allow for enabling more ARSG integration.</td>
</tr>
<tr>
<td>5  Research rigor</td>
<td>The project follows the set of methods outlined in this paper to ensure research rigor.</td>
</tr>
<tr>
<td>6  Design as a search process</td>
<td>The topic of this research paper is too complex for an optimal solution to be found, so an iterative design of gradual improvement was used.</td>
</tr>
<tr>
<td>7  Communication of research</td>
<td>This research paper provides a basis for presenting the result of this research.</td>
</tr>
</tbody>
</table>

8 Conclusions

This paper reports on two research objectives. The first objective was to identify relevant aspects for integrating ARSG as an operator support tool in assembly. Through an iterative design method, a set of question-and-answer alternatives were identified that were judged to be relevant by focus groups. The focus groups contained experts in industrial management, technological implementation in the industry in general, ARSG implementation in the industry in particular, methodology, and user experience design.

The second objective was to develop and evaluate a framework-based web evaluation tool that can evaluate the relevant aspects and generate a recommendation for specific cases. The tool was developed iteratively through the use of focus groups. Once it was deemed stable and complete, it was put through a pilot test with seven participants. Their feedback led to further improvements and the production of a version released to a more extensive test population. The quantitative results from the main test were somewhat lower than for the pilot test (see Figure 5) but were still slightly positive. The qualitative results showed some positive comments. However, there was a desire for the tool to have a broader scope and greater granularity and improved visual design. These were not part of the initial plan for the tool. In part, the lower results from the larger test could be due to the expectations of the test persons rather than the intent of the authors. The authors interpret this as indicating that the concept of the tool is valuable to practitioners but that there is strong interest in extending the tool to provide more detailed support.

9 Future work

The focus of this evaluation tool has been on providing an early estimate of whether ARSG is a worthwhile investment in a specific production case chosen by the user of the
tool. Besides further improvements by applying more iterations, additional functionality could also be helpful. There were some suggestions to improve the graphical feedback to the users by, for instance, adding descriptive pictures or movies. Some participants in the pilot test also expressed an interest in broadening the focus beyond assembly to include areas such as machine operations or evaluating at a factory level. The same interest was said by one of the participants in the main test. Evaluation at the factory level would require significant changes due to the increased uncertainty stemming from the larger sample needed to evaluate the options. However, it is possible to extend the focus to more than just assembly operators. One implementation could be to create a separate tool with questions created for this purpose.

Another implementation could be adding a dynamic functionality, where questions presented will depend on the purpose the user of the tool chooses at the start of using the tool. Another improvement could be to offer guidance on the next steps if a tool user has identified an interesting case. Case-specific data provided by those using the tool could be generalised into a specification list. One question the tool asks is what kind of headgear the operators use. The answers provided could then indicate the limitations this places on ARSG, for example, by indicating that the type of ARSG selected needs to be compatible with mounting on safety helmets. Further improvements could be made by evaluating the use of the tool in real cases and comparing the tool predictions with the actual outcomes.

References
Integration of augmented reality smart glasses as assembly support


Evaluation Framework for Augmented Reality Smart Glasses as Assembly Operator Support: Case Study of Tool Implementation

OSCAR DANIELSSON, MAGNUS HOLM, AND ANNA SYBERFELDT
Engineering department, University of Skövde, 54128 Skövde, Sweden
Corresponding author: Oscar Danielsson (oscar.danielsson@his.se)

ABSTRACT Augmented reality smart glasses (ARSG) have been identified as relevant support tools for the Operator 4.0 paradigm. Although ARSG are starting to be used in industry, their use is not yet widespread. A previously developed online tool based on a framework for evaluating ARSG as assembly operator support is iteratively improved in this paper with expanded functionality. The added functionality consists of practical recommendations for implementing ARSG in production. These recommendations were produced with the help of five focus groups of industrial representatives working in production. The recommendations were evaluated using case studies at three different companies. The recommendations were found to be detailed and a good support for the process of considering ARSG integration into production. The companies overall found the tool and its recommendations to be relevant and correct for their cases.

INDEX TERMS Augmented reality, augmented reality smart glasses, focus groups, framework.

I. INTRODUCTION
It is generally believed that the term “augmented reality” (AR) was first used in [1], which predicted that AR might one day be used to provide assembly workers with direct access to CAD data, thus reducing error rates and costs. AR is defined as having three properties: combining real and virtual objects in a real environment, allowing real time interactivity, and aligning real and virtual objects with each other, making them seem to be part of the same reality [2]. AR can be implemented in three ways: head-mounted, handheld, and placed in the environment [3], [4]. Head-mounted AR has been identified as the most suitable for operators as it enables them to receive hands-free information in their field of view [5, 6]. Head-mounted devices are sometimes referred to as AR smart glasses (ARSG) [7]. In this paper, ARSG are defined as “a wearable device with one or two screens in front of the user’s eyes that can merge virtual information with physical information in the user’s field of view (FOV)” [8, p. 1299]. The fact that ARSG provide information in the operators’ FOV has the additional advantage that operators can receive individual instructions in the same work area.

