Exposing the Potential of Augmented Reality in assembly

Designing a framework to assess augmented reality potential in manual assembly activities to improve assembly performance

By

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Abstract

Objective – This thesis strives to develop an approach with which it is possible to assess Augmented Reality Potential (ARP) for manual assembly activities carried out at a workplace. The framework guides users of it in the process of AR assembly system (ARAS) implementation and leads to better informed decision-making.

Background – Manufacturers of today increasingly must deal with individual customer needs, causing them to fabricate many different types of a product. In order to anticipate to this trend of mass-customization future-proof solutions are sought that increase production capacity. One of these solutions is AR, which is increasingly deployed in assembly operations the past years due to its proven performance benefits of efficiency, quality and improved work environment. Through AR assemblers are enabled to assemble products faster with reduced error rates. This is possible as AR visualizes assembly information in real-time, hence, serves as a supportive system for executing assembly activities. Moreover, the real-time information prevents physical harm. The motivation for this thesis is three-fold: This thesis builds further on the ARP-model from Haagsman (2018), which allows to assess ARP generically. However, it lacks insights on which assembly activities can be ARAS supported. Secondly, until now literature has only partially described assembly activities that offer ARP. Lastly, the industry is struggling to proceed with AR implementation for their assembly operations, due to the lack of knowledge.

Method – A design science study was conducted to answer the research question. Research data was collected primarily through interviews with knowledgeable employees, direct observations of the assembly activities and assembly manuals. In addition, informal talks with the assemblers provided useful insights in the assembly activities.

Results – This thesis contributes to existing knowledge by designation of a stepwise, iterative approach that assists manufacturers in identifying assembly activities that offer ARP. That is, by adopting the perspective of complexity mitigation ARP for assembly activities can be assessed.

Preface

This thesis finalizes my masters' degree Technology and Operations Management (TOM) at the University of Groningen (UoG). The past five months I have dedicated my hours to this project. At first, I was unfamiliar with the concept of Augmented Reality (AR) which forced me to dive in this technology. How does it work? What is its goal? But above all, how could it support in manual assembly? Slowly but surely, I became acquainted with the subject. At the end of these five months, a journey was completed of which I am proud. The result lies before you.

The query for this thesis stems one the one hand from the thesis written by a former student at the University of Groningen and is part of the parent project 'RAAK Assemblage 4.0'. On the other hand, the industry demands for rigor and clarity around AR technology. This thesis fulfills the goal of designing an approach for specifying workplaces that offer AR potential (ARP) by evaluating assembly activities[1]. In particular, the created design aims to aid manufacturers in tackling the plurality of aspects and complexities that inherently are connected to AR Assembly Systems (ARAS). Personally, I hope it lets readers realize the multidimensionality and ambiguity in ARAS design. Namely, the red line through this thesis is that 'one size does not fit all'.

There are a few people I would like to thank for their feedback and support. In the first place, I would like to thank my supervisors, who were able to boost my research when I stranded or lost motivation. They were able to steer my thesis despite the many courses it could pursue. The meetings and excellent support guided me through the project.

Secondly, there are too many people involved in the parent project to thank properly. The researchers from the Hogeschool Arnhem & Nijmegen (HAN) gave important input during monthly project meetings. They provided me with practical ideas to collect my data and made sure the project fitted in the mother project. In addition, I benefitted from debating research ideas with them. I should also not forget the interviewees and employees of involved companies who voluntarily answered my questions and concerns.

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[1] https://www.nwo.nl/onderzoek-en-resultaten/onderzoeksprojecten/i/40/32240.html

At last, I speak out my gratitude to my parents, fellow students and girlfriend. The chats and discussions with them enabled me to reflect on what I was doing, where I was heading and with which purpose I did as such.

May you enjoy reading this thesis,

Keimpe Oenema

Contents

Abbreviations

2D/3D	Two-dimensional/three-dimensional
AA	Assemblability Analysis
AHP	Analytic Hierarchy Process
AR(A)(S)	Augmented Reality (Assembly) (System)
ARP	Augmented Reality Potential
CAD	Computer Aided Design
CCD	Charge Coupled Device
DART	Designers' Augmented Reality Toolkit
DfA	Design for Assembly
ER	Error Rate
FOV	Field of View
HC	High Complexity
HHD	Hand Held Display
HMD	Head Mounted Display
LC	Low Complexity
MR	Mixed Reality
PCB	Printed Circuit Board
PoC	Proof of Concept
TCT	Task Completion Time
UoA	Unit of Analysis

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1. Introduction

Manufacturers are increasingly dealing with demand complexities like growing product variance, shorter product life cycles, smaller lot sizes and accelerated time to market. Mass customization has grounded in all sectors and urges manufactures to respond adequately to individual customer demand on a large scale (Zipkin, 2001). That is, manufacturers need to reduce time to market with the ultimate goal of maximizing customer value (Tu, Vonderembse, & Ragu-Nathan, 2001). As a response, manufacturers seek for strategies to enlarge qualitative output and enhance service levels. At the same time, quality levels must be maintained, while the demands put stress on workload of production staff too (Tatić & Tešić, 2017). A remedy to overcome these challenges may be found in Augmented Reality (AR), which enables you to see real-time digital data, but visualized in the real world (Albright, 2013, p. 99; De Amicis, Ceruti, Francia, Frizziero, & Simões, 2017). The digital data is floating in the environment you are physically residing in. Related to AR is the overarching term of Mixed Reality (MR). The difference between AR and MR is that the latter uses holographic data, whereas AR does not. This difference is omitted in this thesis. Figure 1.1 illustrates this synthesized reality schematically.
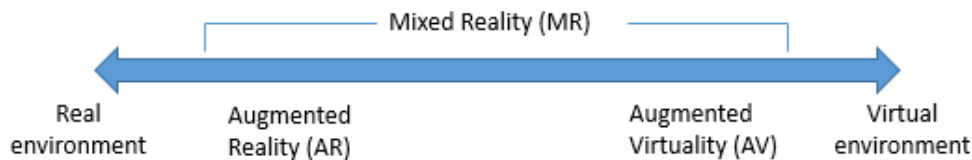
Figure 1.1 The Virtuality Continuum. Adapted from Milgram & Kishino (1994)

The scope of this thesis is manual assembly on workplace level. Thus, the core function of AR in this setting is providing real-time assembly information. This is of interest for the assembler, as humans make mistakes of various kinds (Ishii, Ooishi, & Sakurai, 2013). For instance, assemblers may forget to perform an assembly step, or they may misunderstand assembly instructions. The occurrence of errors could be mitigated, if not prevented, with AR. In this thesis, the theme of poka-yoke is related to AR deployment.

AR assembly systems (ARAS) have been tested extensively as Proof of Concept (PoC) (Antonelli & Astanin, 2015; Boud, Haniff, Baber, & Steiner, 1999; Gavish et al., 2015; Reinhart & Patron, 2003; Tang, Owen, Biocca, & Mou, 2003). Each study deployed a different ARAS configuration that was customized to the situation on hand. Indeed, every assembly context is unique and has specific ARAS design requirements. In spite of these differences, however, literature agrees on attained performance improvements of increased efficiency, quality and safety of the working environment (Haagsman, 2018). The challenge is to

pinpoint in which situation ARAS implementation is economically viable and find the ARAS configuration that optimally supports assemblers.

The potential of AR (ARP) has been investigated on general level (Haagsman, 2018). Potential The ARP-model that was developed in this thesis could serve as a first evaluation tool, but lacks concrete insights on *where* in the assembly process this potential may lie (Thomas, 2007, p. 296). Moreover, the ARP-model does not the specify *what* and *how* an ARAS should communicate assembly information to maximize this ARP. This raises the question of *which assembly activities could be executed better if they were ARAS supported*. Literature has failed to provide a comprehensive list of assembly activities for which ARAS support is possible (Gavish et al., 2015; Tang et al., 2003). Therefore, to expose ARP in detail, this thesis zooms in on assembly activities (F. B. Gilbreth & Kent, 1911; Groover, 2007; Rosenthal, Kane, Wobbrock, & Avrahami, 2010). Figure 1.2 shows the pyramidal structure of a task that is build up from activities and basic motions.

Task – An amount of work that is assigned to an assembler and for which the assembler is responsible. "The activity of collecting components and bringing them together through assembly operations to perform one or more several primary functions" (Albright, 2013, p. 99). A task is considered completed when all activities have been correctly executed (Makris, Karagiannis, Koukas, & Matthaiakis, 2016).

Activity – A series of motions that are logically grouped together because they have a unified function in the task (Groover 2007).

Basic motion elements – A fundamental motion required for the assembler to execute an activity (Groover, 2007). Included in basic motion element are cognitive processes like searching, selecting, planning and finding.

Figure 1.2 Pyramidal structure of a task (Groover, 2007, p. 8)

From the practical side, manufactures currently struggle to bridge the gap between AR deployment and assembler activities. The unique assembly context forces them to reinvent the wheel individually as valuable information on ARAS design is fragmented and dispersed throughout the industry. At the other end of the practical spectrum are the AR suppliers that lack knowledge of the assembly processes of manufacturers. Collaboration is needed to unite interests and streamline implementation. This thesis serves as a tool to initiate collaboration. A framework is designed that aims to structure ARP assessment, which ultimately leads to a more qualitative ARAS implementation.

The described gap leads us to the question whether it would be possible to identify assembly activities that offer ARP in a systematic manner. Hence, the research question for this thesis is as follows;

How can manufacturers systematically assess ARP for manual assembly activities in order to improve quality, efficiency and work environment?

The overall structure of this thesis takes form in the following chapters. Chapter two concerns the research methodology for this thesis. Thirdly, the theoretical dimensions of the research are highlighted. Thereafter, case companies are described. Chapter five reports the analysis results from which the framework is derived and outlined in chapter six. The thesis finalizes with a discussion in chapter seven and conclusions in chapter eight.

2. Research design

Before proceeding to examine the existing literature, it is important to describe the methods used to answer the research question. The thesis takes the form of a design science study and adopts the regulative cycle from Van Strien (1997) as methodological vehicle. Design science strives to develop knowledge to solve for improvement problems and should be used by field professionals (Aken, 2004). In this thesis, the improvement is to concretize how manufacturers should assess ARP on workplace level. Figure 2.1 represents the phases of this thesis.
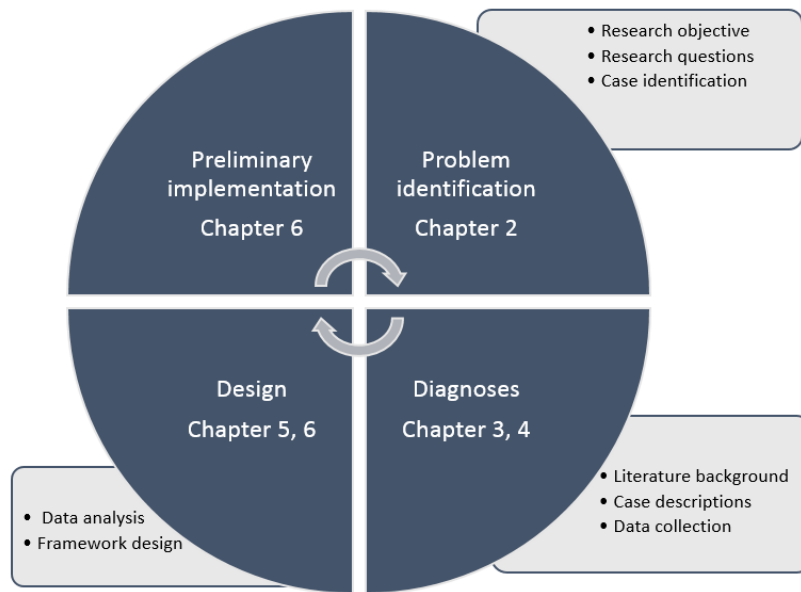
Figure 2.1 The research phases for this research. Adapted from (Van Strien, 1997).

2.1 Problem identification

As mentioned in the introduction, the problem that is tackled concerns the knowledge gap of how to assess whether and which assembly activities can be ARAS supported.

Research objective

In accordance with Aken (2004), the thesis strives to create knowledge to be used in designing solutions. Specifically, the objective is to design a framework which is appropriate to assess ARP of manual assembly activities. Table 2.1 defines key words explicitly.

Term	Specification
Framework	The deliverable of this thesis; A step-wise approach that managers can use to assess ARP on activity level.
Systematically	The framework provides a rigorous and standardized ARP assessment.
ARP	The extent to which an ARAS can be deployed usefully to attain performance improvements.

Table 2.1 Definition of research key terms

Research questions

Table 2.2 summarizes the sub-research questions that form the starting point for the literature review. They are sorted by subject to create structure. The findings were used as a lead in synthesizing the conceptual model. Also, given the explorative nature of this study

Subject (section)	Sub-research questions
Deploying AR (3.1)	- How does AR work? - How is ARAS efficacy established?
Activity performance (3.2)	- How is activity performance defined? o What are important measures? - How is AR deployment related to activity performance?
Activity characteristics (3.3)	- What are typical assembly activities performed by an assembler? - If possible, how can AR support activity execution? o Which complexities play a role?

Table 2.2 Sub-research questions for literature review

In addition, to increase reliability and usability of the framework questions were formulated about the appearance and contents of the framework. Data was analyzed on these aspects. Table 2.3 lists the relevant questions for the design of the framework.

Interest	Question
Lacking knowledge	- What sort of information is lacking from the ARP-model (Haagsman, 2018), but required to know for ARAS implementation? o What are the critical steps and considerations towards ARAS implementation?
Boundary conditions	- What are exclusion criteria for AR deployment?
Form of framework	- How should this information be communicated with users of the framework?

Table 2.3 Research questions regarding framework design

The more key characteristics are defined, the more transparent results will be and the better generalized the framework design (Kennedy, 1979). In this thesis, a case is the assembly of a focal product or product family and is bounded to the workplace level. Assembly layout and production volume are metrics to observe when electing a case. Criteria for selecting the cases were as follows:

1. At least a part of the assembly process is completed manually;
2. Assembly takes place indoor;
3. Company documents are available;
4. Interested in AR.

Table 2.4 describes metrics used in this thesis per case (Abdullah, Popplewell, & Page, 2003; Haagsman, 2018; Jacobs & Chase, 2014). Appendix B – Production layouts provides background information on assembly layouts;

	Case company		
	α	β	γ
Industry	Mechatronics	Boiler manufacturer	Sensors
Market reach	The Netherlands	International	International
Size	105 employees	500 employees	45 employees
Research UoA	Workstation	Assembly workstation in production line	Workstation
Product type	'Crack unit', Piezo-sensing device	'Tzerra', boiler type	'Tasker', sort of cable
Production volume - product variation	High – Low	High - Low	Low - Low
Component count for assembly	High	Low	Low
Assembly layout type	Cellular manufacturing	Product layout	Project based
Acquaintance with AR	Highly interested	Highly interested, early experience	Moderately interested, not particularly in assembly

Table 2.4 Descriptions of the case companies

Additionally, a supplier of AR solutions (ζ) was visited to attain knowledge about current problems with AR from a supplier perspective.

2.2 Diagnosis

The key aspects in the diagnose phase involve reviewing existing literature and provide context of the case companies. Chapter three describes the relevant literature based on the questions formulated in Table 2.2. Literature was searched for with databases as Google Scholar and Web of Science. Also, the software program Mendeley suggested additional literature. Lastly, (e-)books were used for definitions and orientation into specific subjects. Mendeley was used to structure the retrieved literature. Accordingly, chapter four provides insight in the existing production situations of the case companies.

Data collection

Multiple data sources were used to attain a multi-perspective and reduce bias (Voss et al., 2002). Also, a clear picture of the situation can be attained by consulting multiple data collection tools. The research data in this thesis was drawn from the following primary sources:

- *Semi-structured interviews* were held with a manager operations[α], production manager[β] and director[γ] and recorded if consent was given. Interviewees were required to work for over more than a year in the company in order to ensure data quality. Notes were taken during the interviews. Transcripts of the interviews were approved by the interviewees but are excluded for reasons of confidentiality. Transcripts are available on request. Interview questions were formulated in advance and sometimes slightly changed to make questions more concrete for the interviewee. Interviews are conversations aiming to get a better understanding of how phenomena are perceived by the interviewee and allows the researcher to obtain a clear overview of the situation (Alshenqeeti, 2014). The term 'semi-structured' implies that a list of questions is made, but that the interview is not constrained to merely these questions; It allows to probe and asking questions about emerging aspects.

- *Direct observations* were performed to identify assembly activities and complexities. This method has the advantage that it provides the researcher with valuable information without any biases, ability of the assemblers to describe their actions, hence, reconsider reliability of the interview data (Karlsson, 2016, p. 210). Only essential notes were written down, such that the workflow of assemblers was not interrupted, and the researcher was not exposed to information overload. In support of the researchers' own observations and notes, the assembly process was filmed when consent was given, and filming was practically doable.

