# A Framework to Establish an Assistance System by Using Reality Technology in Maintenance

by

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# Declaration

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# Abstract

Maintenance is an increasingly complex and knowledge-intensive field. One approach to deal with complexity and use knowledge effectively is to apply assistance systems based on reality technology. These digital systems offer the possibility of virtually enhancing the real world with information. The benefits of assistance systems based on reality technology for maintenance are known, but there are uncertainties about which system can be employed for which purpose and how they can be utilised in maintenance. In this context, this research study proposes a framework that supports the identification, selection and implementation of assistance systems based on reality technology in maintenance.

For the development of the decision support framework, assistance systems based on reality technology are investigated for application characteristics and implementation requirements in maintenance through a systematic literature review and interviews with experts in the field of maintenance. The examination of the application characteristics includes which type of assistance system based on reality technology – augmented reality, mixed reality and virtual reality – to employ in the line of execution, training or planning of maintenance. The study of the implementation requirements covers the extent to which requirements regarding employees, technology and safety are decisive for the implementation of assistance systems based on reality technology in maintenance.

The objective of the decision support framework is to provide the ideal technological and economic solution. The technological evaluation consists of identifying the hardware and software that are most suitable for the requirements and environment of the maintenance application. The economic assessment includes a comparison of the costs and benefits resulting from the implementation of the assistance system based on reality technology for maintenance. The usability of the decision support framework is validated through a case study in which a solution based on reality technology is investigated for the scheduled and unscheduled maintenance activities of a milling machine.

Keywords: *smart maintenance, reality technology, augmented reality, mixed reality, virtual reality, assistance system*

# Opsomming

Instandhouding is ‘n toenemende kompleks en kennis-intensiewe veld. Een benadering om met die kompleksiteit te handel en die kennis effektief toe te pas, is om realiteitstegnologie hulpstelsels te gebruik. Hierdie digitale stelsels maak dit moontlik om die werklike wêreld virtueel uit te brei met inligting. Die voordele van realiteitstegnologie hulpstelsels vir instandhouding is bekend, maar daar is onsekerhede oor watter stelsels, vir watter toepassing gebruik kan word en hoe dit in instandhouding benut kan word. Binne hierdie konteks, word ‘n raamwerk deur hierdie navorsing voorgestel wat die identifisering, seleksie en implementasie van realiteitstegnologie hulpstelsels in instandhouding kan ondersteun.

Vir die ontwikkeling van die besluitsteunraamwerk, word realiteitstegnologie hulpstelsels bestudeer vir die toepassingskarakteristieke en implementeringsvereistes in instandhouding deur middel van ‘n sistematiese literatuurstudie en ondehoude met kundiges in die instandhoudingsveld. Die ondersoek van die toepassingskarakteristieke sluit in die tipe realiteitstegnologie hulpstelsel – aanvullende realiteit, gemengde realiteit en virtuele realiteit – om aan te wend vir uitvoering, opleiding of beplanning van instandhouding. Die studie van implementeringsvereistes dek die omvang van vereistes rakende werknemers, tegnologie en veiligheid en tot watter mate dit beslissend is vir die implementasie van realiteitstegnologie hulpstelsels in instandhouding.

Die doelwit van die besluitsteunraamwerk is om die ideale tegnologiese en ekonomiese oplossing voor te skryf. Die tegnologiese evaluasie bestaan uit die identifisering van die hardeware en sagteware wat die geskikste is vir die vereistes en omgewing van die instandhoudingstoepassing. Die ekonomiese assessering sluit ‘n vergelyking van koste en voordele in wat volg uit die implementasie van die realiteitstegnologie hulpstelsel vir instandhouding. Die bruikbaarheid van die besluitsteunraamwerk word gevalideer deur ‘n gevallestudie waarin ‘n oplossing, gebaseer op realiteitstegnologie, ondersoek is vir die geskeduleerde en ongeskeduleerde instandhoudingsaktiwiteite van ‘n freesmasjien.

Sleutelwoorde: *slim instandhouding, realiteitstegnologie, aanvullende realiteit, gemengde realiteit, virtuele realiteit, hulpstelsel*

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# List of Acronyms

2D ..... Two Dimensions

3D ..... Three Dimensions

AR ..... Augmented Reality

AS ..... Assistance System

AV ..... Augmented Virtuality

CAVE ..... Cave Automatic Virtual Environment

CR ..... Content Requirement

DoF ..... Degrees of Freedom

DSF-RTM ..... Decision Support Framework for Reality Technologies in Maintenance

EC ..... Exclusion Criterion

FOV ..... Field of View

HHD ..... Hand-held Display

HMD ..... Head-mounted Display

IC ..... Inclusion Criterion

ICT ..... Information and Communication Technology

LR ..... Layout Requirement

MR ..... Mixed Reality

PRQ ..... Primary Research Question

RO ..... Research Objective

RT ..... Reality Technology

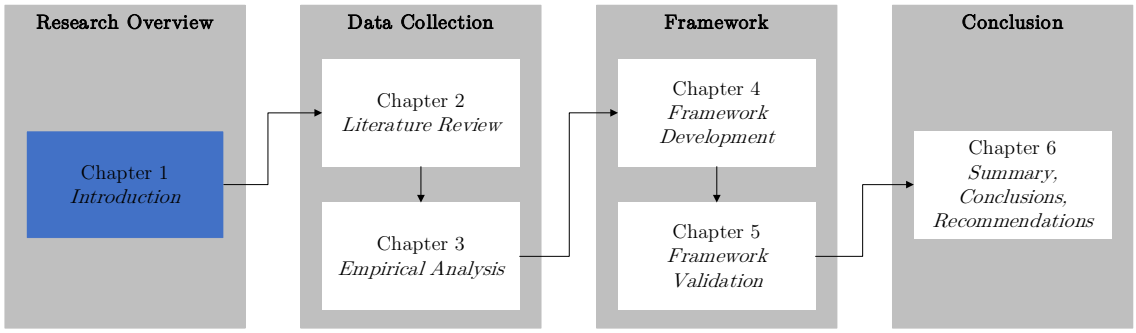
SAR ..... Spatial Augmented Reality

SDK ..... Software Development Kit

SRQ ..... Secondary Research Question

VR ..... Virtual Reality

# Chapter 1
# Introduction




The objective of this chapter is to introduce the research of this thesis. The chapter covers the background and rationale of the research which leads to the research problem and the research questions. The definition of the research objectives follows. Thereafter, the research design and methodology as well as the delimitations and limitations are addressed. Finally, this chapter concludes with the outline of the chapters in this thesis.

## 1.1 Background and Rationale of the Research

Digitalisation is the driver of Industry 4.0, the industry of today (Lasi *et al.* 2014, p. 261). With the disruptive trends of individualisation and globalisation, Industry 4.0 faces challenges in terms of an increasing number of variants, shorter product life cycles as well as customer requirements for higher quality, shorter delivery times and lower costs (Dombrowski and Wullbrandt 2018, p. 16; Schenk 2010, p. 10). The production systems in Industry 4.0 require a high degree of flexibility, availability and reliability to cope with these effects (Henke and Kuhn 2015, p. 7). For this purpose, information and communication technologies (ICT) are employed to enable a more sophisticated and interlinked infrastructure (Richter *et al.* 2017, p. 118). The ultimate objective of Industry 4.0 is the smart factory, which is a digitally interlinked factory which encompasses all elements of the value chain and creates the platform for holistic, optimal decision-making through self-preservation and interaction (Henke *et al.* 2019, p. 6; Soder 2017, p. 16).

The new developments towards a smart factory imply that maintenance has to adapt accordingly along the same lines as the production environment. Maintenance is required

to act innovatively and sustainably to develop into smart maintenance as an enabler to ensure the functionality of all entities that ultimately represent the vision of a smart factory (Henke and Kuhn 2015, pp. 6–7). Thus, the relevance of maintenance increases due to internal reasons shown in Figure 1.1. In addition, changes in legal requirements in recent years have external effects on maintenance (Matyas 2019, p. 31).