As regards the increased complexity associated with Industry 4.0, AR is identified as a visual computing technology that can support Operator 4.0 in performing traditional tasks and in defining new tasks and scenarios [9]. This is why the highest adopters of AR are industrial enterprises [10]. ARSG are estimated to have a compound annual growth rate of 36% from 2019 to 2026, with the expected catalyst for adoption being the incorporation of AR in Industry 4.0 applications [11]. Even so, adoption of AR is currently still low in industry [12]. One of the factors hindering AR adoption may be a lack of experience with AR systems interaction [13]. However, the main challenges for AR in industry are the software ecosystem and organizational integration [12]. Masood and Egger [12] hypothesize that more knowledge of AR is needed to support decisions on whether to adopt it and that external support may also be needed to build the necessary knowledge base. Reasons for companies’ lack of knowledge of AR could be the availability of more cost-effective alternatives and the lack of resources to investigate ARSG [14]. The reasons could also include a lack of knowledge of the capabilities of ARSG in supporting assembly operators [14]. This was the motivation for creating a framework to help those who develop and improve assembly stations for operators to evaluate the suitability of ARSG as a support tool in specific production cases [14]. According to an expert in implementing ARSG for assembly (see “Expert interview” below for further details), ARSG should be seen as just one of many alternatives for supporting operators.
Therefore, there is a need to identify when and how ARSG adds value as operator support in assembly.

To support the industry in identifying when to use ARSG as an operator support, a framework was previously developed as an online evaluation tool [14]. The framework is aimed towards integrators of operator support equipment who wants to be able to quickly assess how high they should prioritize ARSG compared to alternative ways to improve production. It is used by answering 15 questions about a production case, with 5 potential follow-up questions in total. The questions have predefined answers and generates a normalized score, indicating how suitable ARSG is as an operator support tool. Depending on which quartile the score landed in, one of four general descriptions of the case suitability was generated. This first version of the framework received positive feedback, but a limitation of the framework is that it does not provide deeper motivations or practical guidance in how ARSG are suitable or not suitable for a case.

II. AIMS AND OBJECTIVES
The aim of this paper is to improve on the previously developed implementation of a framework [14]. The improvement consists of increasing the functionality of the framework by providing further support once a suitable case has been identified, as well as suggesting what to consider to improve less suitable cases. The framework is made available through an online implementation that provides answer alternatives in response to user input. A corresponding set of recommendations is generated and presented.

The short-term gain from this improvement is to accelerate the rate of ARSG integration into assembly lines, which can increase operator efficiency. By providing practical advice on how to continue the evaluation and on the first steps of implementation, this framework will help to improve understanding of the usability of ARSG in specific cases. The previously identified long-term gain of acquiring a better understanding of the strengths and weaknesses of ARSG is further enhanced by the expansion of the framework in the iteration in this paper.

To achieve this aim, the following objectives have been set:
- Develop more detailed recommendations for all questions and answer alternatives of the framework.
- Evaluate the detailed recommendations to ensure industrial relevance.
- Evaluate the tool implementation of the expanded framework as a whole in relevant production cases.

III. BACKGROUND
Providing decision support for industry for AR is not a new concept. In 2017, Palmarini et al. presented a process for choosing an AR system for maintenance operations [15]. The process assessed AR feasibility, hardware, development platforms, and visualization methods. It was based on a literature study, gray documents, and expert interviews. In the area of assembly, a similar framework was created to support the process of deciding whether ARSG are suitable for operator support [14]. The framework consists of fifteen questions about a production case. Each question has a range of alternative answers, with each answer associated with a particular score, assigned on the basis of feedback from industrial experts. The total score for the production case is then normalized to a score from 1–100 to indicate how strong the case is for using ARSG as operator support. One of four general recommendations is then presented to the user of the tool, ranging from ARSG having a very low probability of being applicable to a very high probability. Some questions have answer options that result in follow-up questions if the topic may be a critical issue or an obstacle to the use of ARSG, as, for example, when operators work where there is traffic. Any critical issues are presented in a table on the results page. The table shows the question, the answer option chosen, the follow-up question, its answer option, and a recommendation on how to handle the issue.

One area of improvement identified in [14] was to extend the tool functionality to provide further support in the steps following the first evaluation of a production case. This support would be similar to the recommendations on how to handle specific challenges in relation to critical issues. This follow-up is expanded in this paper to include all answer options.