    The interview and observation protocols can be seen in Appendix F – Interview and observation protocol

- *Company documents* were reviewed to gain insights on the assembly process, sequence and instructions (Nof, Wilhelm, & Warnecke, 1997). A snapshot of the final assembly or a component lists were considered as infeasible for analysis. A pitfall of using documents as data source could be that they do not contain the information that is required to answer the research question. Also, they can be outdated, implying presence of more recent, but tacit knowledge which is more difficult to retrieve.
- *Introduction meetings* took place to attain knowledge about how the ARAS deployment is viewed from the company perspective and get a feeling of the existing assembly situation.
- *Informal talks* during assembly observations were held with assemblers to retrieve contextual information around the assembly process, experienced difficulties, way of working, et cetera.
- *Parent project meetings* took place on a monthly basis. The meetings were useful for feedback and matching this research with the mother project. Moreover, they provided useful insights for data collection techniques.

Table 2.5 summarizes the data collection methods per company.

	α	β	γ	ζ
Interview (count)	√ (1)	√ (1)	√ (1)	
Direct assembly observations	√	√	√	
o Film/photo			√	
Assembly manual	√	√		
Introduction meeting	√	√	√	√
Informal talks	√	√	√	
Feedback on framework		√		
Feedback on content generation				√

Table 2.5 Overview of data collection per company

2.3 Design

In this phase the theoretical background and case descriptions are used to analyze research data. Furthermore, this phase involves the designation of the framework. The aim of data analysis was to identify similarities in the responses and find support of these by including observation notes and company documents (Edmondson & McManus, 2007). A risk is that qualitative data is hard to analyze, as it is unstructured, descriptive and vastly present after being collected (Karlsson, 2016, p. 214). Hence, identify patterns can be time-consuming. Also, interviewees' subjectivity and bias are hardly measurable. Interview data was transcribed with the program F4Transkript to structure data and enable analysis. Analysis of film data allowed the researcher to identify assembly activities and support observation notes. Data analysis can be found in chapter five. Lastly, chapter six uses the analysis to design the framework.

2.4 Preliminary implementation

Due to time constraints full implementation and validation was not possible. However, the functionality and use of the framework were illustrated by means of the β case which in written parallel to chapter six. The framework was sent to the production manager of β, who had no initial comments on the framework.

3. Literature Background

This chapter explores existing literature and research gaps. Having background information allows to synthesize one conceptual model (Voss et al., 2002). Section 3.1 moves on to describe in detail the working principle behind AR technology and the concept of ARAS efficacy. Section 3.2 elaborates upon assembly performance. Lastly, section 3.3 describes assembly activities and assembly complexities which are then related to AR deployment. The chapter finalizes with a conceptual model synthesized from literature.

3.1 Deployment of Augmented Reality

As mentioned in the introduction, AR visualizes in real time virtual data in the real world. An ARAS enriches in real-time the real assembler environment with simulated virtual assembly information with the underlying aim of enhanced efficiency, error prevention and a safe working environment (Azuma, 1997; Ishii et al., 2013). The remaining subsections outline how assembly information is generated and identifies critical design aspects.

3.1.1 Working principle and configurational options

Literature commonly separates hardware and software elements (Baird & Barfield, 1999; De Amicis et al., 2017; Henderson & Feiner, 2011; Ong, Yuan, & Nee, 2008). Hardware performs core functions and software generates and renders the digital information. (Carmigniani et al., 2011). This digital information will be called 'content' form now on. Krevelen (2017) and Palmarini, Erkoyuncu, & Roy (2017) elaborated on content stages in more detail. The articles discuss the stages through which content is created, see also Figure 3.1. Appendix A – Description of content generation process describes each stage in more detail.
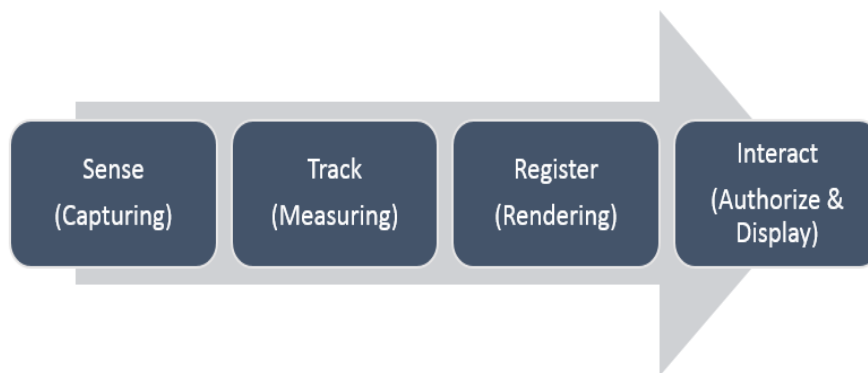
Figure 3.1 Schematic content generation process. Adapted from (R. Van Krevelen, 2017; Palmarini et al., 2017; Reinhart & Patron, 2003; X. Wang, Ong, & Nee, 2016).

ARAS configuration cannot be generalized as needs differ per assembly situation (Haagsman, 2018). Table 3.1 provides an overview of the configurational options for every of the four stages described. Table 3.2 indicates (dis)advantages per option. Some cells remain blank as literature has failed to specify the merits for each option in an assembly context. Also, the register phase is disregarded, as it is too technical for the purposes of this thesis. The following subsection explains how ARAS design leads to efficacy of the ARAS.

	Stage			
Configurational options	*Sense*	*Track*	*Register*	*Interact*

	Image capturing
	• Sensor camera
	• Stereo camera
	• CCD camera
	
	Data format
	• Visual (2D/3D)
	• Aural
	• Textual
	• Any combination (≥2) of the above
		Tracking technique
		• Vision-based
		  o Feature-based
		  o Model-based
		  o Marker-based
		• Sensor-based
		  o Mechanical
		  o Acoustic
		  o Electromagnetic
		  o Magnetic
		  o Optical
		  o Inertial
		• Hybrid
		  o Any combination (≥2) of the above
			Software package
			• ARToolkit
			• DART
			• Studierstube
				Display
				• HMDs
				  o See-through
				  o Video-based
				• HHDs
				  o Mobile phone
				  o PDA
				  o Tablet
				• Projector
				• Monitor
				• 2D Glasses
				Visualization
				• Visual (2D/3D)
				  o Dynamic
				  o Static
				• Aural
				• Textual
				• Any combination (≥2) of the above

Table 3.1 Overview of ARAS configurational options per content generation stage

Evaluation criterion

Sense

Data format	Creation easiness[a]	Update easiness[a]
2D/3D	🟧 orange	🟧 orange
Audio	🟩 green	🟩 green
Textual	🟩 green	🟩 green
Combination	🟧 orange	🟧 orange

Track

Vision-based	Robustness[a,g]	Reliability[a]	Accuracy[a,b,c]	Computational requirement[a]	Latency[c]	Jitter[c]	Operational Range[c]
Feature-based	🟧 orange	🟧 orange	🟧 orange	🟧 orange			
Model-based	🟩 green	🟩 green	🟧 orange	🟥 red			
Marker-based	🟩 green	🟧 orange	🟩 green	🟧 orange	🟩 green	🟩 green	🟩 green
Sensor-based							
Mechanical			🟩 green		🟩 green		🟥 red
Acoustic					🟥 red		🟩 green
Electromagnetic							
Magnetic	🟥 red	🟩 green	🟥 red		🟩 green		🟩 green
Optical	🟩 green		🟩 green	🟩 green			
Inertial	🟩 green		🟥 red		🟩 green	🟩 green	🟩 green
Hybrid							
Combination	🟩 green		🟩 green	🟧 orange			🟩 green

Interact

Display	Weight & Portability[a,d,f]	Resolution[a,d,f]	Latency[a]	Field Of View (FOV)[a,b,e]	Cost[a]	Social acceptability[b]	Enable collaboration[b]
HMDs	🟩 green	🟧 orange	🟧 orange	🟧 orange	🟥 red	🟥 red	🟥 red
HHDs	🟧 orange	🟧 orange	🟧 orange	🟩 green	🟧 orange	🟧 orange	🟥 red
Projector	N.A.	🟩 green	🟩 green	🟩 green	🟧 orange	🟧 orange	🟩 green
Monitor	N.A.	🟩 green	🟩 green	🟩 green	🟧 orange	🟧 orange	🟩 green
2D glasses	🟩 green	🟧 orange			🟧 orange	🟩 green	🟥 red

Visualization	Vividness[a]	Intrusiveness[a]	Creation easiness[a]	Update easiness[a]
Visual (2D/3D)	🟩 green	🟥 red	🟧 orange	🟧 orange
Audio	🟥 red	🟩 green	🟩 green	🟩 green
Textual	🟧 orange	🟩 green	🟩 green	🟩 green
Combination	🟩 green	🟧 orange	🟧 orange	🟩 green

Table 3.2 (Dis)advantages per configurational option

Legend

Positive evaluation	
Medium evaluation	
Negative evaluation	
a	Palmarini et al. (2018)
b	Zhou et al. (2008)
c	Ong et al. (2008)
d	Elia et al. (2016)
e	Krevelen & Poelman (2010)
f	Zauner, Haller, & Brandl (2003)
g	Thomas (2007, Chapter 1)

➢ *Robustness* – The extent of the ARAS to detect and estimate assembler poses under disturbing conditions (Thomas, 2007)

➢ *Reliability* – The extent to which the ARAS can produce adequate augmented views (Thomas, 2007)

➢ *Latency* – The time gap between the action in the real world and the AR display updating the augmented view (Thomas, 2007)

➢ *Jitter* – Trembling of the augmented view

➢ *FOV* – The Field Of View is the width or angle of the augmented scene the assembler is able to see

➢ *Vividness* – The extent to which the displayed information enhances assembler assembly experience

➢ *Intrusiveness* – The blocking impact the augmented view has on assembler perspective

3.1.2 Establish efficacy through ARAS design

Having discussed the configurational options for an ARAS, this subsection discusses the concept of ARAS efficacy. As mentioned earlier, each assembly situation imposes specific design requirements (Caricato et al., 2014; Del Amo et al., 2018; Elia et al., 2016). The question is how to configure an ARAS such that assembler support and ARP are maximized? In this thesis, this idea is defined by *ARAS efficacy,* which is the extent to which the ARAS supports execution of assembly activities. It is a function of *technical feasibility* and *perceived usefulness* (Palmarini et al., 2017). Whereas the former implies whether ARAS implementation is technically attainable, the latter adopts an assembler perspective which is needed to reduce the adoption barrier for ARAS implementation (Bala & Venkatesh, 2008; Jetter, Eimecke, & Rese, 2018). Furthermore, the factor of *perceived ease of use* is relevant, which is the extent to which an user believes the use of the technology is free of effort. Note, however, that usability also adopts an operational perspective. A malfunctioning ARAS implies that assemblers will not be supported and might suspect the new working conditions to be counterproductive. No improvement can then be realized as the assembler is not supported, or loses motivation to do his job properly. In either way, execution will be slower and more mistakes are made.

Secondly, ARAS efficacy is partly determined by the assembly environment (Carmigniani et al., 2011; Del Amo et al., 2018). *Indoor* versus *outdoor* and *fixed* versus *mobile* ARAS contexts were distinguished as configurational options per stage differ per assembly context. This stresses that ARAS efficacy depends on choice for ARAS configuration. In this research operations are indoor. Whether the display should be fixed or mobile depends on the situation on hand (Palmarini et al., 2017) and should not be decided in advance.

In the same vein, Chimienti et al. (2010) formulated "generic guidelines to achieve effective AR implementation with the aim of time savings, error reduction and accuracy improvement". Their systematic procedure is provided in Table 3.3. The authors recognized that decomposition to elementary activities was required to generate useful content. However, the main weakness of their guidelines is the failure to address the idea of ARP which implies the assumption of equal ARP for every assembly context. This oversimplification results in one-dimensional ARAS implementation (Rosenthal et al., 2010). The study would have been more valuable if thoughts were given to ARP assessment. In fact, this is the focal issue in this thesis. A new step will be formulated after step three.

Procedure steps for ARAS implementation	
1. Analysis of assembly procedure	5. Hardware selection
2. Subdivision in tasks, sub-tasks and elementary operations	6. User interface definition
3. Creation of logic-flow charts	7. Software implementation
4. Definition of assembly instructions	8. Validation

Table 3.3 Procedure for effective AR implementation (Chimienti et al., 2010)

In addition, Chimienti et al. (2010) settle in step four how content should be displayed to the assembler, while they decide in step six how much content should be displayed. In the designed framework both steps will be part of the ARP assessment as ARAS efficacy is for a great deal determined by how content is displayed in the real environment (Blattgerste, Renner, Strenge, & Pfeiffer, 2018; Del Amo et al., 2018; Palmarini et al., 2017; Radkowski, Herrema, & Oliver, 2015; Tang et al., 2003).

Taken together, these studies support the need for a framework that integrates ARP assessment in order to ensure ARAS efficacy. As said, this thesis will redesign the procedure of Chimienti et al. (2010) by integrating an ARP assessment step. This step will ultimately reflect on assembly performance to make transparent the effect of ARAS on the workplace. The performance measures are described in the next section.

3.2 Assembly activity performance

Until now the term of 'performance' has not been specified. What is performance and can it be solely operational or are there other factors involved too? And how does AR deployment affect assembly performance? First we need to know how assembly is defined. Nof, Wilhelm, & Warnecke (1997) defined assembly as *"The aggregation of all processes by which various part and subassemblies are built together to form a complete, geometrically designed assembly or product (such as a machine or an electronic circuit) either by an individual, batch or continuous process."* This definition lacks integration of a time aspect: *"Assembly is the productive function of building together certain individual parts, subassemblies and substances in a given quantity and within a given time period"* (Nof & Chen, 2003). Lastly, Nof et al. (1997) stated that industrial assembly has the additional purposes of efficiency, productivity and cost-effectiveness. Throughout this thesis the following definition shall be used for assembly:

Assembly is the conglomerate of manual assembler motions that are aimed at building (sub)assemblies from distinct components within a pre-specified time frame and with the underlying goals of efficiency, productivity and cost-effectiveness.

3.2.1 Performance measures

Literature on assembly performance in the context of AR deployment commonly agrees on the performance benefits of increased efficiency, quality and safety of work environment (Haagsman, 2018).

The focus in this thesis is on objective measures. Appendix C – Objective performance measures in literature summarizes objective performance measures found in literature. What can be seen is that Task Completion Times (TCT), Error Rates (ER) are grounded measures, which is
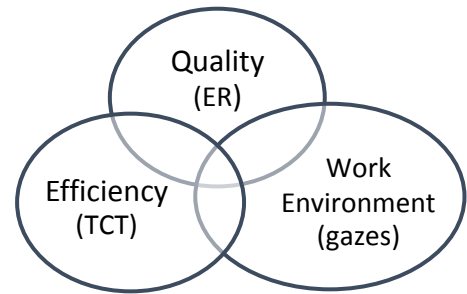
Figure 3.2 Concept of assembly activity performance

confirmed by Dünser, Grasset, & Billinghurst (2008). However, focus should be on work environment too (Tatić & Tešić, 2017), an ARAS should not introduce ergonomic hazards. Rather, it should prevent them. Unfortunately, existing literature is limited in objective measures regarding quality of work environment with only classifying body movements. The *number of gazes* is a frequently used indicator for head movement and will be used as objective measurement for the safety of the work environment. The measures are described below.

- *ER* – Errors are defined as the wrong execution of an assembly step which includes the insertion of a wrong component, wrong insertion of the right component, picking the wrong component, not positioning the component correctly or omitting an assembly step (Ishii et al., 2013; Radkowski et al., 2015; Tang et al., 2003). The ER is defined as the portion of errors made by one assemblers compared to the number of potential errors (Fiorentino, Uva, Gattullo, Debernardis, & Monno, 2014; Uva et al., 2018), that is,

$$ER \; [\%] = \frac{No. \; of \; errors \; made}{No. \; of \; potential \; errors} * 100$$

- TCT – Defined as the time it takes to complete the assembly task. It is the sum of separate activity times and can be used to provide insight on how time is distributed (Funk, Kosch, Greenwald, & Schmidt, 2015). Note that this thesis does not focus on time measurement itself. Rather, it intends to describe the implications of AR deployment on TCT conceptually. For the interested reader the researcher refers to Appendix D – Time measurement systems MTM and MOST, where time measurement methods are described (Groover, 2007, Chapter 14; Wiedenmaier, Oehme, Schmidt, & Luczak, 2003; Zaeh, Wiesbeck, Stork, & Schubö, 2009).

- Gazes – A gaze shift is switch of eye focus from the instruction manual to the place of the assembly and back. It is a head motion that should be prevented, as it introduces physical (head turning) and mental workload (continuously recalling instructions), hence, is a threat for ergonomics. Indeed, ergonomics involve both physical and cognitive aspects and AR can improve both. Worker environment is enhanced through reduction of gaze shifts (Groover, 2007, sec. 22.3; Henderson & Feiner, 2009, 2011; Polvi et al., 2018). In turn, gaze-shifts are reduced when content is displayed in front of the assembler, such that switching eye focus to read instructions is not needed.