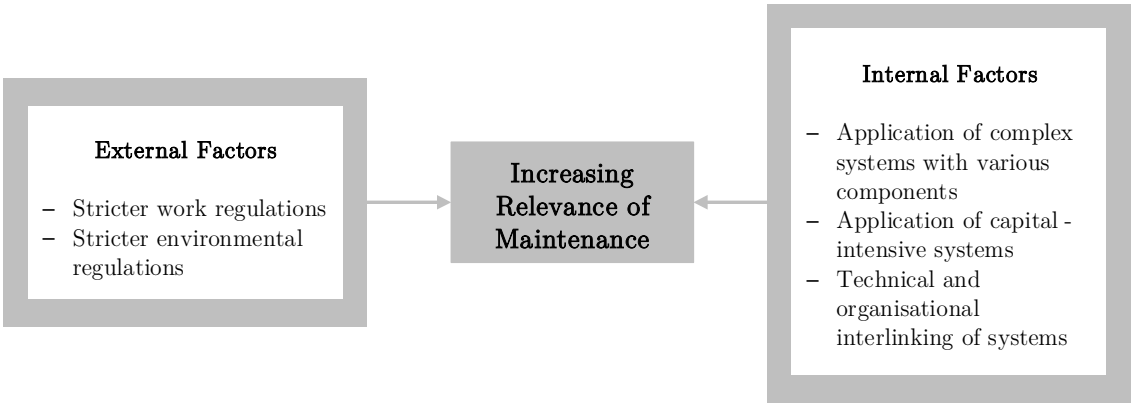



Figure 1.1: Relevance of maintenance
Adopted from Matyas (2019, p. 31)

The implementation of ICT in the scope of Industry 4.0 increases the complexity of the systems and the number of elements to be maintained. In addition, the costs of the systems as well as the interlinking between them increases (Arnaiz *et al.* 2010, p. 41; Strunz 2012, p. 9). Matyas (2019, p. 31) elaborates with further consequences for maintenance based thereon:

- Due to the increasing complexity of elements, troubleshooting and repair require more time, and can only be carried out by qualified personnel.
- Due to the increasing number of elements, machines and plants are more prone to failure and therefore require more frequent maintenance.
- Due to the increasing investment costs for elements, machine hour rates are higher and thus downtime and breakdown costs rise. Therefore, the duration for maintenance tasks must be kept to a minimum.
- Due to the increasing interlinking of elements, in the event of a failure on one machine, several machines may fail at the same time. Thus, downtime costs are increased significantly.

In the context of the external causes, the legal regulations for occupational safety and environmental protection have been adapted, expanded and formalised in recent years. Accordingly, maintenance management is enhanced to ensure occupational health and safety as well as environmental requirements. In addition, the growing number of

regulations result in an increased responsibility and the need for training. Furthermore, companies are forced to retrofit or upgrade their equipment, which involves significant additional investment (Lucke *et al.* 2017, p. 77; Matyas 2019, p. 31; Strunz 2012, p. 10).

To overcome these challenges in the transformation to smart maintenance, the areas of knowledge management and skills development play a key role (Henke *et al.* 2019, p. 15). The structural transition from labour-intensive to knowledge-intensive tasks requires sustainable and simple handling, storage and expansion of knowledge, expertise and skills (North 2016, p. 1). In addition, a certain level of qualified personnel is essential. However, the trend towards an ageing society and a shortage of skilled workers is leading to insufficiently trained personnel (Apt *et al.* 2018, p. 14; Gohres and Reichel 2018, p. 13; Leidinger 2017, p. 126).

Technical support through an assistance system (AS) has the potential to provide the requirements for managing the knowledge-based maintenance (Apt *et al.* 2018, pp. 19–25; Klapper *et al.* 2019, pp. 10–15). In particular, digital ASs based on reality technology (RT) enhance the cognitive performance of the maintenance personnel by making information accessible to everyone at any time and in any place (Henke and Kuhn 2015, pp. 23–24). The information, data and knowledge can be individually adapted to the situation and abilities of the respective user. Thus, the employee is able to handle the immense amount of data by receiving the relevant information and making the right decisions based thereon. In addition, communication and interaction are possible with smart objects in Industry 4.0 (Bauernhansl 2014, p. 24; Hänsch and Endig 2010, p. 270; Schenk 2010, p. 7). Ultimately, the required responsiveness and reaction time, as well as the flexibility and ability of individuals can be ensured by pursuing smart maintenance for the vision of a smart factory (Henke and Kuhn 2015, p. 24).

In this context, Henke *et al.* (2019, p. 14) conducted a survey with 96 participants from 14 different industries about the application of ASs based on RT, such as ASs based on augmented reality (AR) and virtual reality (VR), in maintenance. One question in the survey concerns the greatest benefit of ASs based on AR and VR in maintenance. Figure 1.2 shows the results of this question. The absolute numbers are indicated in brackets.

First of all, the majority of the respondents consider ASs based on RT to be useful for maintenance since only eleven respondents see no benefit for both ASs based on AR and VR. The greatest advantage for ASs based on VR is expected in the area of training of maintenance technicians, because of the possibility of making mistakes without incurring costs. The second promising application area for ASs based on VR is in the planning of maintenance tasks. In contrast, the greatest benefit of ASs based on AR is considered to be in the execution of maintenance tasks. The technical possibility of remote support allows an expert who is not on-site to provide digital assistance, thus, reducing the time required for specific maintenance tasks and increasing quality at the same time. In addition, a

further advantage is that ASs based on AR enable to instruct unskilled personnel directly at the machine, thus saving time and costs (Henke *et al.* 2019, p. 39).

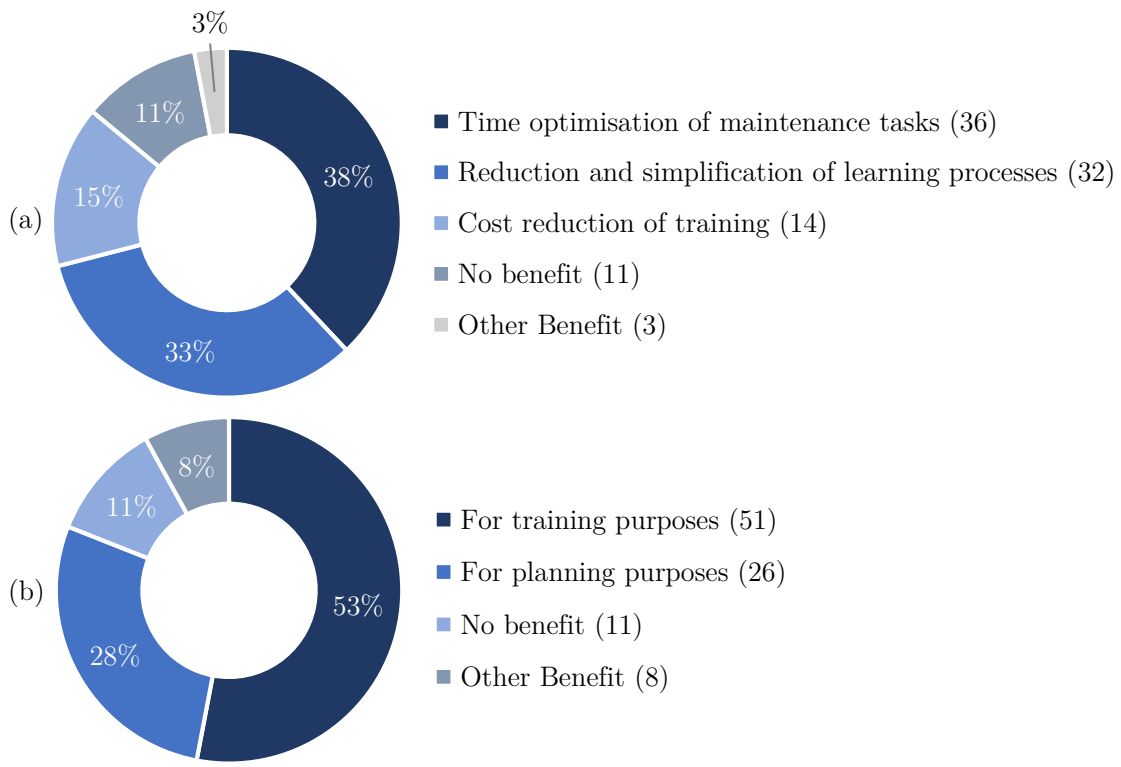



Figure 1.2: Greatest benefit of ASs based on (a) AR and (b) VR in maintenance according to the results of the survey (n = 96)

Adopted from Henke *et al.* (2019, p. 39)

In another question, Henke *et al.* (2019, p. 20) examine the extent to which ASs based on RT are implemented in maintenance. The results indicate that digital ASs are hardly applied and play a subordinate role in maintenance. For instance, 95% of the respondents state that they do not use ASs based on AR in their maintenance environment. The following reasons are mentioned as the main obstacles for the implementation of digital ASs based on RT:

- No internet connection in the production environment
- Lack of acceptance by employees and managers
- Lack of know-how
- Insufficient cost-benefit ratio

## 1.2 Research Problem Statement and Questions

Maintenance is facing new challenges today due to the era of Industry 4.0. These challenges can be addressed with the support of ASs based on RT. The industry has recognised the potential of digital ASs, but the rate of their implementation in maintenance is still low. The problem is that the majority of the companies in the industry do not know which AS to choose for which purpose and which general requirements are essential for their implementation in maintenance.