It is very important to have a clear and accurate understanding of the requirements before starting any system development, but in practice this step is often skipped or downplayed. Thus in two case studies, development was affected by limitations in the requirements inquiry [13]. An advantage of the framework presented in this paper is that it consists of specific questions related to the production case evaluated. The tool developed in this research documents the specific attributes of the chosen production case, thereby laying a foundation for possible continued system development and integration.

IV. METHODOLOGY
The method used in this paper is a combination of two methods: a “method triangle” and “five iterative steps” [16]. Lings and Lundell [17] presented three perspectives on a method: method-in-concept, method-in-tool, and method-in-action. This was conceptualized by Thorvald et al. [16] as a “method triangle.” According to Lings and Lundell [17], the method-in-concept is a social construct of how the stakeholders understand the method. They further state that the method-in-tool occurs when the method-in-concept is realized, and the method-in-action consists of different method-in-tools, used in particular contexts. Both social and technical issues need to be addressed in order to transform a method-in-concept into a method-in-action. Lings and Lundell [17] classification of different instantiations of a method serves to highlight the point that a method should be seen from different perspectives, depending on where in the development and application phase it is.

Another method development process, presented by Blandford and Green, consists of five iterative steps in a life cycle approach [18]. Thorvald et al. [16] combined the method
The connection between the five iterative steps of [18] and the VOLUME 9, 2021

triangle with the five iterative steps of Blandford and Green [18], see Fig. 1. This was done to clarify the steps of method development. When combined like this, the first step focuses on the method-in-concept, followed by a focus on both the method-in-concept and method-in-tool in steps two to four. Step five, finally, is the method-in-action [16].

In this paper, step one (identification of an opportunity or need) is described in the Introduction, and can be summarized as a need to provide knowledge of ARSG for industry. Step two (development of more detailed requirements) was based on previous literature reviews [8], [19], [20] and extended by knowledge gained from the first iteration. This step is described in more detail in the section Straw Man Base. Step three (matching opportunities, needs and requirements) was performed using focus groups. The method used is described in the section “Focus Groups.” The implementation of focus groups is described in the section “Focus Group Interviews.” Step four (development of the tool) followed, where the focus group interviews generated updated content to be added to the straw man base. Step five (testing of the method) is done by using the finalized tool in case studies and evaluating the results.

The tool-implementation of the framework in this paper is based on the Cognitive Load Assessment for Manufacturing (CLAM) method developed by [16]. The CLAM method assesses the cognitive load for assembly operators. The method-in-tool was developed as an online web tool [16]. For this paper, an online web tool is used as the method-in-tool.

Palmarini et al. [15] described a process for choosing an AR system for maintenance. They found that surveys, questionnaires, and case studies were suitable validation processes. Their case studies compared the choices of experts and non-experts using the process developed [15]. In this study, iteration case studies will be used. Experts will use the tool and discuss the recommendations it presents in their cases. This will provide insight into how well the recommendations compare to the views of experts.

A. FOCUS GROUPS

Tremblay et al. [21] shows that focus groups have gained increased attention in information systems. Based on Stewart et al. [22], Tremblay et al. [21] present four reasons for the suitability of focus groups in design science research projects. These reasons are flexibility, direct interaction with respondents, large amounts of rich data, and building on other respondents’ comments. Focus groups were therefore seen as a suitable data collection method in this project. Participants for the focus groups were decided to be people with experience from planning, implementing, or in other ways making decisions regarding operator support tools for production. It was not seen as necessary to have experience from AR-systems since the focus of the framework is on how to integrate ARSG as a support tool and not on how to design and create ARSG or AR-interfaces. The questions relate to production cases and limitations they put on which tools can be integrated and how.

There are five characteristics of focus group interviews: “(1) a small group of people who (2) possess certain characteristics, (3) provide qualitative data (4) in a focused discussion (5) to help understand the topic of interest” [23, p. 6]. According to [24], it is not useful to provide a universal sample size recommendation for focus groups, and ultimately, saturation will be determined during data collection. They do, however, argue that the parameters they identified can help to guide in identifying and justifying sample sizes a priori. The parameters are study purpose, type of codes, group stratification, groups per strata, type of saturation, and degree of saturation. By analyzing 40 focus groups, [25] found that at least 80% of all themes are likely to be captured with a sample size of two to three focus groups, and 90% of themes are likely to be identified with three to six focus groups.

In traditional focus groups, participants congregate at a specific location. However, it is also possible to have the sessions online, an approach that is particularly suited to participants who have busy schedules and are geographically dispersed [26].