The following explains the interdependence between these measures. As explained in subsection 3.1.2 Establish efficacy through ARAS design, perceived usefulness has crucial role in ARAS efficacy. Therefore, ARAS designs should be human-centric (Quandt, Knoke, Gorldt, Freitag, & Thoben, 2018) and emphasize ergonomics (Tatić & Tešić, 2017). Ergonomics concerns the interaction between the assembler and his working environment during assembly. The importance of perceived usability is stressed once more given that the aim of ergonomic design is "to avoid errors and enlarge productivity" (Groover, 2007, sec. 22.1). The higher the perceived usability, the shorter TCT and the fewer errors are made. Furthermore, TCT increases with the number of activities and motions, but also with the occurrence of errors (Boothroyd, Dewhurst, & Knight, 2002; Richardson, Jones, & Torrance, 2004). To enlarge ARP might therefore consider Assemblability Analysis (AA) (Boothroyd et al., 2002). This will be elaborated in subsection below.

3.2.2 Reducing assembly effort

Design for Assembly (DfA) constitutes an interesting perspective, considering the performance measures. The paradigm is to design products with higher assembly efficiency without compromising on product quality (Nof & Chen, 2003). Quality increases with assembly efficiency as the assembly process is less error-prone (Boothroyd et al., 2002, fig. 1.13). In fact, it can be seen as a form of poka-yoke (Ishii et al., 2013; Kurdve, 2018), which "refers to the prevention of errors through the use of (low-cost) devices that detect and/or prevent them" (Groover, 2007, p. 527). Through DfA, content generation requires less programming effort as there are less instructions. Therefore, managers might perform an assemblability analysis (AA) prior to AR deployment (Sääski et al., 2008). *This forms a complementary action in step 1 of the model of Chimienti et al. (2010)*. Appendix E – DfA guidelines summarizes DfA guidelines applied to AR deployment (Boothroyd et al., 2002; Shimon Y. Nof et al., 1997).

Additionally, simplifying assembly instructions complements DfA practices and can be done in parallel, as the goal is to reduce dependency on human error. Gattullo, Uva, Fiorentino, Scurati, & Ferrise (2017) proposed that instructions can be isolated and reformulated such that they comply with Controlled Natural

Language (CNL). Groover (2007, p. 641) also mentioned that instructions should be simplistic and easily understood to avoid errors. Assembly efficiency can be further enhanced, even though the guidelines above have zero effect. *This practice could be considered in step 4 of Chimienti et al. (2010).* One should be aware, however, that an unexperienced assembler needs more instruction detail to maximize the benefits from AR deployment (Funk et al., 2017; Syberfeldt, Danielsson, Holm, & Wang, 2016; Webel et al., 2013).

All in all, this section has listed measures that answer the question of how ARAS efficacy can objectively be evaluated. Through ARAS support the assembly performance is expected to increase. Furthermore, it was argued that it pays-off to redesign assemblies and simplify assembly instructions to mitigate dependence on human errors and thereby increase assembly efficiency. Time consumption as well as market pressure (Porter & Heppelmann, 2017) may hinder companies from conducting AA and instruction simplification. Yet, it can be argued that these practices lower the barrier for ARAS implementation. The following section will first identify assembly activity groups, then explain the role of assembly complexities and ultimately incorporate the role of AR in this respect.

3.3 Assembly activities

This section commences with outlining why basic motions should be aggregated into activity groups in order to evaluate ARP. Then, assembly activity groups are described and related to assembly complexities.

3.3.1 Typifying assembly activities

This subsection describes the basic motions, *'therbligs'*[2] (Frank B. Gilbreth & Gilbreth, 1924; Groover, 2007), see also Figure 1.2 on how motions are fundamental to each task. Therbligs can be categorized along different dimensions, like *electrical* and *mechanical* activities for which joining techniques differ (Nof et al., 1997, sec. 2.3), *physical* and *mental* therbligs (Antonelli & Astanin, 2015; Towne, 1985; J. F. Wang, Zeng, Liu, & Li, 2013; Zaeh et al., 2009) and *productive* and *nonproductive* therbligs (Groover, 2007). Table 3.5 classifies the therbligs along these aspects.

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[2] The term 'therblig' stems from its authors Frank and Lilian Gilbreth. Note that the term is the inverse of the authors' surnames.

Productive therbligs		
Physical	**Transport empty**	Reaching for a component
	Grasp	Grasping a component
	Transport loaded	Move an object horizontally or vertically
	Release	Release a component with the aim to lose control over it
	Use	Manipulating a tool
	Assemble	Also coined joining or connecting. Creating permanent or temporary fixtures between components. A distinction must be made between mechanical and electronic joining techniques (Nof et al., 1997, sec. 2.3).
	Disassemble	Separate components that were joined previously
	Stripping	Removing the encapsulation from a cable of wire for further installation
	Adjusting	Changing, for example, the orientation of a component or location of a component
Mental	**Inspect**	Assessing the component quality, alignment or connection. Also called inspecting, testing or measuring (S. Y. Nof & Chen, 2003).
Delay	**Rest**	Resting to overcome or prevent fatigue of the assembler

Within the **Assemble** row:

Mechanical	Electronic
Fastening by screw or bolt	Soldering
Riveting	Surface mount technology (SMT)[3]
Pressing	Welding
	(Peg-in-hole) insertion

Nonproductive therbligs		
Physical	**Hold**	Control the motion of a component.
	Preposition	Also coined 'commissioning' (Stork & Schubö, 2010) or orienting. Making sure that the components are near the defined location and oriented correctly.
Physical & Mental	**Position**	See 'Preposition'. The difference is that the components are now at the defined location.
	Search	The assembler needs to identify required components for the assembly. Also called locating or identifying.
	Select	Choosing among different components or the proper action that is involved in the assembly instruction.
Mental	**Plan**	Decide on what should be done next.
Delay	**Unavoidable**	Waiting time introduced due to factors beyond the control of the assembler.
	Avoidable	Waiting time introduced but that could have been prevented.

Table 3.4 Productive and nonproductive therbligs, categorized in physical, mental and delay types (Groover, 2007, p. 262)

Aggregating activities allows the researcher to observe and identify assembler activities in a shorter period of time (Groover, 2007, p. 433). Table 3.5 summarizes activity groups that are aggregated from the basic motions which allows for quicker classification during observations and simplify data collection as there are fewer categories to choose from (Groover, 2007, p. 433). Hence, this approach accelerates ARP assessment. Delay motions are disregarded since AR cannot support in idle time. Distinct activities are listed for handling and joining to facilitate transparency. Also, activity groups should not be too long (Groover, 2007, p. 346). P*icking* is the activity of reaching and grasping a component. *Placing* involves

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[3] SMT is a technology is an assembly technique frequently used in the assembly of PCBs. Components are mounted on the surface of the PCB.

laying down a component in its ultimate position and often follows after picking (Regenbrecht, Baratoff, & Wilke, 2005). In the miscellaneous group infrequent activities should be listed (Shimon Y. Nof et al., 1997, p. 24). Note that the set of miscellaneous activities depends on the situation on hand, not every assembly involves stripping or painting. The activity of *prepare* is separated since it is aimed to prepare for assembly or accomplish changeover (Groover, 2007, p. 405). It is not associated with the processing of components.

Physical activity groups

➢ Handling – In this activity the assembler has manual control over the component motions. The group is split up in the following activities;
   a) Picking   b) Transport
   c) Holding
   d) Placing
➢ Joining – Creating permanent or temporary fixtures between components. A distinction must be made between mechanical and electronic joining techniques (Nof et al., 1997, sec. 2.3).

Mechanical	*Electronic*
Fastening by screw or bolt	Soldering
Riveting	Surface mount technology (SMT)
Pressing	Welding
(Peg-in-hole) insertion	
Glue	

➢ Adjusting – Changing, for example, the orientation of a component or the location of a component.
➢ Checking – Assessing the quality of alignment, connection or adjustment (S. Y. Nof & Chen, 2003).
➢ Prepare – Assembler is setting up workplace for a new activity or making ready a component for further assembly
➢ Miscellaneous activities
   a) Stripping – Removing the encapsulation from a cable of wire for further installation.
   b) Cabling & Wiring – Install wires for final use.
   c) Painting – Dye a layer of a certain substance over a component

Mental activity groups

➢ Comprehend – Understand the message of the assembly information.
➢ Plan – Internally select the proper action that is involved in the assembly instruction. Also called interpreting.
➢ Search – Identifying, locating or detecting required components for the assembly.
➢ Select – Choosing among several components or options.

Table 3.5 Different assembly activity groups.

Recall that the core function of any ARAS is to provide assembly information. It is too simplistic to seek for nonproductive activities to improve assembly performance as an ARAS supports the assembler in productive motions too (Antonelli & Astanin, 2015; Radkowski et al., 2015). ARP is present for those activities where the assembler requires cognitive effort to complete an assembly activity, as well as for physical activities through visualizing right joining techniques, orientations and positions (Rosenthal et al.,

2010). The key is that an ARAS reduces 'cognitive overhead' through visualization which allows quicker and more qualitative physical execution of assembly activities.

Furthermore, a paradox in 'adjusting' should be noted. Ideally, a well-designed ARAS makes adjusting a redundant activity, because the assemblers receive appropriate content as assemble without errors. Yet, the activity group is included to account for assembler mistakes.

The next subsection introduces assembly complexities as moderating factors on assembly performance.

3.3.2 Assembly complexities

Assembly complexities are defined as factors in an assembly context of which the effects must be mitigated (Haagsman, 2018), hence, moderate performance benefits from ARAS support (Falck et al., 2017). Assembly complexities have been categorized in product, process, assembler and environmental complexities (Alkan, Vera, Ahmad, Ahmad, & Harrison, 2016). However, not all complexities impede execution. For this reason, a higher-level distinction is made between *structural* and *operational* complexities. Operational complexities act on the workplace level impact activity execution, whereas structural complexities are introduced through on a higher level through assembly system design and do not act on workplace level (Al-Zuheri, 2013). Manufacturers should thus question which operational complexities are present in their assembly situation.

Thus far, it has been argued that mitigation of operational complexities is required to maximize the performance benefits resulting from ARAS support. This thesis adopts an approach that links activity groups (subsection 3.3.1 Typifying assembly activities) and operational complexities to envision how execution of activity groups is moderated by operational complexities. Gradations in complexities are formulated to assess to which extent a complexity is present. An operational complexity is High Complex (HC) if it decelerates activity execution, but Low Complex (LC) if it does not. Table 3.6 describes gradations for each complexity. Complexities for which there was no ARP in the ARP-model were excluded, the other ones were included and classified based on the work of Haagsman (2018). Below changes to the complexity list in the ARP-model are described.

New complexities

Firstly, the ARP-model excluded the partial completion of assemblies through machinery. This is an oversimplification as machinery can be responsible for a diversity of activities like handling, setup and joining. The *degree of automation* is, however, added as process complexity on the structural level as it is introduced by the structure of the assembly system.

Secondly, Haagsman (2018) omitted the aspect of relative m*obility* of the (sub)assembly to the assembler which is introduced by the assembly layout. The latter determines how the activities are executed (Boothroyd et al., 2002, sec. 3.23). Figure 3.3 typifies different assembly setups.

| | | Location of (sub)assembly | |
		Fixed	*Variable*
Location of	*Fixed*	Assembly on site	Moving assembly
assembler	*Variable*	Workshop assembly	Line assembly

Figure 3.3 Typology of assembly organization (Nof et al., 1997, p. 143).

Similarly, *repetitiveness* of activities has been disregarded. However, whether an assembler executes the same activities the whole day or only for one hour has implications for assembly performance. An assembler may get bored from doing the same for a whole shift, which introduces errors, reduced motivation and slower execution of assembly tasks. The degree of repetitiveness is introduced by the design of the assembly system and will therefore be classified as structural complexity.

Deepened complexities

Thirdly, Haagsman (2018) included 'Size product' as product complexity. Yet, it is not merely the size of the product that moderates execution. The following complexities are extensions on operational level. *Component stability* moderates execution when components are held manually for assembly. In addition, *component weight* plays a role when the component is too heavy to transport individually. Next, *component symmetry* influences assembly efficiency. Symmetric components are easier to assemble, hence, could affect joining, handling and planning activity for instance (Boothroyd et al., 2002). Lastly, the *number of components* generally implies assembly complexity (Shimon Y. Nof et al., 1997), but was disregarded by Haagsman (2018).

Lastly, the assembler complexity of 'Physical capability' from Haagsman (2018) is defined more accurately. Groover (2007, p. 595) mentioned that physical strength is affected by *physical condition*, *gender* and *age*. Whereas physical condition determines how activities are executed (operational), age and gender do not directly impact work execution (structural). Physical condition is further decomposed into *sight*, *hearing* and *endurance*. Similarly, *lighting*, *noise*, *temperature* and *humidity* are added as operational environmental complexities as the assembler might be hindered by the presence of some (or all) of them (Groover, 2007, p. 574; Palmarini et al., 2017).

Figure 3.4 summarizes the above findings. The left tree represents structural complexities, whereas the operational complexities are in the right tree. The complexities in blue were changed with respect to Haagsman (2018).

In this section assembly activity groups were defined. Also, the moderating role of operational assembly complexities on assembly performance was explained. It has been argued that manufacturers should carefully assess the presence of operational complexities in their specific situation. This is translated to the framework as follows; Manufacturers should first identify the activity groups present for their assembly. The next step will then be to link operational complexities to the identified activity groups. Then, users should assess which complexities can be mitigated through ARAS support, for which Table 3.6 was created.
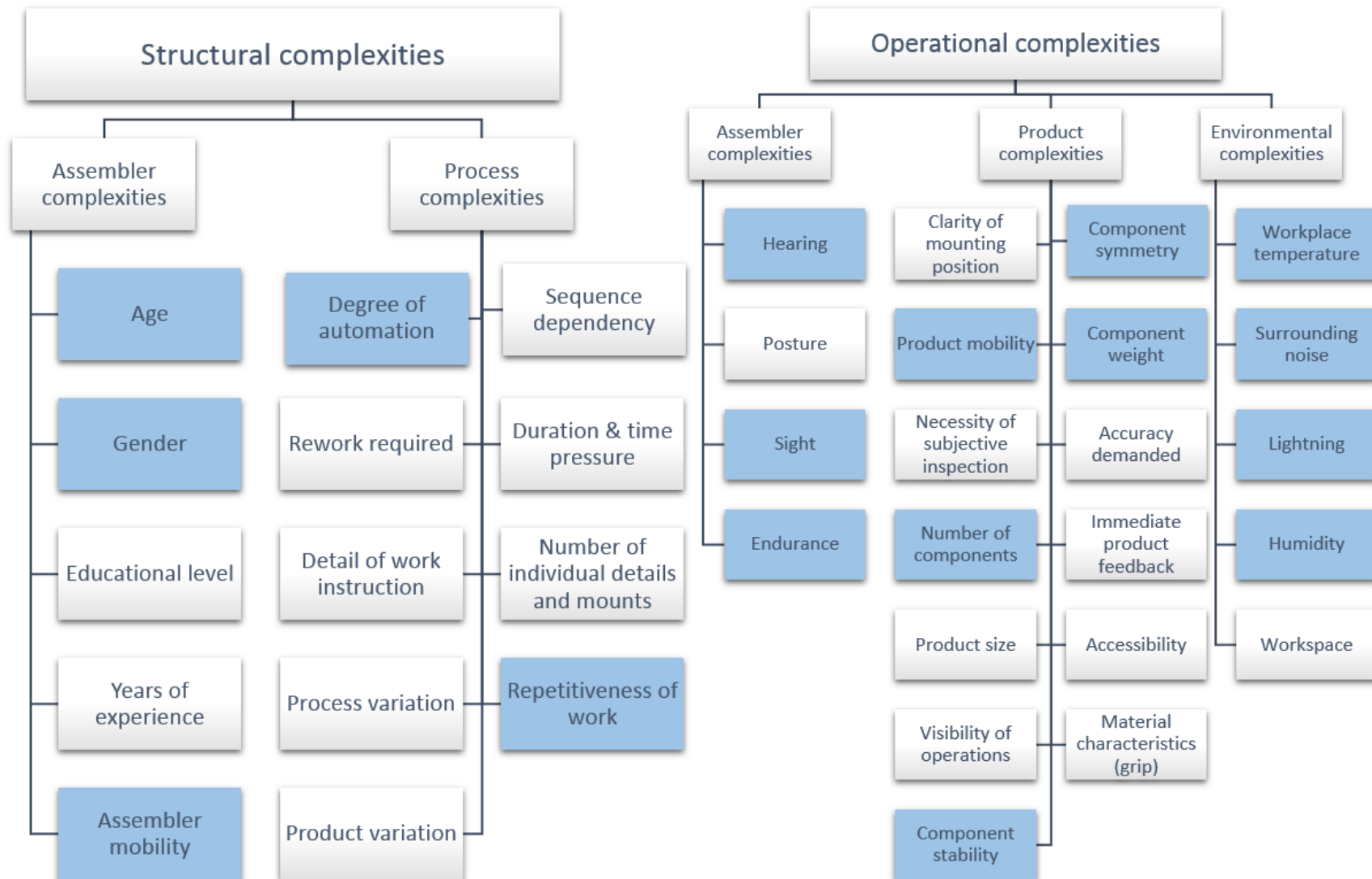
Figure 3.4 Assembly complexities on structural and operational level. Blue complexities represent changes compared to Haagsman (2018).