To address the problem statement, the primary research question (PRQ) is:

***PRQ*** *How can a framework be designed to assist companies with the identification, selection and implementation of ASs based on RT to improve maintenance?*

To investigate the PRQ, the following three secondary research questions (SRQ) are developed. Answering the SRQ leads to knowledge and findings that serve to clarify the PRQ.

***SRQ1*** *What technologies and forms of ASs based on RT are currently available?*

***SRQ2*** *What generic types of activities are used to perform maintenance?*

***SRQ3*** *Which application characteristics and implementation requirements are necessary for successfully establishing ASs based on RT in maintenance?*

## 1.3 Research Objectives

To answer the SRQs and ultimately the PRQ, eight research objectives (RO) are developed for this thesis. The objectives serve to guide the study in the intended direction and to keep the focus on the aim of the research. Table 1.1 shows an overview of the ROs and in which chapter they are addressed.

## 1.4 Research Design and Methodology

The research is conducted based on steps from broad assumptions to detailed methods of data collection, analysis, and interpretation. The plan for conducting the research is defined as the research approach. The criteria considered for the selection of the approach are the nature of the research problem, the personal experiences of the researcher and the audience of the study (Creswell and Creswell 2018, p. 40).

Creswell and Creswell (2018, p. 41) advance three approaches to research: qualitative, quantitative and mixed methods. Qualitative research is characterised by an inductive

approach. The basis is the development of knowledge to establish theories and thus, to generate meaning. In contrast, quantitative research is characterised by a deductive approach. The basis is existing theories and the aim is to prove, disprove or give credibility to these theories. For this purpose, variables are measured and relationships between variables are studied to determine patterns and correlations. Mixed methods research combines the collection, analysis and interpretation of both qualitative and quantitative data (Dresch *et al.* 2015, pp. 17–18; Leavy 2017, p. 9).

Table 1.1: Research objectives

| Question | | Research Objective | Chapter |
|---|---|---|---|
| SRQ1 | i. | Review definitions of ASs based on RT. | 2.1 |
| | ii. | Analyse specific characteristics of ASs based on RT. | |
| SRQ2 | iii. | Review definitions of maintenance. | 2.2 |
| | iv. | Examine generic types of maintenance activities. | |
| SRQ3 | v. | Investigate the relationship between application characteristics and maintenance activities. | 2.3 & |
| | vi. | Investigate implementation requirements. | 3 |
| PRQ | vii. | Develop a framework for the application of ASs based on RT in maintenance. | 4 |
| | viii. | Validate the usability of the proposed framework. | 5 |

The research approach involves the interaction of three components: philosophical worldview, research design and research methods (Creswell and Creswell 2018, p. 43). The interaction of the components is shown in Figure 1.3 in the scope of a framework. The research approach for the thesis is outlined in the following sections based on the framework.

The philosophical worldview describes the view of how to develop knowledge. Based on several assumptions, a research philosophy is developed to underpin the research design and research methods (Saunders *et al.* 2015, pp. 124–125). This research employs the pragmatic worldview. The focus is on the research problem and the research questions, which are approached with practically applied research in order to obtain different views in a reflected way. The aim is to establish a pragmatic solution and not an abstract proposal. Pragmatism implies that a problem can be solved with multiple approaches and

is not limited to one reality, philosophy or method. Thus, the pragmatic worldview fits well with the mixed method approach.

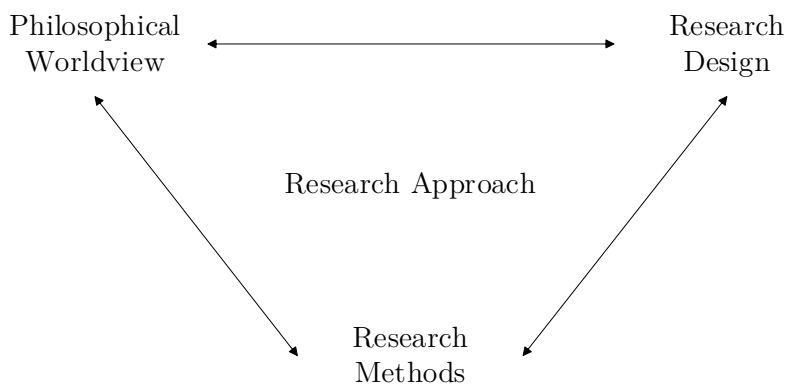



Figure 1.3: Research framework

Adopted from Creswell and Creswell (2018, p. 43)

Research designs represent strategies of inquiries within qualitative, quantitative and mixed method approaches that serve to guide procedures in a research study towards a specific direction (Creswell and Creswell 2018, p. 49). A mixed method design is utilised for this thesis as a research design since the research questions are of an exploratory and descriptive nature. To answer the exploratory research questions, qualitative research is necessary to gain a deeper understanding of the investigated factors. In contrast to this, the descriptive research questions require quantitative research.

Against the background of the research design, the research questions are answered in five research phases. The context and the structure of the research phases are geared towards the development of a conceptual framework to answer the PRQ. Jabareen (2009, p. 51) defines a conceptual framework as a "network, or 'a plane,' of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena". For the methodology, Jabareen (2009, pp. 53–55) suggests utilising multidisciplinary literature types, such as written texts identified through literature reviews and empirical data obtained through interviews, to form theories and ultimately, to create a conceptual framework. Subsequently, a validation of the proposed framework is recommended to evaluate its logic and rationale as well as if necessary implement adjustment.

Accordingly, Table 1.2 shows an overview of the research design and the related research method with the relevant chapter for this research.

Table 1.2: Overview of research design and methodology

| Phase | Approach | Process | Method | Chapter |
|---|---|---|---|---|
| 1 | Qualitative | Data collection | Background literature review | 2 |
| 2 | Quantitative | Data collection | Systematic literature review | 2 |
| 3 | Qualitative | Data collection | Semi-structured interviews | 3 |
| 4 | Qualitative | Data analysis | Conceptual framework | 4 |
| 5 | Qualitative | Validation | Case study | 5 |

## 1.5 Delimitations and Limitations

To ensure an appropriate scope for the thesis, the definition of the delimitations and the statement of the limitations is essential. In this context, delimitations represent the specific boundaries set for this research. In contrast, limitations are the external constraints that cannot be influenced.

This thesis is delimited by the development of a framework intended for application in industrial maintenance. However, the framework is not delimited to a specific industry and it is thus intended to be generic. In addition, the aim is to design a framework that can be used by any person regardless of their position in the company and their knowledge.

Regarding the limitations of the research, the development of the framework is limited by the data available in the literature and the information obtained through the interviews and the case study.

## 1.6 Thesis Outline

The structure of the thesis is derived from the defined research questions as well as research objectives and divided into four parts. The first part consists of chapter 1 and provides a research overview. The second part covers the data collection conducted in chapters 2 and 3. A framework is developed in chapter 4 and validated in chapter 5 in the scope of the third part. In the final part, conclusions are drawn within chapter 6. The structure of the thesis is shown in Figure 1.4.

**Chapter 1** In chapter 1, the research is introduced. The theoretical background leads to the problem statement. Based on this, the research questions and

objectives are defined. The research design and methodology as well as the delimitation and limitations are stated. The chapter concludes with the outline of this thesis.