In this study, the a priori sample size for focus groups was set to three groups. This number was chosen partly based on the parameters provided by [24]. The aim was to have at least three participants in each group. The chosen format was synchronous online focus groups [26] because the target group are experts within geographically dispersed companies, who have busy schedules and are hard to book for physical meetings. Twelve to fifteen questions are suitable validation processes. Their case studies compared the choices of experts and non-experts using the process developed [15]. In this study, iteration case studies will be used. Experts will use

![FIGURE 1. The connection between the five iterative steps of [18] and the three method steps in the “method triangle” from [17], proposed by [16].](image-url)
V. IMPLEMENTATION

A. OVERVIEW

Fig. 2 offers an overview of the methods used in this paper. The hatched sections are the parts of the tool that have been not been updated from the previous version. All the steps are described in more detail in the following sections, but a brief summary is given here. There were three sources of input for the straw man base (step 0): experience within the field of AR built up by the authors, previous literature reviews, the updated literature review for this paper, the previous iteration of the tool, and the feedback from users. This input was then implemented (step 1) in an improved version of the tool with detailed recommendations, acting as a straw man on which to improve. This straw man was then presented to the focus group participants to provide a basic understanding of the concept of the framework (step 2). The feedback from the focus groups and expert interview was then analyzed and used to update the straw man base. This updated version was evaluated qualitatively by case studies (step 3).

The first objective of this study is to identify relevant recommendations for integrating ARSG into assembly production. Knowledge from experienced integrators in industry was considered a relevant form of data for this purpose.

B. STRAW MAN BASE

As in the first iteration of this framework implementation, a straw man formed a basis for further refinement [14]. The straw man is just meant to start discussions by providing an example set of suitable content and therefore it does not need to be evaluated beforehand. The literature reviews done prior to the first iteration were also relevant in this iteration. A meta-analysis of previous literature reviews related to AR in manufacturing, assembly, and maintenance identified relevant aspects of ARSG as operator support [19]. The perspectives identified in that literature review were expanded on in two follow-up reviews. One of these perspectives, the operator perspective, was explored in depth in a literature review covering assembly instructions, human factors, design, and how to validate a design, depending on whether it was intended to support live production or offline training of operators [8]. Two other perspectives, manufacturing engineering and technological maturity, were explored in depth in a separate literature review [20].
demands, ARSG as a product, and tracking technologies. Knowledge derived from these literature reviews provided a theoretical basis for ARSG implementation as assembly operator support and was used, together with experience, as a starting point for the first iteration [14].

The first iteration of the tool resulted in an interactive web page on which fifteen questions with fixed and weighted answer alternatives were presented to users. Each answer alternative had a hidden numerical score, indicating the case’s suitability for ARSG depending on the chosen answers. Five of the questions had some answer alternatives that could indicate a possible critical issue, leading to a follow-up question being asked. If such issues were identified, the result page would present a list of them along with a general recommendation on how to handle each issue. A score from 0–100 was then presented indicating how suitable the case was for ARSG. One of four general recommendations was also presented, depending on the quartile in which the score fell. This was then followed by a five-question survey of the tool itself, which is not a part of the framework.

For this iteration the theoretical base and the framework were revisited to determine relevant areas for expansion. The tool-implementation described above was used as a base to expand upon, as seen in the implementation section of Fig. 2. The questions, their answer alternatives, and their scores were left unaltered. However, a set of recommendations for each answer alternative was created and added to the tool implementation. The recommendations were based on the previous literature reviews, the authors’ seven years of experience in AR for industry, and the knowledge gained during the first iteration.

The straw man base was sent to the focus group participants prior to the focus group meetings. This gave the participants a base to which they could relate the scope and purpose of the framework and how the tool presented it. They then took part in the focus group meetings and gave their feedback on how to change and improve the recommendations. The questions, their answer alternatives, score, and general design of the tool were locked so that they could not be modified during this study. Because the tool was not updated between each iteration of the focus groups, each group had the same starting conditions for the discussions.

### C. FOCUS GROUP INTERVIEWS

Five focus groups were assembled with 2, 5, 3, 2, and 4 participants, respectively. The sessions were held online. The participants represented eight different companies and one university, see Table 1.

Fig. 5 shows the procedure for each focus group. The first step was to ensure consent to record the session. This was followed by introductions, with the discussion leader starting to get all participants acquainted with each other. Then each question from the framework was presented along with the answer alternatives. The discussion leader gave a brief explanation of the purpose of the question and invited the participants to present their views on the question, both from the perspective of their particular company and also from a broader perspective. The focus of the discussions where on what would need to be considered if ARSG were to be used like ‘any other production equipment’ and what information the participants would need. All participants had previous knowledge on at least a basic level of what AR and ARSG are. If there was any uncertainty regarding what ARSG can handle or how they function the participants were free to ask and also did so. The discussion leader is experienced in both research and practical use of AR and ARSG and was able to answer all questions that arose.

After all questions were completed, the discussion leader summarized the highlights of the discussion, and the participants were allowed to comment. The last step, finalization, described what would happen afterwards, namely that the results would be summarized and analyzed, and the participants would be given access to the collected data.