Structural complexities

Category	complexity	Level	Description
Assembler	Age	HC	Assembly activities are executed slower because of the assemblers' age
		LC	Assemblers' age does not affect activity execution
	Gender	HC	Activity execution depends on the assemblers' gender
		LC	Activity execution is independent on the assemblers' gender
	Educational level	HC	The assembler has low educational level, such that learning is more complicated
		LC	The assembler has high educational level, such that learning is more efficient
	Years of experience	HC	The assembler lacks prior knowledge about assembly
		LC	The assembler knows how to assemble the focal product
	Assembler mobility	HC	The assembler needs to leave the workplace frequently to assemble the product
		LC	The assembler stays at the workplace to assembly the product
Process	Automation	HC	Interaction between machine and assembler is needed to perform assembly
		LC	There is no interaction between assembler and machine
	Sequence dependency	HC	Operations must be done in a certain order/sequence
		LC	Independence of assembly order
	Rework required	HC	Need of adjustment
		LC	No need of adjustment
	Duration & Time pressure	HC	Time demanding operations and/or time pressure
		LC	Solutions that are easy and quick to assemble and/or no time pressure
	Detail of work instruction	HC	Assembly instructions needed are detailed, unclear or insufficient
		LC	Self-evident operations that do not need clearly written instructions
	Number of details and mounts	HC	Many assembly steps (per operator) and many parts to be mounted
		LC	Normal amount assembly steps (per operator) and parts to be mounted
	Process variation	HC	Many ways of doing the task
		LC	Standardized (accepted) way to do the task
	Product variation	HC	The level of fitting and adjustment varies between the products
		LC	The level of fitting and adjustment does not vary between the products
	Repetitiveness of work	HC	The assemblers do the same every day, for the whole week
		LC	The assemblers have different tasks per day or daypart

Operational complexities

Category	Complexity	Level	Description
Assembler	Hearing	HC	The assembler has less hearing, has a hearing device or hearing complaints
		LC	The assembler has a good hearing
	Posture	HC	The assembler needs to take uncomfortable body postures during assembly
		LC	The assembler does not need to take uncomfortable body postures during assembly
	Sight	HC	The assembler has difficulty seeing details
		LC	The assembler is able to see detail
	Endurance	HC	The assembler is unable to perform physical activities over a longer period of time
		LC	The assembler is not restrained by endurance (is fit)
Product	Clarity of mounting position	HC	Mounting position of components is not clear
		LC	Mounting position of components is clear
	Product mobility	HC	The product or assembly moves during the assembly process
		LC	The product or assembly has a fixed position during the assembly process

Component symmetry	HC	Assembly activities are less intrinsic due to complex geometric shape (= lack of symmetry)
	LC	Geometric shape of components is symmetric, such that activities can be executed logically
Component weight	HC	Weight is such that more than two hands (= 1 assembler) are required for handling
	LC	Weight is such that one assembler can handle the part
Necessity of inspection	HC	Subjective assembler inspection is needed
	LC	Subjective assembler inspection is not needed
Accuracy demanded	HC	The assembly requires high assembly precision
	LC	No precision demanding tasks, no careful fitting necessary
Number of components	HC	The final assembly has a component count above 30 components
	LC	The final assembly has a component count below 30 components
Immediate product feedback	HC	The product provides no information when it is assembled incorrectly
	LC	Product provides feedback about correctness of assembly
Product size	HC	The component size is such that two assemblers or more need to transport it
	LC	The components size is such that one assembler can transport it
Accessibility	HC	The assembler has poor access to perform assembly steps
	LC	The assembler has good access to perform assembly steps
Visibility of operations	HC	The assembler cannot see where his hands are and what they do during the activity
	LC	The assembler sees where his hands are and what they do during the activity
Component stability	HC	The component must be hold in order to be assembled
	LC	The component is stable due to its geometric shape
Material characteristics (grip)	HC	The material under hands is slippery or flexible
	LC	The material under hands is solid and has no form changes

Environment	Workplace temperature	HC	The surrounding temperature has a negative impact on activity execution
		LC	The surrounding temperature does not affect activity execution
	Noise	HC	Activity execution is inhibited, because the noise is too loud
		LC	It is relatively quiet, so that activity execution is not complicated
	Workspace	HC	The workspace is small such that ergonomic hazards are introduced and activity execution is complicated
		LC	The workspace is big enough to work in without ergonomic threats and complicated activity execution
	Lightning	HC	The surrounding light causes bad sight and hinders activity execution
		LC	The surrounding light does not hinder activity execution
	Humidity	HC	The surrounding air is rather humid, breathing is complicated
		LC	The surrounding air is good to work in

Table 3.6 Gradations of structural and operational assembly complexities.

3.4 Conceptual Model

A conceptual model is a simplification of reality that exhibits the causal relations between core concepts (Goddard, 2010, p. 202). In this project these concepts and their relations are described in the three previous sections. As the scope is on workplace level, only operational complexities are in the conceptual model. The reasoning is as follows: Literature has proven that assembly performance benefits from good ARAS design by providing real-time assembly information. However, the presence of operational complexities complicate the execution of assembly activities and moderate assembly performance. Hence, benefits from good ARAS design and moderation of operational complexities are two competing phenomena and mitigation of operational complexities should increase assembly activity performance. The relations are schematically shown in Figure 3.5
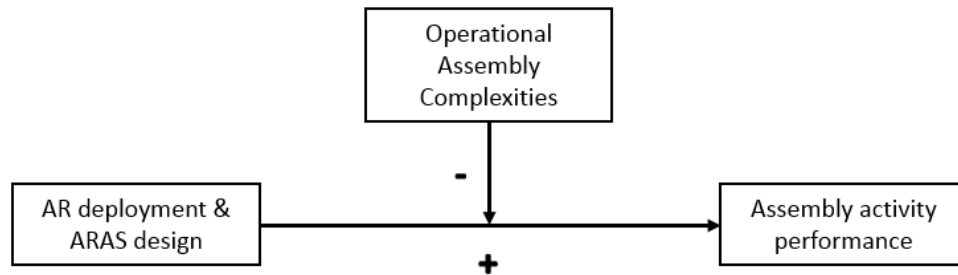

Figure 3.5 Conceptual Model

4. Situation descriptions

This chapter briefly describes the current production situation of the case companies where the data was retrieved. Production layouts, interest in AR and other details are shared here. For the remaining chapters the researcher refers to Appendix G – Data source codes for the list of sources.

4.1 Company α

Company α produces mechatronic devices with a focus on control technology. The employees of the focal product in this thesis, the crack-unit, have a distance to the labor market. The crack-unit is used to check whether there are cracks in eggshells by sensing the interruption of vibrations. It is used in egg sorting machines. The plant is segmented in different cells, varying in required cognitive capacity[α2]. One is coined the assembly cell, where the crack units are assembled in batches. Cross-training is conducted to reduce repetitiveness of work and increase flexibility. The interest in AR is mainly driven through quality and part of the continuous improvement philosophy[α3]. An assembly manual was retrieved, however, direct assembly observations were not possible, due to supply problems.

4.2 Company β

Company β manufactures boilers. The production plant is split up in six production lines. The focus is on one assembly workstation within one of the lines. During assembly the assembler walks with the boiler until the whole assembly task is finished. The prime interest in AR is quality (safety for end-consumer) related but should also be seen in the light of productivity[β3]. The aim is to develop a training facility with AR, to reduce stress during seasonal peaks. In the new situation, new assemblers are then directly able to perform assembly which unburdens permanent assemblers from their coaching role, while it reduces the intimidation experienced by new employees too and increases productivity. Note, however, that the decision to develop a training facility does not have to be made in advance. An assembly manual was retrieved. Filming the assembly process was not doable for practical reasons.

4.3 Company γ

Essentially, company γ manufactures sensors that react to sound. However, it also takes care for housing and package. By sensing air vibrations (i.e. sound), it is possible to detect the location of the vibration source, despite 'noise' in the direct environment. The product being assembled during data acquisition was a cable needed to produce the whole product. The companies' interest is not specifically in assembly, but rather on array visualization of sound waves. However, the case was suitable as the product was rather different from those in α and β. The company only has two assemblers, each being rather experienced. In

addition, they mentioned that the assembly is precise and skilled work[γ4]. A microscope is used to for certain activities to support the assembler. Film data was retrieved during the production of the assembly, so that typical activities could be identified.

Figure 4.1 classifies relative mobility per company that is introduced through their layout.

		Location of (sub)assembly	
		Fixed	*Variable*
Location of assembler	*Fixed*	α, γ	
	Variable		β

Figure 4.1 Classification of assembly organization per case company

5. Analysis

This chapter analyzes the research data in accordance with the research questions. They are shown for clarity below. The aim of data analysis was to find similar interviewee responses with respect to the research questions.

Subject (section)	Relevant sub-research questions
Deploying AR (3.1)	- How does AR work? - How is ARAS efficacy established?
Activity performance (3.2)	- How is activity performance defined? o What are important measures? - How is AR deployment related to activity performance?
Activity characteristics (3.3)	- What are typical assembly activities performed by an assembler? - If possible, how can AR support activity execution? o Which complexities play a role?

Table 5.1 Revisiting the sub-research questions

5.1 Deploying AR

A supplier of AR solutions[ζ] provided feedback on Figure 3.1, the content generation process. The revised versions can be seen and compared with the initial process in Figure 5.1. The main difference is that s*patial mapping* uses the calibration step to base the content on the position, whereas *image recognition* calculates content immediately. Also, tapping the screen is required, which implies authorization by the assembler. In both processes, however, key features are recognized. Figure 5.2 explains the steps for each of the revised processes.

To make the (dis)advantages for the configurational options from Table 3.2 more robust and usable, ζ suggested improvements. First, 2D and 3D data are separated as 3D data is more complicated to generate[ζ2]. Furthermore, weight and portability are separated. A portable object is not necessarily heavy, and a light object is not necessarily portable. Table 5.2 shows the result.
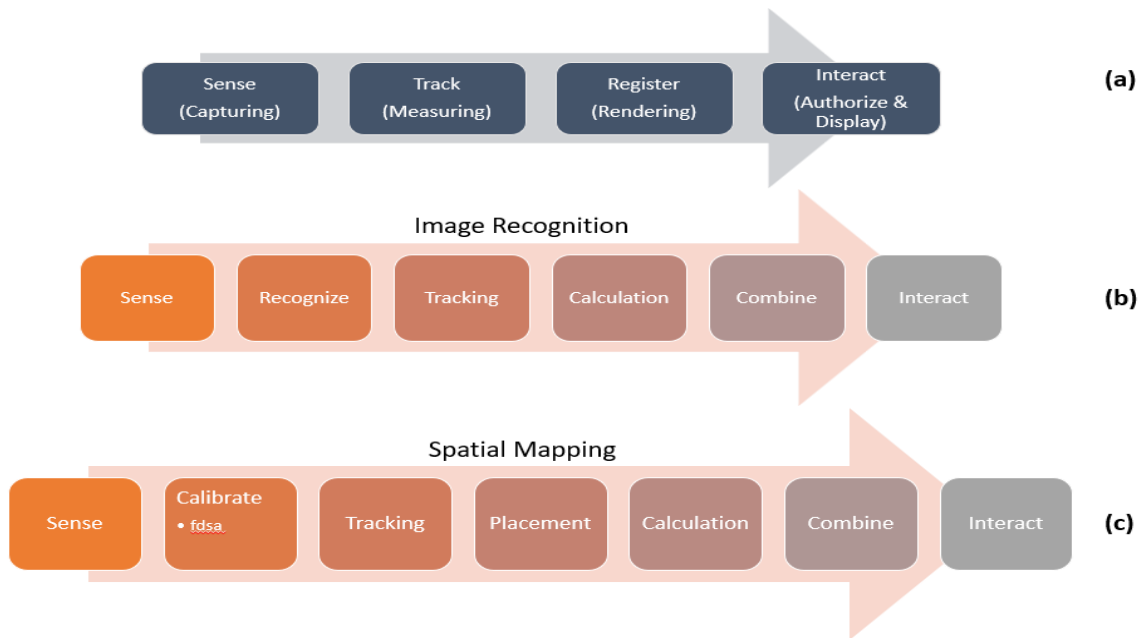
Figure 5.1 Initial content generation process (a) and revised versions for image recognition (b) and spatial mapping (c)

Image recognition
1. Sense — Image captured by camera
2. Recognition — Image is recognized based on key features
3. Tracking — Software computes position and orientation of the image relative to the camera
4. Calculation — Based on position and orientation it is computed how content has to be exposed on the screen
5. Combine — The real-time camera images is merged with the digital content and exhibited on the screen
6. Interact — The communication between the ARAS and the assembler.

Spatial mapping
1. Sense — Image captured by camera
2. Calibration — Software computes position of the mobile device based on camera images and sensor data.
a. Move the camera of the mobile device along a predefined plane
b. Key features are recognized by the software in every frame
c. Displacement of key features in separate frames are compared to the sensor data of the mobile device
d. Once enough data is collected, the mobile device recognizes the planes and calibration is completed.
3. Tracking — The same steps as in step 2 are executed to know how the mobile device moves through space
4. Placement — By tapping the screen of the mobile device, the location of the content is determined.
5. Calculation — Based on position and orientation it is computed how content has to be exposed on the screen
6. Combine — The real-time camera images are merged with the digital content and exhibited on the screen
7. Interact — The communication between the ARAS and the assembler.

Figure 5.2 Description of content generation step for image recognition and spatial mapping

Analysis of the interview data resulted in the identification of two boundary conditions:

1. *Project support* – The initiation of the project has to find support on different aspects and levels of the organization.
    a. Business – "We believe that deployment of AR is a viable business case, otherwise we would not have started the project."[β3]
    b. Assemblers – The assemblers are working with the ARAS every day. Therefore, assemblers should approve the imposed working conditions. A PoC could prove the performance improvements[ζ2] (J. F. Wang et al., 2013).
    c. Technical – Availability of CAD-models would increase assembler support of an ARAS. Humans prefer visuals over text, but CAD-models are a minimum requirement for visual content[ζ2]. Similarly, unambiguous assembly instructions need to be present and documented. If not, the company must act upon this by reducing instruction ambiguity. AR fails to support the assembler when the assembler is not aided in its thinking process during the assembly[β3, α3].
2. A *standard assembly sequence* is required (Haagsman, 2018, p. 144). ARASs are unable to cope with varying sequences. The absence of a fixed sequence is an exclusion criterion to use the framework.

Evaluation criterion

Sense

Data format	Creation easiness[a]	Update easiness[a]						
2D	green ζ	green ζ						
3D	yellow ζ	yellow ζ						
Audio	green	green						
Textual	green	green						
Combination	yellow	yellow						

Track

Vision-based	Robustness[a,g]	Reliability[a]	Accuracy[a,b,c]	Computational requirement[a]	Latency[c]	Jitter[c]	Operational Range[c]	
Feature-based	yellow	green			green ζ	green ζ	green ζ	
Model-based	green	yellow	yellow	red	yellow ζ	yellow ζ	yellow ζ	
Marker-based	green	yellow	green	yellow	green		green	
Sensor-based								
Mechanical			green		green		red	
Acoustic					red		green	
Electromagnetic								
Magnetic	red	green	red		green		green	
Optical	green		green		green		green	
Inertial	green		red		green		green	
Hybrid								
Combination	green	green	green	yellow			green	

Interact

Display	Weight[a,d,f]	Portability[a,d,f]	Resolution[a,d,f]	Latency[a]	Field Of View (FOV)[a,b,e]	Cost[a]	Social acceptability[b]	Enable collaboration[b]
HMDs	green ζ	green ζ	yellow	yellow	yellow	red	red	green
HHDs	green ζ	yellow ζ	yellow	green	green	yellow	yellow	red
Projector	red ζ	red ζ	green	green	green	yellow	yellow	green
Monitor	red ζ	red ζ	green	green	green	yellow	yellow	green
2D glasses	green ζ	green ζ	yellow	green	green	green	green	red

Visualization	Vividness[a]	Intrusiveness[a]	Creation easiness[a]	Update easiness[a]	Intuitiveness			
2D	yellow ζ	red ζ	green ζ	green ζ	green			
3D	green ζ	red ζ	yellow ζ	yellow ζ	green			
Audio	red	green	green	green	red			
Textual	yellow	yellow	green	green	red			
Combination	green	yellow	yellow	yellow	yellow			

Table 5.2 Revised (dis)advantages per configurational option. 'ζ' = feedback from AR supplier.