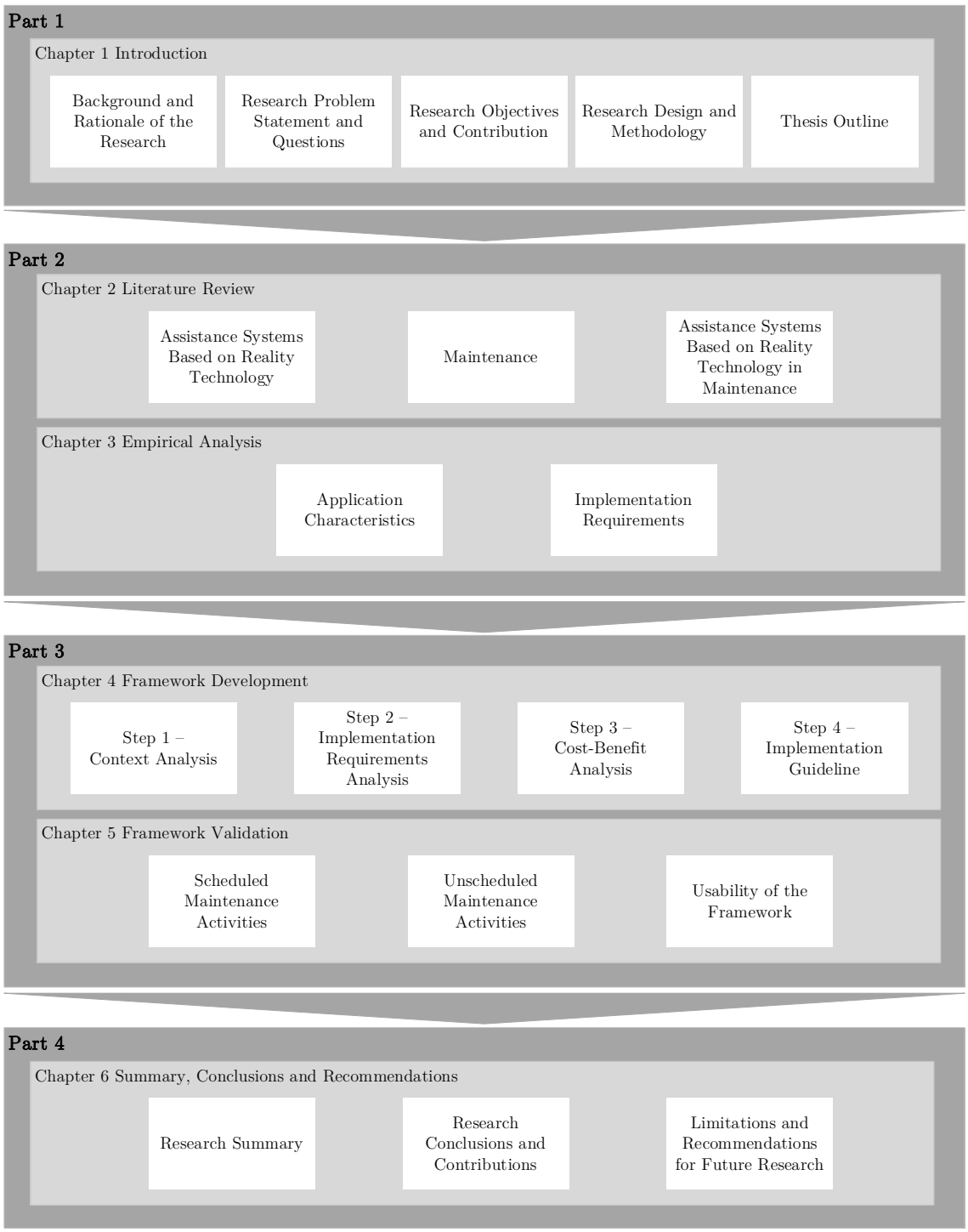



Figure 1.4: Structure of the thesis

**Chapter 2** In chapter 2, a background literature review is carried out on ASs based on RT and maintenance. On this basis, a systematic literature review is performed on ASs based on RT in maintenance. The result of the chapter is the collection of data available in the literature on application characteristics and implementation requirements.

**Chapter 3** In chapter 3, an empirical analysis is done on ASs based on RT in maintenance. For the analysis, semi-structured interviews are conducted with subject matter experts. The outcome of the chapter is the collection of empirical data on application characteristics and implementation requirements.

**Chapter 4** In chapter 4, a framework for the identification, selection and implementation of AS based on RT in maintenance is developed based on the data gathered in the literature review and the empirical analysis. The framework is referred to as *Decision Support Framework for Reality Technologies in Maintenance* (DSF-RTM) and is structured in four steps: context analysis, implementation requirements analysis, cost-benefit analysis and implementation guideline.

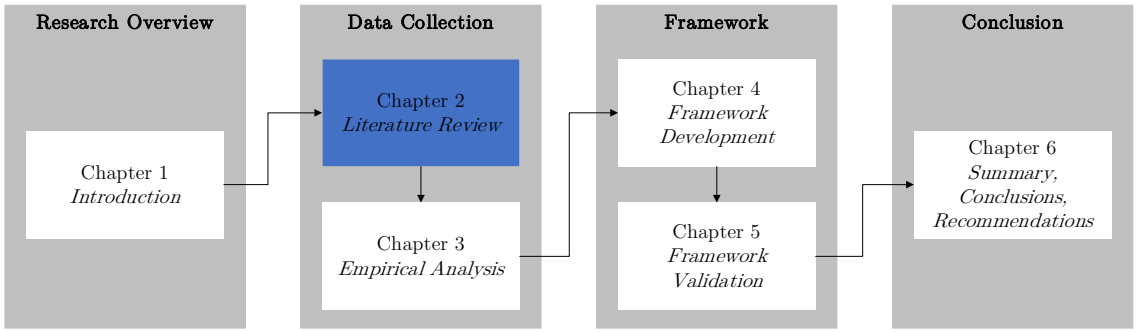
**Chapter 5** In chapter 5, the framework is validated. A case study is utilised as a method for the validation. In the scope of the case study, the framework is employed to identify, select and implement a suitable AS based on RT for the scheduled as well as unscheduled maintenance tasks of a milling machine.

**Chapter 6** In chapter 6, the research is summarised, conclusions are drawn and recommendations for future research opportunities are proposed.

## 1.7 Concluding Summary

This chapter introduces the research and provides background information on ASs based on RT and maintenance as well as the rationale of this research. The problem statement and research questions as well as the research objectives are defined. Subsequently, the applied research design and methodology as well as the delimitations and limitations are outlined. Finally, the outline of this thesis is presented.

# Chapter 2
# Literature Review




The objective of this chapter is to provide an overview of the relevant literature as a basis for this research. The first part of this chapter covers a background literature review for ASs based on RT to review definitions of ASs based on RT (RO1) and analyse the specific characteristics of ASs based on RT (RO2), thus answering SRQ1. The second part includes a background literature review for maintenance to review definitions of maintenance (RO3) and examine generic types of maintenance activities (RO4), thus answering SRQ2. Based on the background literature reviews, the third part concludes the chapter with a systematic literature review of ASs based on RT in maintenance to investigate the relationship between application characteristics and maintenance activities (RO5) as well as the necessary implementation requirements (RO6), thus providing answers for SRQ3.

## 2.1 Assistance Systems Based on Reality Technology

ASs represent a form of human-machine system that aims to support the user. The field of application for ASs is diverse and ranges from driver ASs to robots (Gerke 2015, p. 7). However, digital ASs, in particular, have recently gained in importance due to technological developments. Digital ASs support the user in active work processes and decision-making situations. The support provided by digital assistance can be sensory, cognitive or sensory-cognitive. Sensory assistance is the support of the sensory organs through, for example, image processing to enhance vision. In contrast, cognitive assistance is based on the provision of information through, for example, data visualisation. The combination of both types of support is cognitive-sensory assistance, which is enabled through ASs based on

RT. Those ASs offer various new possibilities (Apt *et al.* 2018, pp. 19–21; Henke *et al.* 2019, p. 20; Klapper *et al.* 2019, pp. 4–6).

In this context, the following sections introduce the concept of RT and proceed to discuss ASs based on RT.

In general, RTs connect the real world and the virtual world in various ways. The concept and the different types of RTs can be outlined using the reality-virtuality continuum developed by Milgram *et al.* (1994, p. 283). The continuum is shown in Figure 2.1.

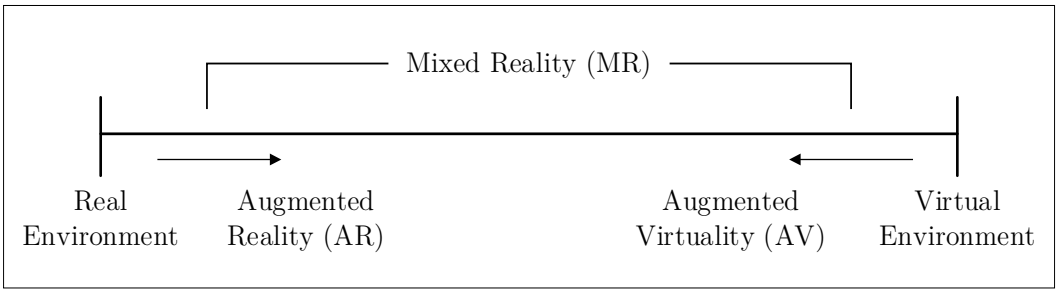



Figure 2.1: Simplified representation of the reality-virtuality continuum
Adopted from Milgram *et al.* (1994, p. 283)

The reality-virtuality continuum covers the range between the two extremes, the real environment and the virtual environment. The real environment describes reality per se, which the user can view either directly in person or indirectly through a video display (Milgram *et al.* 1994, p. 283). The virtual environment is a completely computer-generated environment, which the user can view through a display and interact with using a technological interface (Flavián *et al.* 2019, p. 548). In the range between the real environment and the virtual environment lie the different types of RT, which can be divided into AR, Augmented Virtuality (AV), Mixed Reality (MR) and VR (Farshid *et al.* 2018, p. 2).

*Augmented Reality*

AR is closer to the real environment and aims to enhance the view of the real world by overlaying virtual content. In the commonly accepted definition provided by Azuma (1997, p. 356), AR is described by the following three characteristics:

- Combines real and virtual objects
- Is interactive in real-time
- Registers in three dimensions (3D)

In this context, registration means coherently blending or aligning virtual content with real objects in 3D (Singh *et al.* 2014, p. 820).