All groups had time to discuss all questions. There was some overlap in the recommendations suggested by the groups, but no opposing recommendations were identified. Besides discussing the questions, the groups also discussed specific details of their own cases, feedback more specifically related to the tool design, and general views on the topic of ARSG. In group 3, one feedback was that the questions “made you stop and think.” In group 2 some feedback related to that the tool design and question formulations were somewhat unclear in some cases. Participants in group 2 felt that it was not clear that the tool focuses on assembly and not, for instance, processing. They also wanted it to be clearer at which level of abstraction the tool was to be used at (per station or per factory for instance). The negative feedback was used to improve the design by updating the tooltips and clarifying the introductory text of the tool to remove the identified uncertainties.

### TABLE 1. List of focus group companies.

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Global manufacturer in the automotive sector.</td>
</tr>
<tr>
<td>2</td>
<td>Global manufacturer of electric cars.</td>
</tr>
<tr>
<td>3</td>
<td>Global manufacturer of sheet metal machinery.</td>
</tr>
<tr>
<td>4</td>
<td>Global manufacturer in the field of safety and graphics, healthcare, and consumer goods.</td>
</tr>
<tr>
<td>5</td>
<td>Global company working within the sectors of energy, industry, and infrastructure.</td>
</tr>
<tr>
<td>6</td>
<td>Swedish subcontractor for the automotive sector.</td>
</tr>
<tr>
<td>7</td>
<td>Global manufacturer of trucks, buses, and construction equipment.</td>
</tr>
<tr>
<td>8</td>
<td>Nordic supplier of industrial tools, metrology, service, and the aftermarket.</td>
</tr>
<tr>
<td>9</td>
<td>Swedish university doing research in close collaboration with local industries.</td>
</tr>
</tbody>
</table>
1) EXPERT INTERVIEW

After all focus group interviews had been completed, there was an individual interview with an ARSG expert from industry. The expert is a senior manager at a multinational manufacturing company with around thirty years of experience working with operator instructions, and has had the leading role in testing ARSG as assembly operator support at several manufacturing facilities within that company. This interview was used as a complement to the focus group interviews and was seen as a significant contribution due to the expert’s unique seniority in the company and vast experience in the field of practical integration of ARSG in industry.

The expert indicated that it is important that the ARSG fulfill the requirements set by each company in regard to usability and safety. The goal should be that ARSG should be “like ordinary glasses” so that they can be used for long periods. For short-term usage, like control tasks done periodically, this requirement is less of an issue. What can be shown and how navigation and interaction can be performed are also important challenges. Translating 3D information to the ARSG interface can be a big challenge when there is little 3D information for the product. At the expert’s company, 3D information was therefore more focused on the manufacturing tool side since they had better documentation on those tools. Presentation solutions cannot be standalone: they must connect to the current production system (i.e. digital seamlessness). The expert’s company is currently investigating a multitude of general operator support tools.

The expert mentioned that it was common for there to be an initial sense of euphoria when starting discussions with teams considering ARSG. However, this was followed by a lowering of expectations when they realized that ARSG must be integrated into the production system. Therefore, it is important not to view ARSG as a solution to all problems, but rather as one of many tools available.

The main advantage of ARSG, according to the expert, is that they are hands free and mobile, as mentioned in a previous section. At present, there is not a strong case for continual use by operators in production due to the current weight of ARSG and operators being annoyed when shown too much information, for example, when they already know what to do. One helpful way to alleviate this is to have ARSG that can be “flipped up” so that operators can easily disengage them. At the same time, there is still a need for...
instructions and there is often limited space in production lines to place information equipment such as TV screens. Interaction with information equipment such as keyboards, can also present a challenge. Static production lines versus moving lines can make projector solutions (spatial AR) more feasible.

The experience of the team the expert has worked with is that although there is a big focus on 3D and complex presentations of information, they prefer to look at finding solutions for more practical situations. For example, the expert mentioned that many operators work is set out on printed papers that they need to carry with them, and that screens are sometimes placed where it is hard to look at them. The focus of the company’s work with ARSG was thus on finding solutions that would allow operators to see simple information and navigate in the interface without disrupting their hands-on work on the main task. The expert believed that promotional material for ARSG focuses too much on impressive 3D visualizations, which raises expectations and is disconnected from what is useful in practice.

The strongest cases for ARSG are in education for assembly operators and in maintenance. Dynamic instructions are an interesting aspect, allowing individual operators to see adapted instructions depending on errors, for example.

However, integrity issues need to be considered before this can be implemented. Vision recognition in the ARSG can be very useful if the interaction is to show correction information.