Positive evaluation		
Medium evaluation		
Negative evaluation		
a	Palmarini et al. (2018)	
b	Zhou et al. (2008)	
c	Ong et al. (2008)	
d	Elia et al. (2016)	
e	Krevelen & Poelman (2010)	
f	Zauner, Haller, & Brandl (2003)	
g	Thomas (2007, Chapter 1)	

➢ *Robustness* – The extent of the ARAS to detect and estimate assembler poses under disturbing conditions (Thomas, 2007)

➢ *Reliability* – The extent to which the ARAS is able to produce adequate augmented views (Thomas, 2007)

➢ *Latency* – The time gap between the action in the real world and the AR display updating the augmented view (Thomas, 2007)

➢ *Jitter* – Trembling of the augmented view

➢ *FOV* – The Field Of View is the width or angle of the augmented scene the assembler is able to see

➢ *Vividness* – The extent to which the displayed information enhances assembler assembly experience

➢ *Intrusiveness* – The blocking impact the augmented view has on assembler perspective

5.2 Activity performance

Each company aimed to increase assembly quality with AR in the first place. By standardizing the assembly sequence for every assembler reliability of the production process is enhanced as individual variances are smaller. It appeared that sequences of activities differed between assemblers due to individual preferences, despite the presence of assembly instructions. Giving assemblers the opportunity to diverge from the standard, introduces errors that could affect quality of the consumer product[α3, β3].

Additionally, all interviewees recognized the three performance improvements, which is shown in Table 5.3. Remarkably, no interview mentioned explicitly reduced TCT or ER as objective measure. Rather, they were named in the same breath in the umbrella term 'productivity'. Gaze shift, on the other hand, was explicitly mentioned in one interview[α3]. In addition, β uses the number of finished boilers that were completed in one run as quality measure[β4].

Aspect	Source		Statement
Quality & Efficiency	α3	-	"The assembler has to be sure of the right tool or component to pick"
	γ2	-	"With AR it is possible to show whether the assembler has picked the wrong part"
	γ2	-	"People, experienced or not, make mistakes, due to a lack of discipline or motivation"
	β3	-	"We expect to reduce reliability on new employees, by securing the assembly sequence. It guarantees output."
Work Environment & Quality	α3	-	"AR should prevent the assembler from making gazes. Also, errors are introduced, since instructions are still on the working memory when the assembler must look to the left to read the instruction, then perform the activity. AR can support in this."
Work Environment	α3	-	"The ultimate tool (ARAS) should also not frustrate the assembler."
	β3	-	"How to deal with tools? Assembly sequence can imply safety hazards for the assemblers."
	β3	-	"Training assemblers can both be beneficiary to productivity and safety."

Table 5.3 Statements regarding performance objectives.

Lastly, one interviewee stated that workplace standardization precedes achieving performance benefits; "One can also cover mistakes by organizing the assembly workplace logically such that individual assembler preferences can be omitted. It reduces the time to think. This is complicated through individual preferences of the assembler"[α3]. Standardizing the workplace falls under the umbrella of poka-yoke and cannot be settled with AR but could be done to ease ARAS implementation. Also, if the software can distinguish components from each other, a standardized workplace is not a hard requirement. This relates to a statement made by a different interviewee: "From the manufacturers' perspective, I can only say that AR should be flexible enough such that it can handle individual preferences. In this light, it is not important

which complexities are present, but that any ARAS design can deal with complexities on hand so that it retains its functionality"[β3]. This stresses that content should be adaptive and customized to the assembly context and assembler.

5.2.1 Reducing assembly effort

It is easier to create customized content when the assembly complexity is reduced. As mentioned subsection 3.3.2 Assembly complexities, the number of components could be reduced in that respect, which is the area of DfA. The role of DfA was recognized by all interviewees; "DfA guarantees that the assembly process cannot go wrong"[β3], "the better the design the less components are required, the less complex instructions have to be"[α3]. Also, focus needs to be on unambiguity of assembly instructions; "I always learned that people prefer visuals over text. But the text that is needed, should be formulated in such way, that it leaves no space for interpretation"[β3]. One interviewee, however, mentioned that most manufacturers are unable to perform Assemblability Analysis (AA) *prior* to ARAS implementation. Instead, it should be performed in parallel; "Every redesign or innovation is always too late, because it lags from what you are currently doing. Therefore, AA is always performed in parallel and the results are to be applied by future generations"[β3]. This insight should be taken into account in the framework design, as it was previously mentioned that AA was part of step 1 of the framework.

5.3 Assembly activities

Assembly manuals and observations were analyzed on assembly activities[α1, β1]. Also, film data was analyzed[γ4]. In general, the activity groups that were identified in literature were confirmed. However, also new activities were identified like scrubbing, tinning and cutting. These activities are classified as miscellaneous activities as they were not performed frequently; "Some of these activities I call 'soft specs'. Is 7/10 is good enough, or is it required to produce a 9/10?"[α2]. Figure 5.3 exhibits the identified activities. A drawback here is that the assembly manuals only provide the activities to be executed and disregard the activities outside the scope of the manual.
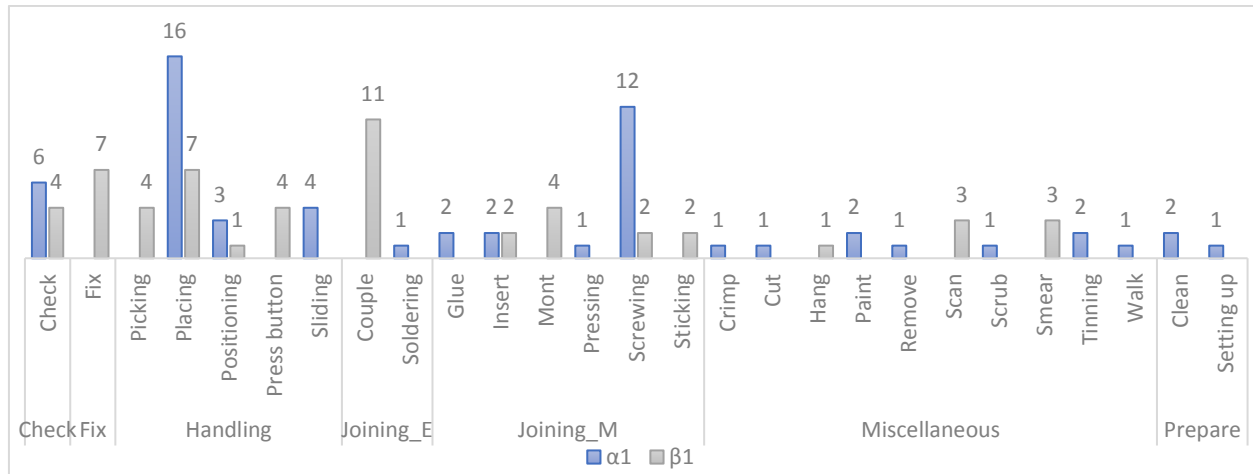
Figure 5.3 Frequencies of individual activities and activity groups.

Secondly, some activities that are classified in a different activity group serve the same purpose (Groover, 2007, p. 346); For mechanical joining (Joining_M), 'mount', 'press' and even 'couple' (Joining_E) imply merging two components, while 'sliding' and 'insert' could also be interpreted as such. Similarly, 'Check' results from verbs like 'inspect' and 'test'. The activity group could be coined 'Examine' or just 'Check' (Gattullo et al., 2017). Interpretation of instructions causes no problems in the current situations as the assemblers have learned to work with them and build up tacit knowledge[α2β2]. However, for new assemblers reduction of instruction ambiguity accelerates learning. Thus, tacit knowledge needs to be concretized in order to assess ARP.

What is more, differences within one activity were observed. For example, screwing can differ due to variety in screws to be used[α1, β3]. The difference illustrates that each context is unique, hence, ARP should be assessed per case and content must be customized for optimal usability (Kourouthanassis, Boletsis, & Lekakos, 2015). For β one could imagine that a simple 2D-model suffices for instruction, whereas the assemblers in α might require detailed numeric support to prevent joining with a wrong screw. This, again, depends on the assembler profile too. Manufacturers should thus distinguish assembler profiles prior to content creation.

Answers to which assembly activities could be ARAS supported converged; "Assemblers will always have to think for themselves. In our situation, the aim of training new assemblers is to facilitate self-confidence, because the real assembly line can be quite intimidating with unfamiliar colleagues that already got used to the work"[β3]. This quote suggests ARP for both mental and physical activities as assemblers do not require time to learn in the real assembly workplace and already know how to execute the activities. As

mentioned in subsection 3.3.1 Typifying assembly activities the mental activity is supported, which allows for quicker physical execution.

Lastly, it is important to elaborate on the notion of batch production[α3]. Regardless of varying or fixed batch sizes, the ARAS should allow the assembler to navigate between ARAS instructions. By offering this flexibility the barrier to implement an ARAS is lowered since activities can be executed without being constrained to finishing an assembly first before commencing with the next. "By allowing to navigate between steps it is possible to complete sub-assemblies first."[α3] Note that facilitating navigation is something different then having a fixed assembly sequence: The sequence of assembly activities is the same for every assembly.

5.3.1 Assembly complexities

One interviewee argued that the separation between structural and operational complexities as given in Figure 3.4 is debatable as they depend on the context[β3]. Hence, each company should analyze which complexities are present and decide accordingly which complexities are operational. The separation is made better with the involvement of assemblers as they have valuable (tacit) knowledge and experience complexities every day[β4, γ4]. Thus, the separation between operational and structural complexities depends on the unique characteristics of the workplace and should not be made in advance. Analysis of the data also revealed additional assembly complexities, which are shown in Table 5.4

Source	Additional complexity	Category	Reason for inclusion
α3, γ3, γ4,	Concentration level (can be interpreted as discipline[γ2])	Assembler	"Sometimes an employee is easily distracted, causing them to forget with which assembly step to proceed"[α3]. In γ, the assembly requires high accuracy and errors are easily made. Thus, high concentration is needed to execute the activities.
HC – The assembler is easily distracted, which introduces errors, loss of efficiency and ergonomic hazards			
LC – On an average day, the assembler stays focused during assembly			
γ3, γ2	Motoric stability	Assembler	The assembler is required to have a stable arm and fingers, due to the small size of the components and required accuracy.
HC – The motoric stability of the assembler hinders proper execution of assembly activities			
LC – The motoric stability of the assembler does not influence execution of assembly activities			
γ3, γ2	Component fragility	Product	A thin cable needs to be stripped without squeezing forces, whereas thick cables require more squeezing forces. Fragility is a complexity that indicates how a product should be handled.

HC – The components need to be handled carefully so as not to break

LC – The components do not need special handling

α3	Presence of dust	Environment	"Components have to be free of dust to meet quality standards"

HC – Components must be dust free in order to be assembled and meet quality standards

LC – Quality standards are not violated in the presence of dust

Table 5.4 Additional complexities

In sum, the influence of a well-designed ARAS on the performance measures has been confirmed by the research data. Likewise, the set of assembly activity groups created in chapter three was confirmed. Also, the moderation of complexities has been acknowledged. However, the distinction between operational and structural complexities was not valid. That is why it was decided to leave this decision to the manufacturers. The next chapter stepwise guides readers to the final framework.

6. Designing the framework

Before proceeding to the actual design it is important to specify the needs around the framework. Recall the questions in Table 2.3 regarding the pitfalls in the ARP-model from Haagsman (2018) and appearance of the framework. The interviewees were unanimous in the view that the ARP-model lacks insights on which activities could be ARAS supported: "*It gives an indication of how interesting AR deployment could be to enhance the whole production process*"[63]. In all cases, it was unclear which data formats were required. Hence, the question what information should the framework communicate? Table 6.1 provides some interviewee suggestions. There is a clear need for streamlining thoughts to assess ARP.

Source	Statement
α3	1. I would like to know what information is required to deploy AR and in which formats we must deliver it. The type of interaction is interesting to know too. Does the assembler press a button when he has finished an assembly step or is it something else? 2. I think it is useful to have a flow map with questions like "is there a static workplace?", which ultimately guides you to a hardware decision.
β3	1. I think the framework should be in the form of a flow map, which guides you towards I potential assessment through "Yes" or "No" questions. 2. It does not mention how AR should communicate, remains superficial.
γ2	1. I think it is good to develop a scan with 20 questions or so, such that a manufacturer reasonable can argue whether AR offers potential to support their assembly.

Table 6.1 Statements regarding framework design

The following steps constitute the framework design. It describes key activities per step and ultimately constitutes a procedure for ARAS implementation. Note, however, that the focus of this thesis is on step 3, ARP assessment. To concretize the use of the framework, the case from β is used as illustration.

Step 1 – Analyze the assembly process(es)

Should companies base ARAS design on experienced problems or based on the operational complexities that can be mitigated? The decision implies a focus on either performance improvements (AR is deployed in the most problematic workplace) or maximizing ARP (AR is deployed for the workplace for which most complexities can be mitigated). Ideally, these two workplaces are identical, but this cannot be guaranteed. Nonetheless, it is an important decision to be made in this step, since the focal workplace is defined that is assessed on ARP in the following steps. β is problem-driven: "At the assembly station the operators are working on their max. We think a training facility would offer a good solution"[β3].

Boundaries

As was mentioned in section 2.1 Problem identification, the scope of the framework is manual assembly, hence, manufacturers are discouraged to use the framework in absence of manual assembly activities. Also, recall the two boundary conditions of section 5.1 Deploying AR. β has full availability of CAD-models,

but it was observed that individual preferences exist for the sequence of assembly activities. A standardized sequence is present, but assemblers do not always stick to it[β3, β4]. Hence, future effort should be to train existing assemblers to stick to the prescribed sequence of assembly steps. Existing assembly instructions were slightly ambiguous and should be analyzed on simplicity[β1]. Simplifications of assembly instructions are to be implemented in step 4. Figure 6.1 displays a decisional chart that was designed to structure decisions. The hierarchy in these is debatable, and the figure is more indicative for manufacturers such that these issues are not omitted. Furthermore, DfA practices are initiated. As these practices can be cumbersome and time-consuming (Boothroyd et al., 2002), immediate redesigns are not expected[β3].

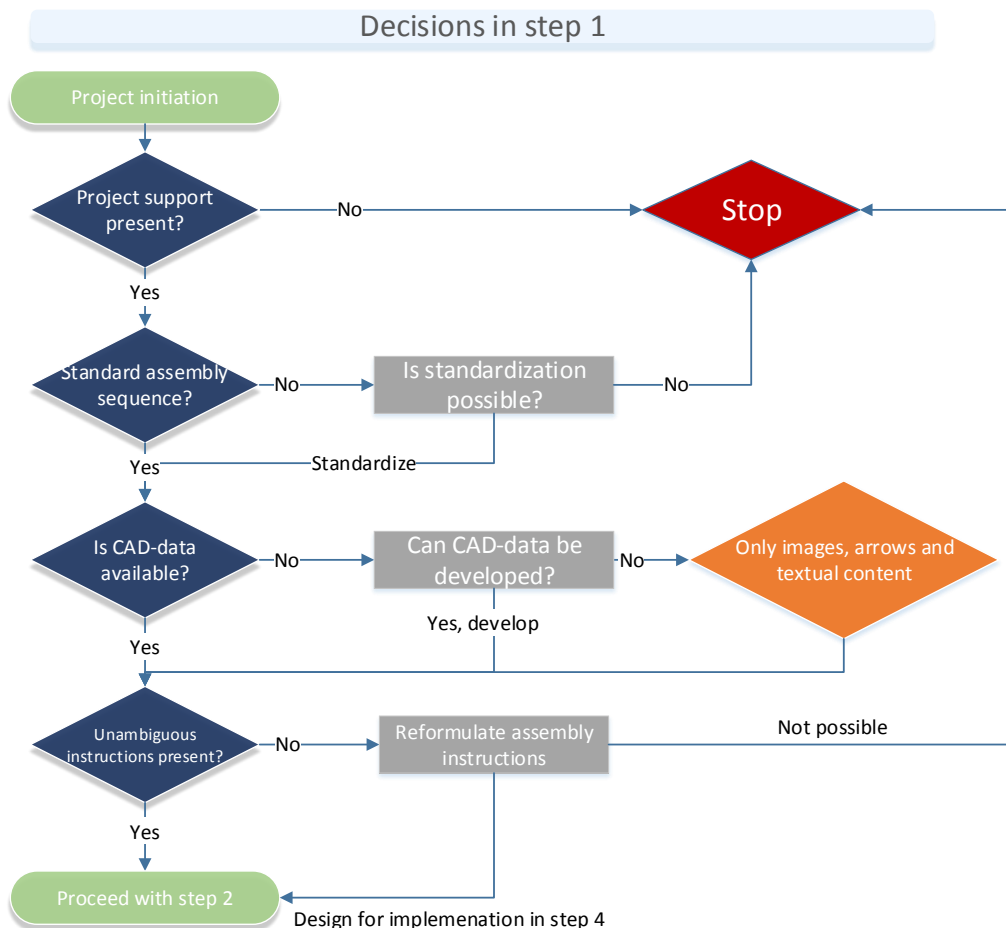*Figure 6.1 Decisional chart for step 1*

Step 2 – Inventory individual assembly activities

Accordingly, the assembly process should be mapped. As for all steps, it is important to include assemblers because of the tacit knowledge. Hence, this step requires cooperation between management and assemblers. The aim is to identify individual assembly activities on the workplace, which differ per

situation. For instance, the assembly station in β involves no soldering, where it does for α. And only γ supports assembly with a microscope.

The assembly manual of β was analyzed on those activities executed at the assembly station[β1]. The result shown once more in step 3.1, where the individual activities are aggregated into activity groups.