Carmigniani *et al.* (2010, p. 342) summarise the definition of AR as a real-time view of the physical world enhanced by superimposing computer-generated information. Thus, AR represents an extension of the perspective on the real world (Kind *et al.* 2019, p. 22). The extension through virtual content can be enabled in two different ways. The virtual content is added onto either a direct or indirect view of the physical world. A direct view is defined as optical see-through AR and an indirect view as video see-through AR (Zhou *et al.* 2008, p. 197). Optical see-through AR allows a view of the real world through a transparent screen on which computer-generated information is superimposed. Video see-through AR allows a video view of the real world with computer-generated information overlaid (Sutherland *et al.* 2019, p. 39). Figure 2.2 shows the different types of visualisation of the real world through AR.

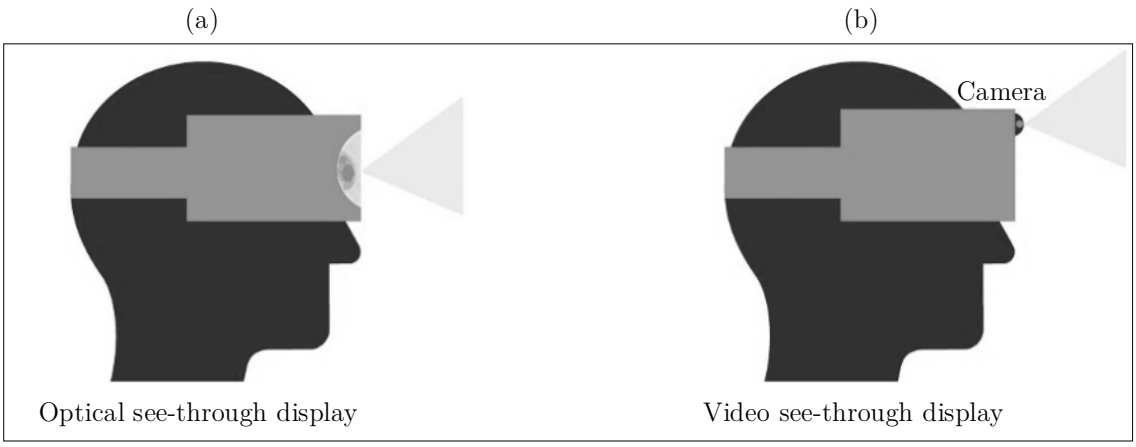



Figure 2.2: (a) Direct view or (b) indirect view of the real world through AR
Adopted from Etonam *et al.* (2019, p. 198)

*Augmented Virtuality*

In contrast, AV is closer to the virtual environment and aims to enhance the view of the virtual world by overlaying content from the real world. However, AV is still unexplored and not implemented in practice (Bekele *et al.* 2018, pp. 3–4; Carmigniani *et al.* 2010, p. 342; Flavián *et al.* 2019, p. 549; Sutherland *et al.* 2019, p. 39). Therefore, AV is not considered further in the scope of this thesis.

*Mixed Reality*

In literature, MR is generally described with the aim of blending the real environment and the virtual environment (Bekele *et al.* 2018, p. 3; Farshid *et al.* 2018, p. 4; Zind 2019, p. 20; Zobel *et al.* 2018, p. 25). However, inconsistencies arise in the detailed definition of MR. Milgram *et al.* (1994, p. 283) state that MR covers the range between the real environment and the virtual environment in the reality-virtuality continuum and they therefore classify

AR and AV as part of MR. In addition, many authors equate or do not clearly delineate the terminology related to AR and MR (Espíndola *et al.* 2010, p. 5; Snider *et al.* 2018, p. 5; Wolfartsberger *et al.* 2020, p. 10).

Flavián *et al.* (2019, p. 549) therefore emphasise that MR needs to be clearly distinguished and defined as a dimension between AR and AV. Thus, in contrast to AR, where virtual content is superimposed on the real environment, in MR the real elements and the virtual elements are blended in a way that they cannot be distinguished from each other. MR allows the user to interact with the real objects and the virtual objects in real-time as well as enabling the objects to interact with each other. In order to underline the difference between MR and AR, an example is given. In an MR environment, the user would need to bend down to see a virtual box under a real table. However, in an AR environment, the virtual box is superimposed onto the real table and is visible to the user without having to bend down (Flavián *et al.* 2019, p. 549).

*Virtual Reality*

VR applies purely to the virtual environment and aims to enhance perception and interaction with the virtual elements (Bekele *et al.* 2018, pp. 3–4; Carmigniani *et al.* 2010, p. 342). VR is defined by Kind *et al.* (2019, p. 20) as a "three-dimensional, completely computer-generated environment in which the user is fully immersed through suitable devices". Milgram *et al.* (1994, p. 283) refer to VR as a virtual environment and emphasise the total absence of the real world. According to Sherman and Craig (2019, p. 6), four key elements are essential for creating the experience of VR: virtual world, immersion, feedback and interactivity.

The virtual world per se should exist and as stated by Kind *et al.* (2019, p. 20) the user should be fully immersed. According to Raffler (2016), immersion defines the experience of being realistically immersed into a computer-generated environment. The perception of immersion is realised by substituting the five basic human sensory impressions – sight, hearing, touch, smell and taste – with virtual stimuli. In addition, the user should receive sensory feedback. If the user, for instance, looks to the right, the VR device should show the right side of the virtual environment. Furthermore, the final element is interactivity. The user should be able to modify and interact with the virtual environment (Muhanna 2015, pp. 347–348).

Regardless of the type, ASs based on RT include four fundamental hardware and software elements: output device, input device, tracking device and development platform. Those elements are described in detail in the following sections.

### 2.1.1 Output Devices

The purpose of output devices is to present the virtual content and create the illusion of a virtual world. The presentation or feedback of the virtual content can be provided through the five basic human sensory perceptions. In practice, however, the main focus is on visual, auditive and tactile output devices. Output devices based on smell and taste are still immature and not relevant in a practical context (Bekele *et al.* 2018, p. 8; Kind *et al.* 2019, p. 22; Sherman and Craig 2019, p. 261).

The illusion of AR, MR or VR cannot be created with every type of output device. The kind of RT generated by visual output devices depends on the type of display. In contrast, auditive and tactile devices are often additionally used to increase the immersive VR experience (Burdea *et al.* 1996, pp. 10–12; Kind *et al.* 2019, pp. 27–28). However, the sole application of those devices represents an enhancement of the real environment. Therefore, auditive and tactile devices are defined as devices capable of creating AR in the scope of this thesis.

Table 2.1 shows an overview of which types of output devices are capable of creating which type of RT. In the following sections, only the output devices commonly applied in practice are described.

Table 2.1: Possible output devices depending on the type of RT

| | AR | MR | VR |
|---|---|---|---|
| **Visual Output Device** | | | |
| Head-mounted Display | X | X | X |
| Hand-held Display | X | | X |
| Screen-based Display | X | | X |
| Projector-based Display | X | | X |
| **Auditive Output Device** | X | | |
| **Tactile Output Device** | X | | |

#### 2.1.1.1 Visual Output Devices

The visual presentation of virtual content is possible through different types of displays: head-mounted displays (HMD), hand-held displays (HHD), screen-based displays or projector-based displays (Bekele *et al.* 2018, p. 8; Carmigniani *et al.* 2010, p. 349; Kind *et al.* 2019, p. 22; Palmarini *et al.* 2018, p. 218; Zhou *et al.* 2008, p. 197). The various types of displays are further discussed in the following sections.

*Head-mounted Display*

One type of visual output devices are HMDs. Carmigniani *et al.* (2010, p. 346) define a HMD as a "display device worn on the head or as part of a helmet". HMDs can be used for the display of AR, MR and VR.

In general, HMDs capable of creating AR are referred to as smart glasses or AR glasses (Wursthorn 2017, p. 23; Zobel *et al.* 2018, p. 25). Based on the presentation of the real world, optical see-through HMDs and video see-through HMDs can be distinguished (Zhou *et al.* 2008, p. 197). Optical see-through HMDs allow the user to see the real world through semi-transparent mirrors mounted directly in front of the eyes of the user. The mirrors are used as displays to reflect virtual content into the eyes of the users using an optical prism and a mini-projector. Video see-through HMDs allow the user a video view of the real world by capturing the real world with miniature video cameras positioned on the head gear. The computer-generated content is displayed on top of the video view (Rhodes and Allen 2014, p. 3; Rolland *et al.* 1994, p. 293). Furthermore, a distinction between monocular and binocular HMDs can be drawn. A monocular see-through HMD displays content in one eye and a binocular HMD in both eyes (Catanzaro *et al.* 2006, p. 1). A well-known example of a monocular optical see-through HMD is the Google Glass and for a binocular optical see-through HMD the Epson Moverio (Delabrida *et al.* 2016, p. 253). Both types of HMDs are shown in Figure 2.3.