2) REFINEMENT

The input from the focus groups and expert interview were analyzed after all of them were completed. Each focus group session was replayed and all recommendations made by participants during the session were added as data to the corresponding question. Table 2 gives an example of the data collected from the groups for question 3 in the operator section. Some recommendations clearly belonged with another question, and were then transferred to that question. When all focus groups had been summarized, each question was analyzed in turn. All groups were analyzed in parallel for each question to ensure no conflicting recommendations existed. Then the data gathered in Table 2 were condensed into more direct practical recommendations. An example of this is presented in Table 3 for question 3 in the operator section. Thereafter the recommendations were mapped to relevant answer alternatives. The mapping was done by first summarizing all recommendations from the groups into one list, resolving any duplicate entries and combining similar ones. For instance, group 2, 3, and 5 all brought up that fluids can be harmful to ARSG. Group 3 also mentioned non-fluid particles as an issue. These three points were combined to warn against fluids and particles. Each of the four answer options to the question were then sequentially given a combination of the recommendations. The combination depended on the context given from the discussions.
TABLE 2. Example from the focus group protocol. These are the thoughts of the respective groups on question 3 (The work environment requires safety glasses) in the operator section, translated from Swedish.

<table>
<thead>
<tr>
<th>GROUP</th>
<th>OPERATORS</th>
<th>SUMMARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>Protective glasses fit very tightly nowadays, including from the side. The size of ARSG mean that they might need customization to offer side protection. In process industries where there are things like fluids, there are risks. Important to consider if ARSG are for production, training, or maintenance.</td>
<td></td>
</tr>
<tr>
<td>Group 2</td>
<td>It affects which glasses can be chosen. Maybe there is a need to choose bigger glasses. A solution can also be customization of the glasses. Do protective glasses include visors? A bit unclear how question 3 and 5 differ. There was a desire for more clarity to evaluate the case. A bit unclear on which basis the evaluation should be done.</td>
<td></td>
</tr>
<tr>
<td>Group 3</td>
<td>It will be hard to wear both protective glasses and ARSG. It is better if they are used where protective glasses are not. Can they be combined? There are manufacturers that consider protective gear but options will be reduced or customization will be needed. How do normal glasses work? This depends on the model; some ARSG allows for glasses, some need custom-made lenses, which can be another limitation. It might cost more but would be convenient. Fluids and particles are a risk for ARSG if used as protective glasses. It can be damaging for the technology, almost more than for the operator.</td>
<td></td>
</tr>
<tr>
<td>Group 4</td>
<td>If ARSG fulfills the same function as safety glasses, they might replace them. But sometimes they have different functions and then you would need to have both. One might not be able to choose as freely when there needs to be room for ARSG or if ARSG can fulfill the requirements by themselves. It also depends on the cost of ARSG; maybe one wants to protect them more than protective glasses. A casing or similar might be placed around the ARSG, a cheap material that protects.</td>
<td></td>
</tr>
<tr>
<td>Group 5</td>
<td>Protective glasses affect the possibility of introducing ARSG. It is hard to have both ARSG and protective glasses. It should be considered since it should be developed for production, and in many cases you need protective glasses. It should be a possibility in the future. But it limits the choices. If you have very specific requirements, there might be a need to custom order. Are they protected against fluids? Protective glasses are expendable but not ARSG; one needs to consider protecting the ARSG as well. An alternative can be to change between protective glasses and ARSG if it fits in the production.</td>
<td></td>
</tr>
</tbody>
</table>

The resulting combined recommendations consisted of a set of sentences. In the final step, they were formulated into cohesive paragraphs for each corresponding answer alternative to present a concise but easily readable text. Table 4 is an example of recommendations for the different answer alternatives for question 3 in the operator section. Note that there are large similarities in the recommendations for the last three answer options. For answer options 2-4, the differences lie in the first sentences since the frequency of the need for safety glasses affects how they can be combined with ARSG. Regardless of frequency, the other recommendations are relevant. Once all answer options to all questions had recommendations, the recommendations and summaries of the discussions were sent out to all participants. They were given opportunity to raise any critique they had of the summaries and the recommendations. No critique was reported.

VI. EVALUATION

The framework consists of fifteen questions and five follow-up questions. Including the different answer alternatives, there are a total of 82 answer alternatives for which the tool gives a recommendation to the user, discounting the “I don’t know” answer alternatives. It is not feasible to assess all possible permutations, so it was decided to assess the tool implementation by using a set of industrial cases. A criterion for choosing cases was to have a diverse set of industries represented to provide a broad view of the tool’s validity in a range of assembly cases.

A. CASE STUDIES

Three case studies were done to verify industrial relevance, and they all followed a specific procedure. Meetings were booked with company representatives at their location. This was done to reduce the time investment for the company, to have close access to the production case for reference, and to have the industrial representatives in a familiar environment to allow full focus on the tool evaluation. A physical meeting was possible as all industrial representatives in each case were part of the same company.