Step 3 – Assess ARP

Step 3 is the step that was lacking in Chimienti et al. (2010) and is newly defined in this thesis. The step involves the actual assessment of ARP for the defined workplace and is divided into five sub-steps.

Step 3.1 – Aggregate individual activities

First, the individual assembly activities from step 2 are aggregated into activity groups based on their purpose. Involvement of the assemblers is advised as they have a deep understanding of the activities that are executed by them. The aggregation of individual activities is shown in Figure 6.2.

The absence of the 'adjusting' activity in the assembly manuals does not imply that assemblers never adjust. Adjusting is introduced when a previous activity is erroneously executed. Hence, adjusting always follows checking, which makes them mutually inclusive.
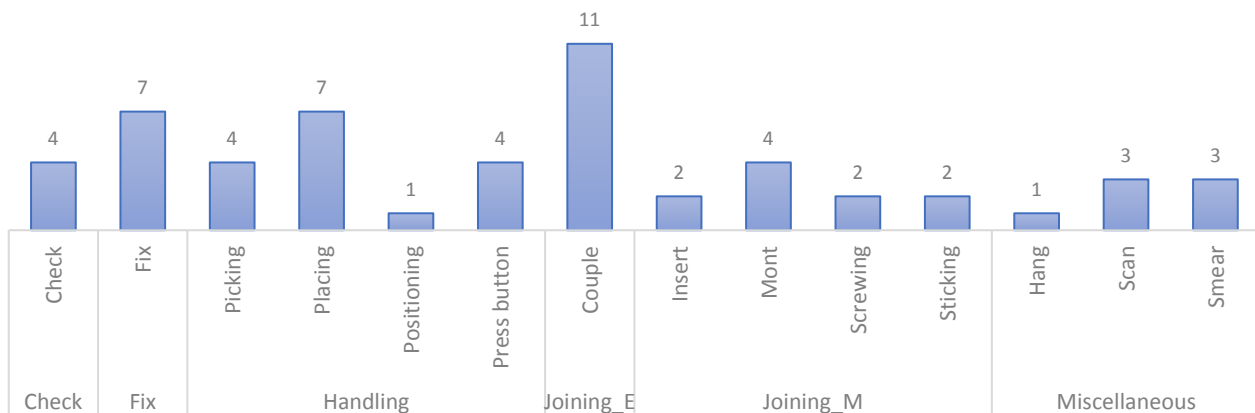
Figure 6.2 Aggregation of assembly activities for company β. Source: β1

Step 3.2 – Identify operational complexities

Accordingly, complexities are identified and classified as operational or structural complexities and HC or LC. Like activity groups, operational complexities are unique for every context. Time pressure is absent in α and γ[α3, γ3], but the former has a high component count compared to the other cases. β hangs the boilers in carriers, whereas the assembly is manipulated manually in the other cases due to instability[α1] or flexibility of wires[γ3]. This illustrates that generalizing the set of operational complexities is impossible and should be considered per workplace.

Step 3.3 – Link activity groups and operational complexities

In step 3.3, the results of steps 3.1 (activity groups) and 3.2 (operational complexities) are merged into a table which shows how the execution of activity groups is moderated by operational complexities. The table should be used to envision where performance pitfalls might occur, hence, creates focus. Figure 6.3 illustrates this tabular overview. An assembly coordinator of β was asked to fill in this table. The complexities were translated into Dutch to prevent misunderstanding due to own interpretation. What strikes is that the joining activities deal with the same complexities. This could be explained by noting that the 'Couple' activity does not involve soldering, welding or SMT and essentially involves pressing (i.e. mechanical joining) two *electrical* components together. This approves the notion that activities should be grouped based on their purpose. In the case of β the 'Joining_E' activity groups should be removed from the table.

	Activity groups								
	Physical					Mental			
	Joining_M	Joining_E	Check	Handling	Fix	Comprehend	Plan	Search	Select
Assembler									
Hearing			x						
Endurance, force	x	x		x	x				
Posture of operator	x	x	x	x	x				
Sight	x	x	x	x	x	x	x	x	x
Required concentration	x	x	x	x	x	x	x	x	x
Environmental									
Humidity									
Lightning	x	x	x	x	x	x		x	
Noise			x						
Space for work	x	x	x	x	x			x	
Temperature of workplace									
Product									
Clarity of mounting position	x	x		x	x				
Component symmetry				x					
Component weight	x	x		x					x
Degree of accuracy demanded	x	x	x	x	x	x			x
Degree of immediate feedback			x			x			x
Ease of accessibility	x	x			x	x			x
Material characteristics (grip)	x	x		x	x	x			x
Mobility during assembly process	x	x			x				x
Necessity of subjective inspection	x	x	x		x	x			x
Number of components	x	x	x	x	x	x	x	x	x
Size product	x	x	x	x	x			x	x
Stability of component	x	x	x	x	x				x
Visibility of operations	x	x	x	x	x	x	x		x

Figure 6.3 Linking operational complexities and assembly activities for β

Step 3.4 – Select operational complexities

Having identified the operational complexities, sub-step 3.4 aims to remove those complexities that cannot be mitigated with an ARAS. Hence, the critical question to ask: *For this activity group, is it possible to mitigate this complexity through an ARAS?* For instance, an ARAS is unable to mitigate the moderation of endurance on activity execution: An assembler has either good or bad endurance. Similarly, an ARAS cannot compensate for unworkable temperature on the workplace, except that it can warn to take a pause regularly. However, this does not support execution in one of the activity groups. On the other hand, an

ARAS can support the assembler when being concentrated is required: An ARAS prevents the assembler from being distracted and making errors. An ARAS can also warn for harmful body postures hazards when an heavy component has to be handled. Thus, for every activity group the role of the ARAS has to be questioned, which can be time-consuming. This role is described in the next sub-step.

Step 3.5 – Describe ARP

After having selected the operational complexities that can be mitigated, sub-step 3.5 describes the actual role of the ARAS for each activity group. The step here design the interface and involves two questions;

1. *How* – How should the content appear on the display?
2. *What* – What should the ARAS communicate to the assembler?

These choices aim to maximize complexity mitigation and the results are described in terms of the performance measures. As mentioned in step 1, visual content is preferred over text and sound, as it is more concrete and intuitive[β3, ζ2] (Dünser, Grasset, Seichter, & Billinghurst, 2007; Gavish, Gutierrez, Webel, & Rodriguez, 2011; Hou & Wang, 2013). Hence, the goal is to visualize activities whenever possible, without exaggerating content richness (Blattgerste, Strenge, Renner, Pfeiffer, & Essig, 2017). For instance, Radkowski et al. (2015) found that 2D visuals are more practical for precision and accuracy, but that 3D models should be used when spatial structures must be assessed. Also, an unexperienced assembler may require a combination of textual and visual content, whereas an experienced assembler only uses a static exploded view of the finished assembly[β3, ζ2]. Therefore, content richness must be customized to the assembler (Chimienti et al., 2010; Quandt et al., 2018) and difficulty levels of assembly activities (Radkowski et al., 2015; Syberfeldt et al., 2016; Webel et al., 2013). Table 6.2 describes ARP per activity group in general. The miscellaneous activity group is excluded as the individual activities differ too much between case companies to be generalized. ARP is described per case in Appendix H – Description of ARP. Lastly, visual content can take different forms (Blattgerste et al., 2018; Funk et al., 2017; Henderson & Feiner, 2009; Marner, Irlitti, & Thomas, 2013; Mura, Dini, & Failli, 2016; Radkowski et al., 2015):

- The actual content can be 2D or 3D models, images, arrows (2D or 3D), annotations, symbols and labels
- Content may also vary in brightness level, color and texture.
- Content can be static or animated
- In-view (in the assemblers' sight) or in-situ (simulated/projected within the workplace)

Physical activity group	ARP		
	How	What	Result
Handling	V + T	- Highlight positions for placements and locations of components to pick, animate CAD-model motion. - Show symbols/arrows that indicate ergonomic hazards. - Textually show numeric details, tools to use or which ergonomic hazards are involved.	First time right positioning and orienting which reduces ER and TCT. Number of gazes remains equal for picking as software still requires recognition of key features. It reduces gazes for placing and holding when CAD-models are used as the location and orientation then can be visualized.
Mechanical joining	V	- Animate how two components are joined (and thereby indicate which components are joined). - Show tool to be used. - Highlight mounting location on component	The assembler knows the first time the right orientation, position and joining technique of the components, which reduces ER and TCT. Number of gazes can be prevented through highlighting mounting locations, instead of having to look to paper instructions or work from memory.
Electrical joining	V	- Highlight soldering locations on component or - show CAD-model and locations to perform welding, soldering or SMT. - Warn visually for heated components.	Welding locations can be highlighted which prevents wrong location and orientation of connection. Gaze shifts are prevented as assembler does not need to find out how and where to connect.
Adjusting	V + T	As adjusting is corrective in nature and repeats an activity that should have been executed correctly earlier, content can be displayed in the same manner. However, extra details may be provided to ensure right execution. The assembler must be able to navigate to the right assembly step.	The (extra rich) content ensures quality through repairing errors made earlier, while it also reduces TCT as it is a memory support. It cannot, however, neutralize these errors. Thus, ARP is there for the activity itself, but losses on overall quality and efficiency have to be taken.
Checking	V + T	- Stepwise instruct the assembler to perform routine checks on (sub)assembly. - Content can be visual to checking whether placement is correct and textual to ask if there are any loose components and other errors for which assembler insight is needed.	The content enables quicker validation of assembly quality. Therefore, it prevents propagation of errors and reduces TCT. If the content is shown on the assembly gaze shifts are reduced.
Prepare	V + T	- Stepwise show which components and tools must be picked for assembly. - Textually instruct numeric details to inform about required numbers.	The content prevents the assembler from forgetting components or tools by showing what must be picked and where to pick it. Thus, the ARAS reduces the time to prepare, while it is done the first time right.

Table 6.2 General ARP descriptions per physical activity group

Concerning the 'how', the above table illustrates that textual and visual content can be complementary. Textual content can provide important information that cannot be visualized and vice versa. The challenge is to customize content for each assembler.

What is more, the results indicate that the assembler is always supported in his thinking processes; The ARAS serves as a memory support through highlighting objects (search, plan, select) or shows joining techniques, orientation and location of objects (comprehend). Table 6.3 describes ARP for mental activities.

Mental activity group	ARP
Comprehend	Visualization lets the assembler understand at the first try what needs to be done and how it must be done correctly. Hence, TCT is also reduced while it ensures correct activity execution. Textual content does not improve activity execution as the assembler still needs to interpret the instruction.
Plan	Visual content reduces the time to select the proper action. The same holds for textual content, but due to lesser intuitiveness it can be expected that thinking time increases.
Search	Searching is mainly related to picking components or tools. Searching time only decreases if exact locations are highlighted, as the assembler still needs to find the location of the component in case of textual instruction and therefore the ARAS will be non-supportive.
Select	If the location is highlighted, selecting will be done the first time right. Textual support does not very much support the assembler.

Table 6.3 General ARP descriptions for mental activities during assembly

Step 4 – Define assembly instructions

Having identified for which activities it pays-off to support activities with an ARAS, in step 4 the actual instructions, textual and/or visual, are created. Recall that the analysis results of instruction ambiguity (step 1) are implemented here. The decision of content richness is made here, taking into account the individual assembler needs. The richness of the content determines to a great extent the perceived usefulness of the support, hence, the ARAS efficacy (Radkowski et al., 2015).

In the case of β, some ambiguity was observed. Hence, this is an improvement to be made. As mentioned in section 5.3, joining activities illustrate the ambiguity currently present in the assembly instructions. The second action would be to profile assemblers based on prior knowledge of the boiler assembly in order to create customized content. With ambiguous instructions manufacturers are discouraged to proceed with

the remaining steps, as it introduces increased implementation effort, wastes in time and assembly errors[β3].

Step 5 – Choose hardware

In this step the most important decision concerns the display type. As explained in subsection 3.3.2 Assembly complexities this depends primarily on the assembly layout. Figure 6.4 outlines which displays could be used for different layouts.

Figure 6.4 Recommended types of displays for different assembly layouts

Other factors like workspace, exposure time, need of helmets and/or glasses, the environmental heat, humidity and lighting and the ability to collaborate should be considered too (Dünser et al., 2007; Palmarini et al., 2017; Radkowski et al., 2015). Table 5.2, which exhibits (dis)advantages per hardware option, can be used to make a better informed decision.

Recall the intentions of β to develop an ARAS supported training facility. Training time is less than the duration of one work shift[β3], hence, an HMD would be appropriate considering usage time. There are other incentives to use HMDs: The assembler assembles individually, has low relative mobility, has enough workspace and uses two hands during assembly[β4]. Yet, an HHD is an option too. Lastly, immobile hardware is an option, but only if the workstation is fixed. Fixed displays are discouraged to use for the 'real' assembly line. Due to lack of knowledge and focus on hardware selection, a specific recommendation cannot be provided.

Step 6 – Choose software

Having chosen the hardware components, we now turn to the issue of software selection. The most important issue here is that data has to be optimized to suit the hardware, hence, the hardware choice has implications for the software architecture[ζ2] as it determines required computing capacity (Wagner & Schmalstieg, 2009). Therefore, the ultimate choice for hardware and software is iterative. Display types must change if content requirements are not met, such that computational power suffices.

Secondly, the software decision concerns the issue of in-house development or buying a commercial package from AR suppliers. Although it may be possible to develop software internally, it may be more

efficient and qualitative to outsource this (Palmarini et al., 2017). This thesis focuses not on the software decision. Therefore, no specific recommendations are provided.

Step 7 – Implement and evaluate ARAS efficacy

The last step involves a reflection of the ARAS that has been designed and is essentially an efficacy check. The critical question is: *Does the ARAS support the assembler such that fewer mistakes are made, enable quicker activity execution and/or reduce the number of gazes?* If this is not the case, but ARP was envisioned, the ARAS should be redesigned. This makes the whole framework iterative.

Figure 6.5 allows to compare the initial framework of Chimienti et al. (2010) and the redesigned version created in this thesis. The final design can be seen in Figure 6.6.

Chimienti et al. (2010)	Framework design
1. Analysis of assembly procedure	1. Analyze assembly process(es)
2. Subdivision in tasks, sub-tasks and elementary operations	2. Define individual assembly activities and workplaces
3. Creation of logic-flow chars	3. Assess ARP for specific workplace
4. Definition of assembly instructions	4. Define assembly instructions
5. Hardware selection	5. Choose hardware
6. User interface selection	6. Choose software
7. Software implementation	7. Implement and check ARAS efficacy
8. Validation	

Figure 6.5 Initial framework (left) from Chimienti et al. (2010) and the newly designed framework (right)
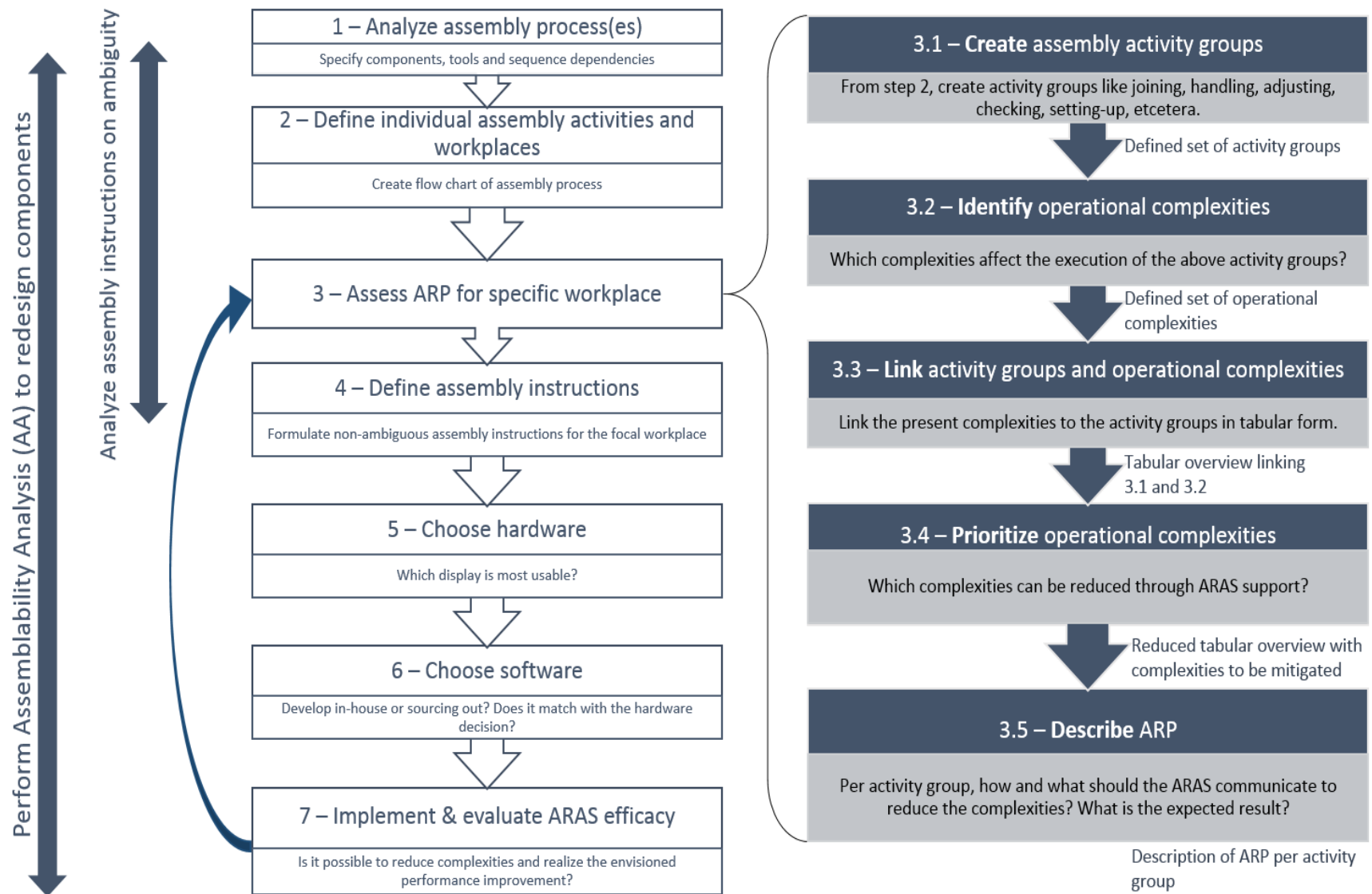
Figure 6.6 The framework towards ARAS implementation. Step 3 is the focus in this thesis.