Figure 2.3: (a) Google Glass Enterprise Edition 2 and (b) Epson Moverio BT-350 (Glass 2020; Epson 2020b)

Currently, the only way to experience MR is through HMDs. Those devices are often referred to as MR glasses. There are very few HMDs available on the market that are capable of generating MR and which would be relevant for a practical application (Flavián *et al.* 2019, p. 549; Zobel *et al.* 2018, p. 27). Therefore, the concept of this type of HMD is explained using a specific model. The most mature model is the Microsoft HoloLens, which is a lightweight, wearable headset with an optical see-through display (Hanna *et al.* 2018, p. 639; Miller *et al.* 2020, p. 1742). In contrast to HMDs capable of creating AR, the display

covers not a part but the entire field of view (FOV) of the user. Holograms or 3D objects are generated and integrated into the real-time environment of the user for the MR experience. A variety of sensors allow the user to interact with the virtual content through gestures, speech and head movements (Zobel *et al.* 2018, p. 27). Figure 2.4 shows how the user can interact with a virtual chair using his hands. Furthermore, the application area of the Microsoft HoloLens is for instance in healthcare, manufacturing or construction (Bahri *et al.* 2019, p. 235; Miller *et al.* 2020, p. 1742; Zuo *et al.* 2020, p. 193).

Figure 2.4: Possible interaction with a virtual object using the Microsoft HoloLens 2 (Microsoft 2020b)

The immersive experience of VR is possible through HMDs, which are also referred to as VR glasses. The difference from HMDs capable of creating AR or MR is the non-transparent display and a fully closed housing of the glasses, which is shown with the Oculus Quest in Figure 2.5. Thus, the virtual environment is displayed in the FOV of the user without any influences from the real world. To achieve an authentic presentation of the virtual world, various sensors are applied. The sensors register the eye and head movements of the user to adapt the virtual content accordingly (Kind *et al.* 2019, p. 26; Zobel *et al.* 2018, pp. 22–23). In addition, the position of the user is tracked to ensure a coherent perspective of the virtual environment (Bekele *et al.* 2018, p. 9). HMDs capable of creating VR are well established in the entertainment industry and especially in the gaming industry. Another widespread field of application is in training or further education (Kind *et al.* 2019, p. 21).

Figure 2.5: Oculus Quest
(Oculus 2020b)

*Hand-held Display*

Carmigniani *et al.* (2010, p. 347) define HHDs as "small computing devices with a display that users can hold in their hands". The display shows the virtual content, with which the user interacts mainly by touch (Bekele *et al.* 2018, p. 12). Besides the display, the components of an HHD are a processor, a memory card and several built-in sensors such as a camera, GPS and accelerometer. HHDs are in the form of smartphones or tablets capable of creating AR and VR experiences (Chowdhury *et al.* 2013, p. 419; Sherman and Craig 2019, p. 341).

The presentation of AR on an HHD is based on the video see-through approach. The display illustrates a video view of the real environment captured by integrated cameras and overlaid with virtual content (Bimber and Raskar 2005, p. 79). HHDs are used in the field of, for example, gaming, marketing, education or manufacturing (Sääski *et al.* 2008, pp. 398–399; Chowdhury *et al.* 2013, p. 419; Wagner and Schmalstieg 2006, p. 35).

The experience of VR through an HHD is non-immersive. The user can view the virtual environment on the display and the real world at the same time. However, the two environments are not connected to each other (Bekele *et al.* 2018, p. 12). The perspective of the virtual world is adjusted as the user moves the HHD (Sherman and Craig 2019, p. 338). This type of HHD is mainly utilised for simulation or training tasks (Kind *et al.* 2019, p. 21).

*Screen-based Display*

In contrast to the mobile applications HMDs and HHDs, screen-based displays are a stationary application. Desktop-based displays can be used to generate AR and VR experiences.

For the creation of a screen-based AR experience, the real environment is captured using one or multiple cameras and illustrated on a computer screen. The virtual content is overlaid with the video view of the real world (Carmigniani *et al.* 2010, p. 348; Palmarini *et al.* 2018, p. 222). Figure 2.6 shows an example of this type of display for AR. A physical dinosaur footprint is captured with a camera and displayed on a screen showing the virtual locomotion of a dinosaur (Bimber and Raskar 2005, pp. 83–84).


Figure 2.6: Screen-based AR – virtual overlay of a footprint
(Bimber and Raskar 2005, p. 84)

The screen-based experience of VR is non-immersive (Bekele *et al.* 2018, p. 12). This type of visual presentation is also known as fish tank VR. The concept is to display the 3D virtual world on the two-dimensional (2D) screen of a computer. Thus, the user is able to view the virtual world through a screen like a world inside an aquarium through its glass. The user can fully explore the virtual world and, for instance, look over and under virtual objects, but is unable to enter the environment and be fully immersed. In a non-immersive VR experience adapting the scene of the virtual world to the movement of the user is possible but not necessary. Thus, for a coherent scene rendering, the head of the user is tracked. The location and not the position of the head is essential since the user has to look at the screen. Optical tracking technologies such as a camera are sufficient for this purpose and in most cases integrated into the computer system (Muhanna 2015, p. 350; Sherman and Craig 2019, pp. 301–302).

*Projector-based Display*

Another type of visual output device is projectors, which can be used to create AR and VR. Projector-based displays that allow AR experiences are referred to as spatial augmented reality (SAR) displays. The VR applications that are generated by projectors are based on stereoscopic projection systems and the so-called cave automatic virtual environment (CAVE).

The general characteristic of SAR displays is that the virtual content is directly integrated into the real environment and not into the FOV of the user or on a screen (Raskar *et al.* 1998, p. 1). The virtual content is directly displayed onto the surface of the physical object using one or more projectors. Thus, the concept of an SAR display is called direct augmentation. An example is shown in Figure 2.7. A coloured pattern is projected onto a silver car through six projectors mounted on the ceiling (Marner *et al.* 2014, p. 75). Furthermore, SAR display allows several users to experience AR at the same time and is therefore widely implemented in universities, laboratories or museums (Bimber and Raskar 2005, pp. 7–8; Gervais *et al.* 2015, pp. 381–382).

Figure 2.7: Direct augmentation – projection of a coloured pattern onto a silver car (Marner *et al.* 2014, p. 75)

Another projector-based application is enabled through stereoscopic projection systems which allow semi-immersive experiences of VR. The virtual world is presented on a 3D display or a large stereoscopic screen through a projection system. Thus, the user has the impression of being slightly immersed into a virtual environment (Arendarski *et al.* 2008, p. 484; Li *et al.* 2012, p. 80). Similar to SAR displays, stereoscopic projection systems can be applied for a large number of users and are therefore widespread in museums. Tracking is not intended for multiple user experiences. However, tracking is useful if the system is

used by a single person in order to adjust the perspective of the virtual world (Bekele *et al.* 2018, p. 12).

In contrast, CAVE is a projector-based application which allows immersive VR experiences. A CAVE is a room in which all four walls, the ceiling and the floor are 3D projection screens (Maciejewski *et al.* 2020, p. 2). The user has to wear special glasses in order to have a stereoscopic view of the virtual content on the screens. In addition, sensors are integrated into the glasses to track the position of the user and adapt the virtual content according to the perspective of the user (Muhanna 2015, p. 353). The application of a CAVE allows the user to be inside a virtual environment and interact with other users in a natural way (Bekele *et al.* 2018, p. 13). The CAVE is often utilised in the military, education and healthcare sector (Muhanna 2015, p. 355).

#### 2.1.1.2 Auditive Output Devices

Burdea *et al.* (1996, p. 10) state that visual output devices can be complemented with auditive output devices in order to increase the degree of immersion. However, auditive output devices can be a viable alternative for visual output devices if the visual presentation is of poor quality or is impaired by a bright environment (Sherman and Craig 2019, p. 344).

Auditive feedback can be realised in form of headphones which are either integrated into HMDs or worn separately (Kind *et al.* 2019, p. 27). Headphones allow the user to be isolated from the sounds of the real world or superimpose natural sounds with virtual sounds. In addition, loudspeakers can be applied in order to provide auditive feedback for multiple users at the same time. The loudspeakers are either integrated into most devices such as smartphones or tablets, or otherwise separate loudspeakers can be used (Sherman and Craig 2019, pp. 353–355).

Muhanna (2015, pp. 354–355) introduces the idea of using loudspeakers in a CAVE to increase the degree of immersion. The loudspeakers are placed in specific positions inside and outside the CAVE in order to enhance the visual illusion by imitating sounds from the real world.