The meeting began with a brief introduction to establish rapport and familiarity with the process. After consent was established, a voice recording of the meeting was started for later analysis. Then the researcher presented the tool to the
TABLE 4. Final recommendations for the different answer options for question 3 in the operator section. Translated from Swedish.

<table>
<thead>
<tr>
<th>QUESTION 3: THE WORK ENVIRONMENT REQUIRES SAFETY GLASSES</th>
<th>RECOMMENDATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never</td>
<td>Safety glasses are no hindrance to wearing ARSG.</td>
</tr>
<tr>
<td>For some stations</td>
<td>If safety glasses are only needed sometimes a convenient alternative could be to wear ARSG were safety glasses are not needed. If this is not feasible, then either both need to be worn at the same time, or ARSG have to be used as safety glasses. ARSG involve sensitive technology, so if safety glasses are needed it is important to assess the risk of damage to the ARSG in the environment. Fluids and particles pose a particular risk to the electronics. The risk could be reduced by enclosing the ARSG in an additional protective casing or by wearing safety glasses on top of the ARSG. Regardless of the solution, it will reduce the available options and may increase costs when customizing. It is important to review ergonomics and functionality for the new solution.</td>
</tr>
<tr>
<td>For most stations</td>
<td>It is probably not suitable to switch between ARSG and safety glasses if they are needed at most of the stations. If this is not feasible, then either both need to be worn at the same time, or ARSG have to be used as safety glasses. ARSG involve sensitive technology, so if safety glasses are needed it is important to assess the risk of damage to the ARSG in the environment. Fluids and particles pose a particular risk to the electronics. The risk could be reduced by enclosing the ARSG in an additional protective casing or by wearing safety glasses on top of the ARSG. Regardless of the solution, it will reduce the available options and may increase costs when customizing. It is important to review ergonomics and functionality for the new solution.</td>
</tr>
<tr>
<td>Always</td>
<td>If safety glasses are always needed, then either both need to be worn at the same time or ARSG have to be used as safety glasses. ARSG involve sensitive technology, so if safety glasses are needed it is important to assess the risk of damage to the ARSG in the environment. Fluids and particles pose a particular risk to the electronics. The risk could be reduced by enclosing the ARSG in an additional protective casing or by wearing safety glasses on top of the ARSG. Regardless of the solution, it will reduce the available options and may increase costs when customizing. It is important to review ergonomics and functionality for the new solution.</td>
</tr>
</tbody>
</table>

participants and walked through each question. The participants discussed among themselves and decided on the answer to each question, with the researcher available for clarification when needed. Once all questions had been answered, the results were presented and explained by the researcher. Each critical answer and recommendation, if any, was walked through and discussed, followed by the detailed recommendations for each question. For each recommendation, there was a summary discussion about what the recommendation said and how well it coincided with the participants’ views. They were actively encouraged to raise their concerns or opposing views, and to elaborate on the case and the recommendation. After all recommendations had been discussed, the participants were presented with the survey of the tool on the last page and filled it out jointly. There was then a debriefing and finalization of the meeting. The recorded material was later analyzed to compare the feedback from the participants for each recommendation and see what improvements were needed.

The first case involved a global manufacturer of sheet metal machinery. Two industrial representatives used the tool and discussed it. The estimate before starting with the tool was 64 (see the middle of Fig. 3). The score after running the tool was 77. The participants reached consensus on how to respond to each question in the tool. In general they agreed with the recommendations presented by the tool. A strength they identified was that the recommendations were condensed to key points, making it easier to get an overview by reading through the recommendations. The recommendations were also practical and relevant, and explanations were provided about how to consider and proceed with ARSG in their case.

The second case involved a global manufacturer in the automotive sector. Three industrial representatives used the tool and discussed it. The score from the tool was 77 (the initial estimate was 50). The participants also reached consensus on how to respond to each question in the tool. A critique that was raised was that the answer alternatives regarding the number of errors (very rarely, rarely, somewhat often, often, and very often) were a bit vague and diffuse. There was consensus in the group that the recommendations were good and relevant overall.

The third case involved a Swedish manufacturer of grain-handling equipment. Two industrial representatives used the tool and discussed it. The score from the tool was 84 (the initial estimate was 63). The participants reached consensus on how to respond to each question in the tool. Some comments from the participants were that the recommendations were very detailed and explained in a good way. According to the participants, the tool gave a good picture of whether ARSG would be suitable and especially why and how.

In summary, all participants in the three case studies generally agreed with the recommendations that the tool presented for their respective cases. They found the recommendations relevant and useful for considering if they should integrate ARSG in their cases and how to start this process. The critique from group two is understandable, but it referenced a deliberate design decision to make the framework suitable for general cases. It is not possible to set a specific percentage for error rates because what is acceptable in one industry may be unacceptable in another. The three cases were from three different companies, active in three different sectors, and in three different cities. Even so, they all independently expressed a positive view of the recommendations presented by the framework.