7. Discussion

Whereas the ARP-model from Haagsman (2018) allows to assess ARP on a generic level, this thesis zooms in on assembly activities to assess ARP. General descriptions of ARP have been provided for different activity groups, which allows manufacturers to evaluate viability of AR supported assembly operations. In relation to the work of Chimienti et al. (2010) the framework designed in this thesis adds an ARP assessment step, which benefits decision quality of implementing an ARAS. However, the drawback of the assessment step is that it lacks quantification which was also lacking in the ARP-model. If ARP has been identified on both general level (ARP-model) and activity level (this thesis), how can manufacturers then estimate the economic viability of an ARAS? There are no exclusion criteria for this, hence, development of these would enhance usability of the framework.

On a different note, manufacturers should be careful not to push possibilities of ARASs and introduce counter productivity. As explained, content must be customized such that perceived usefulness is optimized. For instance, an experienced assembler could be distracted by textual content which costs time and might even go at the expense of assembly quality. On the other hand, an unexperienced assembler might require additional content to produce at the same quality level. Nonetheless, if content can be adapted to the individual needs of the assembler, the possibilities to improve assembly performance is promising as each individual assembler is optimally supported (Dünser et al., 2007). However, this requires adaptability and scalability of the ARAS. Without becoming too technical, the question is thus how flexible the system architecture is and will be in the future in order to cope with individual assembler needs. The (future) scalability of ARASs is an interesting aspect to assess technical attainability and economic viability. Secondly, management should be aware that an ARAS generates sensitive (assembler) data. An ARAS can monitor assembler behavior, which could arise questions about assembler privacy (Kourouthanassis et al., 2015) and data security (Palmarini et al., 2017).

7.1 Limitations and future research

First, separating structural and operational complexities in advance seemed a good idea to structure the overwhelming number of assembly complexities. Data showed, however, that this is risky practice since complexities might be classified as structural but are operational in a specific situation. Therefore, in situ separation would be better practice. What is more, further research should focus on aggregation of complexities to attain more efficiency in ARP assessment (step 3). Also, the robustness of the complexity definitions might be questionable. When does an assembler have a bad sight or hearing? Is it quantifiable?

Without doubt, this depends on the situation, implying that generalizing complexities is challenging. All in all, the complexities in this thesis provide some opportunities for future research.

Secondly, the subject of display selection is not evaluated too much as it was not the focal issue in this thesis. However, the thesis has shown that there are many aspects involved in hardware selection and the ultimate choice is far from unequivocal. In fact, multi-criteria assessment is required to choose among different display options. This issue also deals with the data format manufacturers must deliver in order to implement an ARAS[ζ1, α3]. This would be a fruitful idea for future research.

Thirdly, concerns exist about subjectivity and bias of the interviewees' responses that could limit the value of this research. For example, it appeared that companies sometimes already had an idea of the final ARAS configuration, especially with respect to the display choice. This thesis has pointed out that it would be wise to first assess ARP before choosing an ARAS configuration. Also, the choice of gaze shift as performance measure is questionable. Focusing merely on gaze shift limits research insight as there might be other measures to assess physical and cognitive ergonomics. To the contrary, literature fails to define simple objective ergonomic measures. More frequently, research focused on subjective evaluation of work load with the NASA-TLX (Hart & Staveland, 1988). Future research should therefore emphasize definition of objective ergonomic measures.

Fourth, the scope of this thesis is limited in terms of long-term implications on line level. In some situations, ARP might be scattered throughout the assembly process, as activities are scattered. This could incentivize assembly redesign where activities are grouped based on ARP, such that the actual use of the ARAS is grouped. Observing scattered activities might even be a reason to not implement an ARAS at all if redesign is not possible too. Likewise, if performance benefits are expected from ARAS implementation, manufacturers need to realize that an imbalance is introduced between stations which causes disrupted flow of goods in the assembly line (Hopp & Spearman, 2011). Hence, ARAS implementation implies rebalancing production paces between workplaces and stations.

A natural development of this thesis would be to perform activity time measurement. The time distribution of activity groups could lead to further exploration of ARAS opportunities. Time measurement offers chances to evaluate viability of ARAS implementation as it visualizes the proportion of assembly activities that can be ARAS supported. Appendix D – Time measurement systems MTM and MOST shows that time measurement should consider the characteristics of the specific situation.

To summarize, there are several knowledge gaps to be filled. Not only are certain aspects of ARAS implementation underexposed, overall validation of the framework evidently needs to be performed to prove its usability in different assembly contexts. Improvements are then identifying additional complexities, aggregating complexities, explore lacking steps or changing the sequence of the framework. Nevertheless, the current framework certainly adds to our understanding of ARP assessment for assembly activities.

8. Conclusions

This thesis was initiated to bridge the knowledge gap regarding AR deployment in assembly operations and facilitates the debate around ARP in assembly operations for AR suppliers and manufacturers. What is more, from a theoretical perspective a need for rigor and clarity was identified. Research on ARAS implementation has been performed but fails to provide robust and comprehensive insights. Therefore, for this thesis the following research issue was formulated:

How can manufacturers systematically assess ARP for manual assembly activities in order to improve quality, efficiency and work environment?

This question has been answered by exploring the subject of AR technology first. (Dis)advantages for different configurational options were identified that informs framework users and can be used to enable better decision-making. Accordingly, this thesis has built further on the work of Chimienti et al. (2010) and Haagsman (2018) by integrating a step that assesses ARP for the assembly activities carried out on a focal workplace. This step adopts the approach of mitigating operational complexities through ARAS support with the goal to reduce error rates, completion times and gaze shifts. Furthermore, the thesis found barriers for ARAS implementation such as absence of a standard assembly sequence and unavailability of CAD-data. Moreover, unambiguous assembly instructions and DfA practices were identified as important aspects for ARAS implementation. The essence through this thesis is two-fold. First and foremost, readers should have realized that details in ARP assessment, hence, ARAS implementation differ per assembly context. Secondly, users of the framework should be aware that ARAS designs are created through multiple iterations to optimize AR deployment.

Lastly, a final note to AR as a supportive assembly technology is written. Although the future looks bright for ARASs, the fact that more research is needed in various aspects of the technology cannot be neglected. Research areas like ARAS flexibility, implications on plant level, data security and infrastructure are important to investigate in order to fully integrate AR in the industry. This may take probably years and requires intensive collaboration between AR suppliers and manufacturers. Hence, there is a need for development of a 'AR agenda' which streamlines the interest of both parties and facilitates innovation.

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Appendix A – Description of content generation process

In the s*ensing* stage the environment is captured through a camera lens, a depth sensor camera, a stereo camera or a CCD camera (X. Wang et al., 2016). The lens detects images or interest points like lines, edges or texture. Distinguishing one object from another is made possible by feature detection or edge detection (Carmigniani et al., 2011). Also involved in this stage is the processing of images (X. Wang et al., 2016). Additional to the image capturing device in this stage is the decision on how the captured data is transmitted and processed. Elia, Gnoni, & Lanzilotto (2016) reported that data can be transferred to a computer in visual (2D or 3D), aural or textual format. The computer processes the information captured by the camera that is used for the next stage, tracking (Balcisoy, Kallmann, Fua, & Thalmann, 2000; X. Wang et al., 2016).

The *second* stage is tracking, which means that the software computes the relative position of the assembler to his surroundings (Palmarini et al., 2018). The main objective of tracking is that virtual elements need to be posed correctly in space, hence, accurate localization and measurement is essential (X. Wang et al., 2016). Three main tracking techniques are frequently used in ARSs (Nee, Ong, Chryssolouris, & Mourtzis, 2012).

- *Vision-based* tracking which uses visible recognition points that may also vary in color or geometry. It generally has the advantage of high computational efficiency but loses performance on the fact that points can be hard to detect. Also, not every component is big enough to have a marker attached to it. Hence, practical feasibility is sometimes debatable. Vision-based tracking is subdivided in *feature-based* tracking and *model-based* tracking . Whereas the former seeks to find 'correspondence between 2D image features and their 3D world frame coordinates' (Zhou et al., 2008), the latter seeks for distinctive contours in the real world to match with a pre-modelled virtual 3D model (Nee et al., 2012). In addition to these two tracking techniques, there is also the option of *marker-based tracking*, which is the most commonly used technique (Palmarini et al., 2018). For this technique it is needed to put markers, i.e. recognition points, to the assembly products. Recognizing the marker then becomes recognizing the product.
- *Sensor-based tracking* makes use of sensors that are triggered mechanically, acoustically, electromagnetically, magnetically, optical or via inertia. Every technique has its own advantages and disadvantages, for which the researcher refers to Ong et al. (2008) and Zhou et al. (2008) for specific examples.
- The last way of tracking is a *hybrid* form of the two previous tracking schemes, combining the best of both worlds. A tracking technique is hybrid when it uses vision-based and sensor-based tracking hardware to estimate the position of the camera in space. For instance, a hybrid tracker can apply magnetic and video sensors to achieve rapid localization and diminish disadvantages of both tracking techniques individually (R. Azuma et al., 2001).

The *third* stage involves generating content (Carmigniani et al., 2011; X. Wang et al., 2016). Digital visualizations are created in a server with the aid of software packages like ARToolkit and DART (Ong et al., 2008). The prime function of these packages is to process the data that comes from the previous stage and convert it to 2D or 3D CAD models, textual or aural instructions, or a combination of these and render them in the real world.

The key function performed in the last stage is communicating the generated content. Critical in this stage is how content is communicated to the assemblers. Namely, content effectiveness depends on

intuitiveness of the communicated instructions (Wiedenmaier & Oehme, 2003). Recall, too, that the content must support the assembler, hence, it should not hinder the view or exhibit redundant information (Kourouthanassis et al., 2015). Content is communicated through either Head Mounted Displays (HMDs), Hand Held Devices (HHD), projectors, 2D glasses and monitors . 2D glasses are similar to HMDs, except that they i) are only able to render 2D content and ii) do not operate in real-time (Hoover, 2018). Thus, it strongly depends on the ARAS what kind of display is chosen. Also, there is the issue of how assemblers obtain timely feedback and authorize to proceed to the next assembly step. Authorization involves giving a signal to the ARAS that an assembly step has been completed. Different authorizations exist, the assembler can press a button, interrupt a light beam or vocally authorize. Only when a step is completed, the ARAS shows the next assembly step. Content can be visual (2D or 3D, static or dynamic), textual, aural or a combination of these (Elia et al., 2016; Fiorentino et al., 2014; Palmarini et al., 2018).

Appendix B – Production layouts

Assembly layouts are explained briefly here. The dimensions that can be plotted against each other is *product standardization* and *production volume*. The following figure was adapted from (Jacobs & Chase, 2014, fig. 6.3)
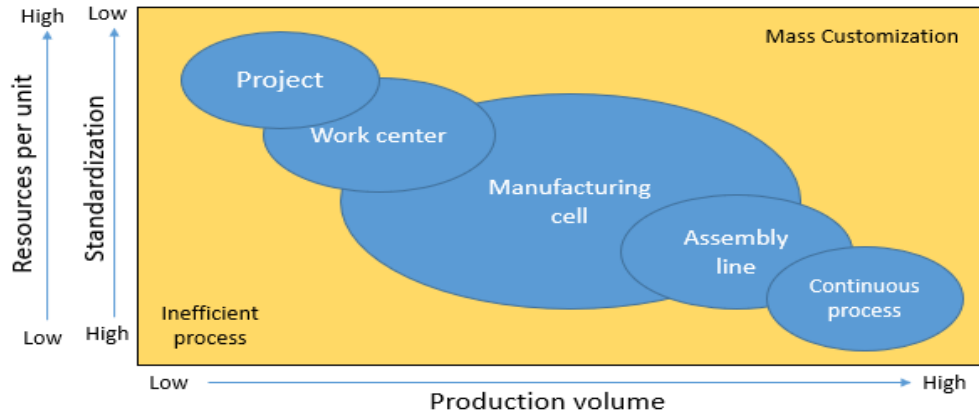
- Project layout
    - In a *project* or *fixed-Position* layout the assembly remains on a fixed position. Here the size of the assembly plays a determinant role. Large assemblies like houses and bridges are assembled like this.
- Process layout
    - In a *work center* layout or *job shop* the objective is to optimize the pace and movement of material and (sub)assemblies. Machines with the same function are grouped together, such that products with the same needs (i.e. high repetitiveness or low standardization) can quickly flow through the processing operations.
    - In a *manufacturing cell* or *focused factory,* it is all about grouping machines for products that have similar processing requirements. Indeed, this resembles the previous layout. However, the main difference is that in this category the variety of products that can be made is bigger. Work centers are only able to produce one type of family and therefore are more dedicated. The objective is the same: to optimize flow for (families of) products so that high production volume is attained.
- Product layout
    - In an *assembly line* each (sub)assembly follows a predetermined sequence of assembly steps. As all the (sub)assemblies are the same (high standardization) which enables high production volume. Often a form of time management is applied to guarantee productivity.
    - The *continuous process* resembles the assembly line, except for the fact that the product being made is not discrete like cars and shavers, but continuous. Examples are fluids and chemicals.

Appendix C – Objective performance measures in literature

Objective performance measure	Literature sources
Task Completion Time	(Blattgerste et al., 2018, 2017; Bottani & Vignali, 2018; Boud et al., 1999; Fiorentino et al., 2014; Henderson & Feiner, 2009, 2011; Hou & Wang, 2013; Jetter et al., 2018; Krichenbauer, Yamamoto, Taketom, Sandor, & Kato, 2018; Marner et al., 2013; Mathews et al., 2007; Radkowski et al., 2015; Rosenthal et al., 2010; Stork & Schubö, 2010; Tang et al., 2003; Uva et al., 2018; Westerfield, Mitrovic, & Billinghurst, 2013)
Error rates	(Blattgerste et al., 2018, 2017; Bottani & Vignali, 2018; Fiorentino et al., 2014; Gavish et al., 2015; Henderson & Feiner, 2011; Hou & Wang, 2013; Jetter et al., 2018; Marner et al., 2013; Mura et al., 2016; Radkowski et al., 2015; Rosenthal et al., 2010; Stork & Schubö, 2010; Tang et al., 2003; Uva et al., 2018; Westerfield et al., 2013)
(Head) Motion	(Henderson & Feiner, 2009; Krichenbauer et al., 2018; Marner et al., 2013; Polvi et al., 2018; Stork & Schubö, 2010; Uva et al., 2018)
Number of attempts	(Hou & Wang, 2013; Mathews et al., 2007)
Score	(Gavish et al., 2015)
Localization time	(Henderson & Feiner, 2009)

Table 0.1 Frequently used objective measures for task execution evaluation
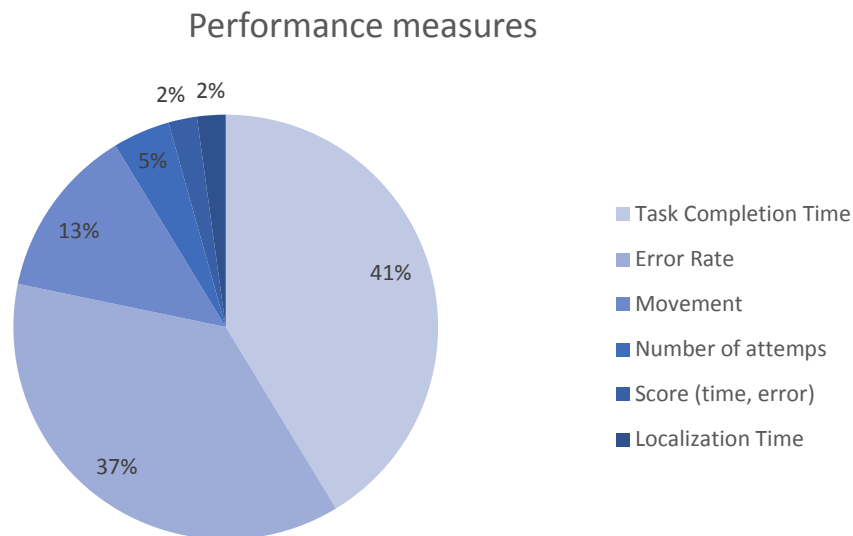

Figure 0.1 Objective performance measures mentioned in literature

Appendix D – Time measurement systems MTM and MOST

Methods-Time Measurement (MTM) is a procedure which analyzes any manual operation or method into the basic motions required to perform it and assigns to each motion a predetermined time standard which is determined by the nature of the motion and the conditions under which it is made. Essentially, it is a first-level system and constitutes an analysis tool to improve work methods. In addition, higher-level systems exist in which basic motions are aggregated into motion groups or activities. The table below provides characteristics for first-level and higher-level systems. Where MTM-1 applies only basic motions, MTM-2 and even MTM-3 apply aggregated motions.