#### 2.1.1.3 Tactile Output Devices

Besides visual and auditive output devices, tactile systems are another possibility for increasing the immersive and authentic experience of a virtual environment. Tactile output devices stimulate the sense of touch or kinaesthetic channels by rendering mechanical signals (Bermejo and Hui 2017, p. 2; Khalid *et al.* 2013, p. 140). Sherman and Craig (2019, p. 357) emphasise that tactile feedback can be categorised according to the type of stimulus: tactile feedback and force feedback. Tactile feedback includes the sensation of touching a surface and feeling its roughness, stiffness, texture or temperature. The sensation is simulated on the skin by heat, pressure, vibration or pain. In contrast, force feedback refers to the sensation of feeling resistance and is perceived by the end sensory organs of

muscles, tendons and joints. Thus, for example, realistic tactile experiences of virtual objects can be realised. The user can receive tactical feedback by feeling the roughness of the virtual texture or force feedback by feeling the weight of the virtual object (Bermejo and Hui 2017, pp. 2–3; O'Malley and Gupta 2008, p. 43; Preim and Botha 2014, p. 797).

In general, the technology and the configuration of tactile devices are very complex and still immature. Currently, only the so-called vibrotactile bracelet is used commercially in the industry. Figure 2.8 shows a vibrotactile bracelet and its components. Those devices apply tactile feedback in form of vibration stimuli to the arm, forearm or wrist of the user. The vibration stimuli are generated by six actuators which are integrated in the bracelet at equal distance from each other. The intensity of each vibration actuator can be adjusted individually, thus, allowing the user to experience different sensations such as rotational or translational movements (Webel *et al.* 2013, p. 400). Furthermore, vibrotactile bracelets are both output devices and input devices. The function as an input device is described in section 2.1.2.


Figure 2.8: Vibrotactile bracelet
(Webel *et al.* 2013, p. 400)

### 2.1.2 Input Devices

The purpose of input devices is to convey information to the AS and enable interaction with the virtual content or the virtual world (Kind *et al.* 2019, p. 22). The selection of an input device can be determined by the type of output device. Many output devices have embedded input devices or require certain input devices to function properly. In addition, the selection of an input device can depend on the conditions of an application. If a requirement for the user is to be hands-free, input devices that need to be held with the hands or include unnatural gestures can be excluded. Furthermore, more than one input device is in most cases employed for the application of an AS (Carmigniani *et al.* 2010, p. 350).

Sherman and Craig (2019, pp. 193–194) note that among other qualities, input devices can be distinguished by whether the user input is passive or active. For the authentic illusion of virtual content or a virtual world, the AS is required to track the user. The tracking information is an input to the AS but is provided by the user, not in an active but in a passive way. In contrast to this, active input describes that the user indicates his intentions by deliberate actions.

Passive input devices that solely aim to track the user through sensors or cameras are discussed in section 2.1.3. Thus, the following sections focus on passive input devices employed for tracking and interaction as well as active input devices. In addition, only the input devices commonly used in practice are presented.

As with the output devices, a distinction can be made between visual, auditive and tactile input devices. Table 2.2 shows an overview of the types of input devices and whether they are based on active or passive input.

Table 2.2: Types of input devices

| **Visual** | **Auditive** | **Tactile** | |
|---|---|---|---|
| **Passive Input** | **Active Input** | **Active Input** | **Passive Input** |
| – Camera | – Microphone | – PC mouse/ space mouse<br>– Keyboard<br>– Buttons<br>– Touch surface/ screen<br>– Joystick<br>– Controller | – Data glove<br>– Vibrotactile bracelet |

Passive visual input can be provided by cameras, which are used for screen-based AR experiences or are embedded in certain models of HMDs. For screen-based AR applications, a camera is employed to capture the user or an object. The captured images are overlaid with virtual content on a screen (Bimber and Raskar 2005, p. 84; Kind *et al.* 2019, p. 22). Furthermore, the camera embedded in, for example, the Microsoft HoloLens is used for the tracking of gaze, gestures or head movements and allows the user to interact with the virtual content shown on the display (Zobel *et al.* 2018, p. 27).

Active input can be carried out through speech using microphones. The approach is feasible for ASs with speech recognition systems. Those systems classify audio sounds to specific command strings, which are linked to pre-programmed possible responses. Auditive input

devices are suitable for applications that require the user to be hands-free (Sherman and Craig 2019, pp. 252–254). Most HMDs and HHDs have embedded microphones (Miller *et al.* 2020, p. 1743; Rhodes and Allen 2014, p. 3).

Another type of active input is enabled by tactile devices. The conventional forms are PC mice and space mice as well as keyboards which are primarily used for screen-based applications (Bekele *et al.* 2018, p. 10; Bimber and Raskar 2005, p. 84). Buttons are another conventional and at the same time simple form of tactile input (Sherman and Craig 2019, p. 205). For example, certain models of HMDs generating AR or MR have buttons attached to the frame (Microsoft 2020b). However, other models of these types of HMDs have a touch surface instead of buttons. The user can indicate his intentions by moving or tapping his fingers on the surface (Glass 2020). The same concept applies to a touch screen, which is the general input device for HHDs (Chowdhury *et al.* 2013, p. 419).

Furthermore, joysticks and controllers can be utilised as active tactile input devices. A distinction can be made between non-tracked and tracked devices. Non-tracked joysticks and controllers are solely employed for interaction and used with HMDs capable of creating AR (Sherman and Craig 2019, p. 194). The device and the HMD can be connected by a cable (Epson 2020b). Tracked joysticks and controllers combine the interaction and tracking function. These types of devices are especially utilised for SAR displays or immersive VR experience through a HMD or in a CAVE (Muhanna 2015, p. 353; Thomas *et al.* 2014, p. 48).

For a more intuitive and natural interaction, passive tactile input devices such as data gloves and vibrotactile bracelets can be applied (Bekele *et al.* 2018, p. 10). Data gloves and vibrotactile bracelets have embedded sensors that convey the hand or arm position and movements of the user to the AS (Sherman and Craig 2019, p. 39). The aim is to provide a higher degree of flexibility to the user. These kinds of devices are therefore applied with stereoscopic projection systems, in a CAVE or in addition to an HHD (Li *et al.* 2012, p. 80; Muhanna 2015, p. 355; Webel *et al.* 2013, p. 400).

### 2.1.3 Tracking Devices

ASs based on RT employ tracking devices to determine the relative six degrees of freedom (DoF) pose: three DoF – x- , y- and z-axis – for the position and three DoF – roll, pitch and yaw angle – for the orientation of the user (Cutolo *et al.* 2020, p. 2). Ong *et al.* (2008, p. 2709) underline that accurate tracking of the location and movements of the user in reference to the surroundings is a crucial requirement for an RT-based application.

However, the ultimate purpose of tracking is different depending on the type of RT. In AR and MR, tracking is used to register the virtual content coherently to the real-world view. In VR, on the other hand, the purpose of tracking is to correct the perspective on the virtual world according to the perspective of the user (Bekele *et al.* 2018, p. 5; Cao *et al.*

2020, p. 257). Rigby and Smith (2013, p. 6) emphasise that tracking is not limited to calibration, a one-time adjustment, but includes a continuous re-evaluation.

In general, tracking devices can be classified into sensor-based tracking and camera-based tracking. Multiple tracking devices can be used for an RT-based application. The combination of both types of devices is referred to as hybrid tracking (Bekele *et al.* 2018, p. 7; Zhou *et al.* 2008, p. 196).

*Sensor-based Tracking*

Sensor-based tracking techniques employ electromagnetic, acoustic, inertial, optical or mechanical sensors (Zhou *et al.* 2008, p. 195). The approach of electromagnetic tracking is to monitor the position of the user by measuring the intensity of a magnetic field within a predefined area in various directions and orientations. In contrast, acoustic tracking is based on calculating the time required for ultrasonic waves to travel from an emitter to a sensor. The emitter is placed on both the output device and the input device employed by the user if the point of view and the interaction are tracked. Inertial tracking techniques utilise gyroscopes as well as accelerometers and function like a navigation system. The gyroscope measures the rotation and the accelerometers capture the motion of the user in order to determine pose and velocity (Bekele *et al.* 2018, pp. 6–7). Furthermore, optical tracking techniques enable the position of the user to be determined using visual information. The visual information can be acquired through various methods. The most common method is to implement one or more cameras at a fixed position (Sherman and Craig 2019, pp. 210–213). In contrast to the other tracking techniques, mechanical tracking is based on a physical linkage between the user and a fixed reference point. The physical connection is, for example, a telescopic boom or arm. The position and orientation of the user are identified using forward or inverse kinematics (Ong *et al.* 2008, p. 2709). An example of physical tracking is shown in Figure 2.9. A virtual vehicle is displayed on a tablet, which is mounted on a mechanical telescopic arm. The user can steer the tablet through the room to move around and through the virtual vehicle (Art+Com 2020; Sherman and Craig 2019, p. 210).