VII. DISCUSSION

The results and validity of the results and of the method are discussed in the following section.

A. VALIDITY OF RESULTS

A set of case studies as manufacturing companies was used to ensure that the results are relevant. Two possibly severe
critiques were identified. First, by only evaluating a subset of the possible answer combinations, the evaluation does not ensure full coverage. Secondly, having a researcher meet the company representatives in person created a risk of social factors interfering, such as being accommodating or intimidated and adjusting the interaction accordingly.

The first point was addressed by considering the spread of the chosen companies. The companies were chosen from different areas to ensure diversity in testing. While located relatively close geographically, they were in three different cities and were active in distinctively different markets. The risk of the companies influencing each other is thus minimal. The second point was addressed by taking precautions to minimize the risk of noise in the data. As described in the evaluation section, the assessments were done at the companies’ location to ensure that the participants were in a familiar environment so they could focus on the assessment.

**B. VALIDITY OF METHOD**

The method used in this paper is based on the development process proposed by [16] and is a form of design science. While design science has utility as its goal, it must be differentiated from routine design or system building [27]. Hiver *et al.* created seven guidelines to support the process of evaluating whether a research project is to be considered design science [27]. Since this paper has followed the same method as in the previous iteration of this tool [14], similar conclusions regarding adherence to the guidelines have been drawn in this paper; namely that the research follows the guidelines and that design science is a relevant and valid method. The main difference, and also the main critique, is that the tool can be seen as less novel than in the first iteration [14]. There are two main arguments for why this iteration is still considered novel research. The first argument is that the framework has been expanded to encompass a new aspect of ARSG implementation, that is, general practical advice on how to proceed. The second argument is that the evaluation in this iteration has used case studies, a new form of data collection that has produced more in depth discussion of specific application cases. Thus this research is considered as relevant and valid design science.

**VIII. CONCLUSION**

There were three research objectives for this paper. The first objective was to develop *more detailed recommendations for all questions and answer alternatives of the framework*. The straw man base for the framework expansion was created by revisiting previous literature reviews, the first iteration of the framework, and the accumulated experience of the authors. The recommendations were then successfully integrated into the framework and implemented in the web-based tool previously created. Thus the first objective was achieved.

The second objective was to *evaluate the detailed recommendations to ensure industrial relevance*. Relevant recommendations were identified by consulting industrial experts from a number of different manufacturing companies using focus groups and an individual interview with a leading expert in the field. This resulted in a set of recommendations of relevant aspects to consider when integrating ARSG as an operator support tool in assembly.

The third objective was to *evaluate the tool implementation of the expanded framework as a whole in relevant production cases*. The tool was evaluated in three case studies involving a diverse set of manufacturing companies. The results showed that the company representatives found the tool easy to use and the questions relevant for evaluating the suitability of ARSG for their specific cases. They generally agreed that the recommendations were correct and relevant, indicating an added functionality of the tool: further practical guidance once a suitable case has been found or better understanding of why a case might not be suitable. Thus this evaluation of the tool as a whole showed that the second objective had been achieved by improving the framework with added functionality. This framework now provides more in depth understanding of how and what to consider if ARSG are to be implemented as an operator support tool in assembly.

**IX. FUTURE WORK**

This paper reports on the expansion of a previously developed framework-based tool. It provides further support in the initial steps when deciding whether ARSG can be used in a specific assembly case, and indicates what to consider in regard to implementation. Evaluation was done using studies of real assembly cases at three different manufacturing companies. More case studies will yield more data to further enhance the accuracy of the tool. Currently the tool is only available in Swedish, which means it can only be used by industrial representatives who know that language. Translating the tool into other languages will allow it to be tested on a more varied set of assembly cases. Other future work includes broadening the focus to include machine operations and evaluation at a factory level.

**ACKNOWLEDGMENT**

The authors express their appreciation for the high level of commitment of the industrial representatives from a multitude of companies.

**REFERENCES**


PUBLICATIONS IN THE DISSERTATION SERIES


42. Lennerholt, Christian (2022) Facilitating the implementation and use of self service business intelligence.

43. Liu, Yu (2022) Integrating life cycle assessment into simulation-based decision support.

44. Tavara, Shirin (2022) Distributed and federated learning of support vector machines and applications.


47. Toftedahl, Marcus (2022) Being Local in a Global Industry: Game Localization from an Indie Game Development Perspective.
Oscar Danielsson received his MSc in Automation Engineering from the University of Skövde in 2015 and his licentiate degree from the University of Skövde in 2021.

In this thesis Oscar uses mixed method design science to develop a framework that supports strategic decisions and integration of augmented reality smart glasses into production as an operator support tool. The framework considers both the operator perspective and the manufacturing engineering perspective.