Characteristic	First-Level systems	Higher-Level systems
Accuracy	Most accurate	Less accurate
Application time	Much time to set standard	Less time to set standard
Suited to specific types of tasks	Highly repetitive	Repetitive or batch
Cycle times	Short cycle (e.g., 1 min)	Longer cycle times feasible
Motion elements	Basic motions	Aggregates of basic motions
Methods description	Very detailed	Less detailed, easier to apply
Flexibility of application	Highest flexibility	Less flexibility

Table 0.1 Characteristics of Predetermined Motion Time Systems (PMTS)

A different time measurement system is the Maynard Operation Sequence Technique (MOST), which is based on the MTM-system. However, the focus of the measurement is on work activity, including object motion. It is believed that the motion of objects and tools implies a pattern of body motions, a sequence, and that only details differ per object. Therefore, motions are collected to form aggregates which are executed in a sequence of actions. It taxonomy of movements is outlined in the figure below.
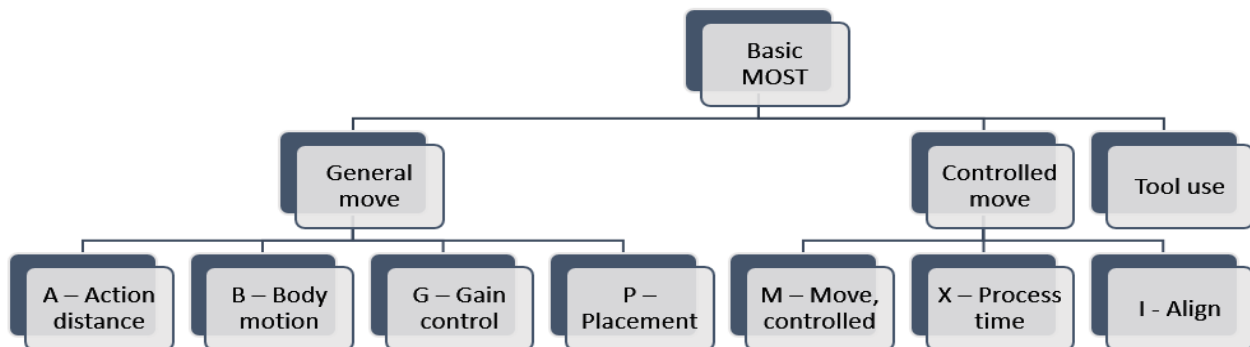

Figure 0.1 Taxonomy of actions in the Basic MOST model (Groover, 2007, sec. 14.3)

Appendix E – DfA guidelines

Issue		Guidelines
1.	Number of parts	Minimize the number of parts and levels of assembly and simplify product complexity.
2.	Modularity	Design products from modular subassemblies so that modules can be scheduled, built and tested independently.
3.	Base part	Ensure the product has a suitable base part on which the rest of the assembly can be built; usually, it is the largest, heaviest part.
4.	Locating features	Ensure the base part has features to locate it readily in a stable position, preferably in a horizontal plane
5.	Layers	Design a product to be built up in layers, so each component can be added from above and located positively, without a tendency to move during subsequent motions or steps

Table 0.1 DfA: Product considerations. Adapted from Nof et al. (1997, p. 88)

Issue		Guidelines
1.	Chamfers	Facilitate assembly operations by providing chamfers or tapers to help guide and position fasteners.
2.	No repositioning	Eliminate or minimize the need for repositioning an assembly once it is fixed.
3.	Shortest distance	Minimize motion distance, within practical limits, to reduce motion time and improve accuracy.
4.	No adjustment	Eliminate or minimize the number of electrical and mechanical adjustments
5.	One-way assembly	Design 'foolproof' operations: parts can be assembled only one way; if misassembled, subsequent parts cannot be added.

Table 0.2 DfA: Operation considerations. Adapted from Nof et al. (1997, p. 89)

DfA guidelines according to Boothroyd et al. (2002):

- Avoid connections
- Design so that access is not restricted
- Avoid adjustment
- Use kinematic design principles

Product guidelines for ARAS implementation
- *Reduce number of parts* – The fewer the component count in an assembly the faster the assembly process, because of less assembly activities required. Moreover, the assembly is less error prone to assembler mistakes. In the light of AR deployment, less component count prevents errors made due to weak presentation of assembly instructions (Stork & Schubö, 2010).
- *Create locating features* – Having components that orient themselves, due to their geometric characteristics, will ease the complexity of assembly instructions. Namely, information regarding position and orientation does not have to be provided any longer, which is considered as intrusive and impeding the assembly motions. The latter also enhances assembler safety.

Operation guidelines for ARAS implementation
- *Shortest distance* – Less motion distance of the assembler makes it possible to consider more display options to deploy AR. Moreover, it reduces TCT and has the potential to enhance ergonomics.
- *No adjustment* – This is related to the locating features mentioned above. If components are designed such that they orient themselves, assemblies become less prone to errors made by assemblers. Also, the instructions provided by the AR display can be simplified.
- *One-*way *assembly* – See previous.

Appendix F – Interview and observation protocol

This appendix contains the data collection protocol. It shows the questions asked during interviews and aspects that had attention during the observations. The

Research questions were used as a lead to form the interview questions.

Interview questions

Introduction

1. Could you please introduce yourself?
    a. What is your current role in the company you work in?
2. What kind of products does the company make?
3. Why is the company interested in AR deployment?
    a. What are the problems experienced in the assembly process?
4. Do you already have experience with AR?
    a. In assembly contexts too?

Deploying AR (mainly for experts)

1. What are, according to you, the critical functions of AR?
    a. *Show process of data from thesis, do they recognize it? Do they have additions?*
2. When a firm is willing to invest in deploying AR, what are critical design decisions to be made?
    a. And, to what extent should the aim of deploying AR be coherent with the firms' strategic goals? (A firm can focus on productivity, quality of the work environment safety)
3. Are there any problems with firms that are willing to deploy AR, but do not know *how* yet?
    a. If yes, why is this a problem?
    b. What kind of knowledge is lacking?
        i. How could this knowledge be attained?

Assembly activity performance

Each assembly is buildup from a procedure of single assembly steps. Each assembly step can be decomposed in different activities, specific actions an assembler needs to perform to create the final assembly.

1. What are typical measures to be evaluate the performance for a specific activity? *(TCT, ER, assembler position).*
2. In what ways can AR contribute
    a. to executing tasks faster,
    b. prevent errors made by assemblers and
        i. What kind of errors are made frequently?
    c. establish a safer work environment?
3. Do you agree that deploying AR can be simplified through redesigning a component by performing assemblability analysis (AA)?
    a. Why?
4. Do you agree that deploying AR can be simplified by analyzing and reformulating instructions from the analogue instruction manual into Simplified Textual English (STE)?
    a. Why?
5. What do you expect from AR deployment for this specific product?

Assembly activity characteristics

The execution of assembly activities can be impeded by product, process, assembler and environmental complexities.

1. *Explain the list of assembly activity groups for an assembler found in literature*
   a. Ask if they recognize the activity groups and if they have any additions. Does it comply with activities of the assembly under focus?
      i. *Eventually synthesize a list of activities specifically for this company, if not done earlier*
2. In which activities do you think losses in time and quality mostly occur?
   a. Which specific activities are the most labor intensive?
      i. How do you define labor intensive? (Multiple assemblers for one activity, exposition to uncomfortable positions, lifting heavy weights, high cognitive effort required)
   b. Are these also the activities where the gains can be expected when they are supported with AR technology?
3. Do you agree that some complexities have to be deepened to understand where ARP can be found?
   a. Do you recognize or admit that the additional, deepening complexities are important to this? *Show the list of complete complexities*
4. How can AR support in the execution of assembly activities? (prevention and warning, correction and feedback, pure instructive. And what is the data format of the instructions? Visual, textual or aural?)
5. Would the ARP differ when an assembler has a variety of activities to perform over a day? (Because the set of activities to be performed differs for every assembler)
   a. Why?

Framework questions

This framework is intended to assess assembly activities on ARP. With her ARP model (Haagsman, 2018) it is possible to value an assembly context with respect to AR deployment.

1. Is it possible for you to predict where, in the assembly process, AR should be used with the ARP-model of Haagsman (2018)?
   a. If so, is it true then that an additional framework is redundant, or could it be a complementary part of the whole assessing process?
   b. If not, what kind of information is lacking according to you?
   c. And, where in the assembly process would you start looking for possibilities to deploy AR? (Bottleneck assembly step, the activity where cognitive workload is the biggest, something else? Relates to labor intensity → consistency check)
2. Would a framework, guiding you in assessing assembly activities on ARP, be of use for you?
   a. Why or why not?
   b. What should the framework look like? What are design requirements?
      i. Do you have suggestions for possible steps that have to be present? *(if not, provide suggestions from your first framework and see if interviewee agrees)*
      ii. What is the information that you want to retrieve from the framework? *(if no idea, suggest a table where cells indicate potential, interaction mode, nature of information)*

Conclusion

1. Do you have any further questions, or do you want to add something?

Observation protocol

Company visits were conducted with the aim of getting to know the assembly context, how the assembly for a specific product was organized. During the company visits valuable information was retrieved through informal talks with assemblers and direct observations of the assembly process. Below aspects are listed that received specific attention.

- ➢ Assembly layout
  - o What kind of layout does the focal product follow?
    - ▪ Is there product variation in the layout?
    - ▪ High or low volume product?
  - o And how does the assembler move during the assembly process? (Why?)
- ➢ Product complexity
  - o Does the finished assembly contain a lot of (standard) components?
  - o Two hands needed to hold?
  - o Supportive tools?
  - o Own insight needed to proceed with assembly?
- ➢ Errors
  - o What are typical errors made during the assembly of the product?
  - o What is the nature of these errors? How come that they exist?
- ➢ Assembly activities
  - o What are typical activities present during the assembly process?
  - o Are these activities executed by one assembler or multiple assemblers?
    - ▪ Does one assembler have only one activity to execute or multiple?
  - o How do assemblers respond to making a mistake?
- ➢ Statements or body postures during the assembly process that show a sign of cognitive or physical stress?

Appendix G – Data source codes

Case company	Data collection method	Type	Source
α			
	Assembly manual	1	α1
	Introduction meeting	2	α2
	Interview	3	α3
β			
	Assembly manual	1	β1
	Introduction meeting	2	β2
	Interview	3	β3
	Observation notes	4	β4
γ			
	Introduction meeting	1	γ1
	Interview	2	γ2
	Observation notes	3	γ3
	Film data	4	γ4
ζ			
	Feedback on content generation	1	ζ1
	Introduction meeting	2	ζ2

Appendix H – Description of ARP

	Case					
	α		**β**		**γ**	
Activity group	*Activity*	*ARP (ARAS function)*	*Activity*	*ARP (ARAS function)*	*Activity*	*ARP (ARAS function)*
Mechanical joining	Glue	*How* – V *What* – Show static CAD-model with locations to glue. *Result* – Ensuring quality and improve cognitive ergonomics	Insert	See 'insert' at α		
	Insert	*How* – V *What* – Highlight places to insert. Base component requires a fixed position. In addition, show CAD-model to be picked. *Result* – Ensuring quality, less time needed to complete activity	Mont	*How* – V *What* – Animate how a component is correctly mount of fixed. *Result* – Ensuring quality, less time needed to complete activity		
	Press	*How* – V + T *What* – Remind assembler to perform step. Show animations of how one component is pressed on to the other with right orientation on the right location. *Result* – Ensuring quality, improve efficiency	Screw	*How* – V + T *What* – Show annotations of locations to screw, so no screw is omitted and thereby reminding assembler to perform step. *Result* – Ensuring quality, less time needed to complete activity		
	Screw	*How* – V + T *What* – Show annotations of locations to screw and which components and tools to pick. Specify settings. Remind assembler to perform step. *Result* – Ensuring quality, less time needed to complete activity	Sticking	*How* – V *What* – Highlight location where a sticker has to be placed. Only if this is not clear from the product itself. *Result* – Ensuring quality		

		How – V + T What – Shows textually what must be soldered and visually the location of soldering and maybe CAD models of the right component to solder. Warn for heated tools or components Result – Ensuring quality, less time needed to complete activity and improve ergonomics	Couple	How – V What – Highlight location of coupling Result – Ensuring quality, less time needed to complete activity	Soldering	How – T What – Remind to solder. Specify temperature, tool and which wires have to be soldered. Warn for toxic gas. Result – Ensuring quality, increase efficiency and ergonomics
Electrical joining	Soldering					
Checking	Checking	How – V + T What – Ask the assembler textually to check if the right components are in the right place and correctly joined. Subjective inspection involved. Also, show how (sub)assembly should look like Result – Ensuring quality	Checking	See 'Checking' at α.	Checking	See 'Checking' at α
Handling	Placing	How – V What – Show which component has to be placed where and with which orientation Result – Ensuring quality, increase efficiency	Picking	How – V What – Assemblers are most supported with CAD-model, eventually with (numeric) details. In this case, the component to pick is heavier. Hence, the ARAS should warn for wrong body posture. Result – Ensuring quality, increase efficiency and ergonomics	Picking	How – V What – Show where to pick and what to pick Result – Ensuring quality Ensuring quality, less time needed to complete activity
	Positioning	How – V What – As location and orientation are crucial here, is important to visualize it. Textual instructions may be even counterproductive. Result – Ensuring quality, increase efficiency	Placing	See 'Placing' at α	Positioning	How – V What – Show how wires should lay with CAD-model Result – Ensuring quality, less time needed to complete activity
	Sliding	How – V + T What – Animate how one component should be slid over the	Positioning	How – V What – Animate with CAD-models how a component should be	Sliding	How – v What – Animate which component is shoved over the other.

		other. Hereby, it is also specified which components are involved. *Result* – Ensuring quality, increase efficiency		positioned. ARAS prevent harmful body postures *Result* – Ensuring quality, improve ergonomics		*Result* – Ensuring quality, increase efficiency
			Press button	No ARP envisioned, as quality is ensured through a pick-to-light method		
Fix			Fix	*How* – V *What* – Highlight location of components that are fixed. *Result* – Ensuring quality, improve efficiency	Fix	*How* – V *What* – Show how assembly should be fixed in which orientation *Result* – Ensuring quality, improve efficiency
Prepare	Clean	*How* – T *What* – Instruct what should be cleaned. If there is not much variation in the place that have to be cleaned, visually show which locations are to be cleaned. *Result* – Ensuring quality, improve efficiency			Setting up	See 'Setting up' at α
	Setting up	*How* – V+T *What* – ARAS provides a stepwise list of what should be prepared. As walking is involved text supported with a visualization of a CAD-model is appropriate. *Result* – Ensuring quality, improve efficiency				
Adjusting						
Miscellaneous	Crimp	*How* – V + T *What* – Remind to perform step, show tool to pick, warn the assembler for heated objects. *Result* – Ensuring quality, improve efficiency and ergonomics	Hang	*How* – T *What* – Remind to hang the papers of the boiler. *Result* – Ensure quality	Strip	*How* – V + T *What* – Highlight appropriate tool to use. Warn to use not too much force and sharp tools. *Result* – Ensuring quality, improve efficiency, ergonomics
	Cut	*How* – T	Scan	*How* – V + T	Fold cable	*How* – T

	What – Remind to perform step, as exact cutting location and quantity is impossible to visualize *Result* - Ensuring quality		*What* – Highlight location of code to be scanned. Inform the assembler if scanning went wrong. *Result* - Ensuring quality		*What* – Remind to perform step *Result* – Ensuring quality
Smear	*How* – V + T *What* – Show with CAD-model and annotation where the liquid has to be smeared. *Result* – Ensuring quality	Smear	See 'Smear' at α	Smear	*How* – T *What* – Remind to smear flux on contact surface before soldering *Result* – Ensuring quality
Remove	*How* – T *What* – Remind to perform step and specify what has to be removed and which tool is used. *Result* – Ensuring quality				
Scrub	No ARP is envisioned, as not every crack unit requires scrubbing[α3]. Low standardization.				
Tinning	*How* – T (V) *What* – Remind to perform step, warn that not too much tin should be used. (Maybe show which tool to use) *Result* – Ensuring quality				