*Camera-based Tracking*

In literature, no well-defined classification of camera-based tracking is established. In general, however, a distinction can be drawn between marker-based tracking and vision-based tracking. Vision-based tracking is also known as markerless tracking (Bekele *et al.* 2018, p. 6; Pressigout and Marchand 2006, p. 52; Rigby and Smith 2013, pp. 6–7; Viyanon *et al.* 2017, p. 2; Zhou *et al.* 2008, p. 195).

Marker-based tracking techniques utilise a camera to capture a digital image of easily recognisable markers placed in the real world (Rigby and Smith 2013, p. 6). The digital image is analysed to determine the pose of the markers relative to the camera. Thus, the

virtual content can be superimposed on the digital image of the real world (Viyanon *et al.* 2017, p. 3).

Figure 2.9: Mechanical tracking of a tablet
(Art+Com 2020)

In contrast, vision-based tracking techniques determine the camera pose by detecting natural geometric features on the digital image of the real world compared to a template image (Cao *et al.* 2020, p. 257). A distinction can be made between a feature-based and model-based tracking technique: the feature-based approach identifies 2D features and the model-based approach uses an explicit model such as a 2D model or CAD model (Pressigout and Marchand 2006, p. 52).

### 2.1.4 Development Platforms

Data acquired through input devices and tracking devices are processed to create virtual content that enhances or overlays the perceived reality (Kind *et al.* 2019, p. 23). For this purpose, one or more of the following platforms can be employed to develop the application of an AS based on RT:

- Programming languages
- Game engines
- Software platforms
- Software development kits (SDK)

Programming languages are used for the development of applications from the ground up. The widespread programming languages for the application of RT are C#, C++, Java, JavaScript, Python and Swift. In addition, compatible libraries of functions can be applied. For example, OpenCV for image processing and computer vision or OpenGL for 2D or 3D graphics rendering (Palmarini *et al.* 2018, p. 223).

Convenient tools to develop applications are so-called game engines, which are real-time 3D development platforms. The most common game engines utilised for AR, MR and VR applications are the Unity Engine from Unity and Unreal Engine from EpicGames. The user-friendly editors allow the rapid development of applications with a minimum knowledge of programming languages. The Unity Engine is based on C# and the Unreal Engine on C++ (Anthes *et al.* 2016, p. 9; Miller *et al.* 2020, p. 1743; Palmarini *et al.* 2018, p. 223). The target applications are desktop computers or mobile platforms based on Windows, macOS or Linux as well as mobile devices based on iOS or Android (Epic Games 2020; Unity 2020b).

Other tools for the development of an application are software platforms. These platforms provide content for applications either related to the type of RT or the hardware manufacturer. For example, ARToolKit is useful for the creation of AR experiences. This simple tool allows any developer with or without previous knowledge to create AR applications (Ong *et al.* 2008, p. 2713). Moreover, many manufacturers offer platforms that are linked to their devices or systems. For example, Oculus provides a software platform for their HMDs Oculus Rift and Oculus Quest (Kind *et al.* 2019, p. 24).

As an addition to the other tools, SDKs can be utilised. SDKs are collections of programming tools and libraries. The selection of an SDK depends on the required features and the chosen platform (Palmarini *et al.* 2018, p. 223). For example, the most common SDK for creating AR experiences with mobile devices is Vuforia. Using computer vision algorithms, 3D objects can be tracked in real-time and overlaid with virtual content (Miller *et al.* 2020, p. 1744). Furthermore, Oculus offers SDKs that support the creation of avatars and enable audio experiences in VR applications through Oculus devices (Oculus 2020a).

## 2.2 Maintenance

The German Institute for Standardisation (DIN31051, p. 4) describes maintenance in the DIN 31051 with the following definition:

> *Maintenance is the "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function".*

In this context, an item is a "part, component, device, subsystem, functional unit, equipment or system that can be individually described and considered" (DIN EN13306,

p. 12). The usage of an item leads to unavoidable wear due to chemical and physical processes. Typical examples are corrosion, fatigue and friction (Matyas 2019, p. 34; Ryll and Freund 2010, p. 27).

In general, the main objectives of maintenance are safety, availability, reliability and value preservation, which are achieved equally or in specific prioritisation (Leidinger 2017, p. 15). According to Siener and Aurich (2011, p. 15), availability and reliability are the primary maintenance objectives. The first objective includes the requirement to avoid any risk from the system to health, safety, security and the environment. Legal regulations define the type, scope and frequency of recurrent inspections regarding the condition of the respective system and its safety equipment. The objectives of availability, reliability and value preservation are internal goals of the operator and are defined by criteria of overall economic efficiency (Leidinger 2017, pp. 15–16). The German Institute for Standardisation (DIN EN13306, pp. 15–17) defines the objective of availability as the "ability of an item to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided" and the objective of reliability as the "ability of an item to perform a required function under given conditions for a given time interval". The last objective describes the value preservation of the plant, achieved by a long remaining life expectancy (Leidinger 2017, p. 15). Furthermore, Matyas (2019, p. 32) adds cost minimisation as another objective of maintenance. The costs refer, for example, to material, personnel or downtime and consequential time.

The main objectives are achieved through the four basic maintenance measures: Service, inspection, repair and improvement. The four maintenance measures are defined according to DIN 31051 and described in the following sections.

*Service*

Service includes all "measures taken to delay the reduction of the existing wear margin" (DIN31051, p. 5). The wear margin describes the margin for the functional performance of an item. The course of the wear margin during a certain period of time is shown in Figure 2.10.

In the initial state, a new item has the maximum wear margin and therefore, for example, a maximum level of performance or accuracy. The wear starts with the commissioning of the item and the margin is reduced resulting in lower performance or rotational speed deviation. Once a predefined wear limit is exceeded, maintenance measures are performed and weak points are eliminated. Full utilisation of the wear margin results in failure of the item (DIN31051, p. 8; Matyas 2019, p. 34). Therefore, the objective of service is to preserve the initial state of an item and thus to increase its service life and to guarantee occupational safety (Matyas 2019, p. 38). Sub-measures of service are, for example, cleaning, lubrication or replacement (Strunz 2012, p. 44).

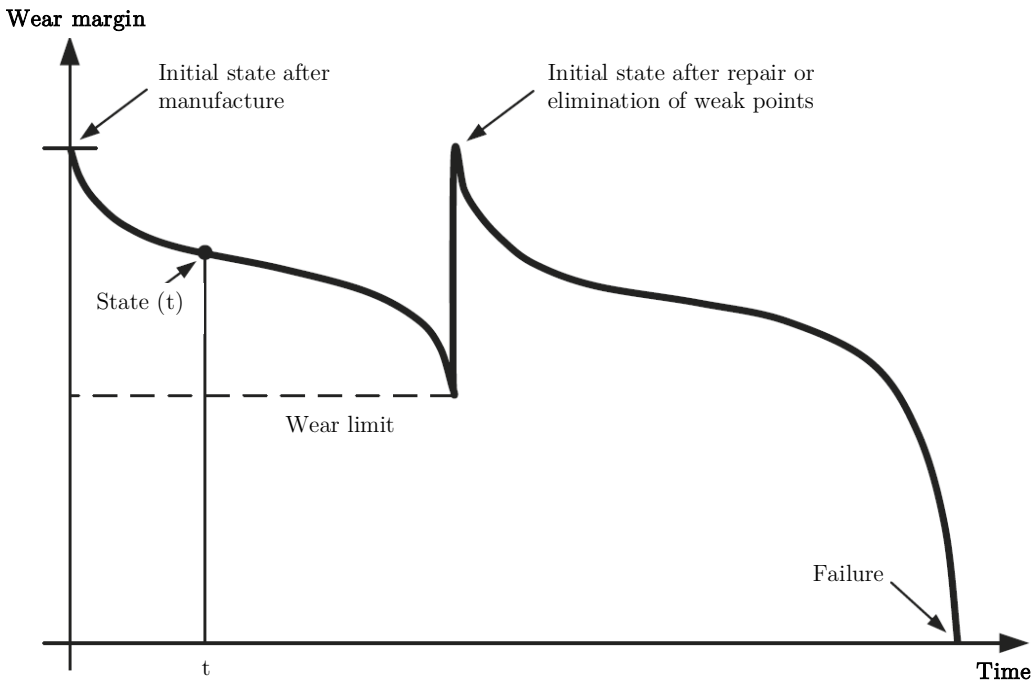



Figure 2.10: Course of the wear margin
Adopted from Matyas (2019, p. 34)

*Inspection*

Inspection is the "examination for conformity by measuring, observing, or testing the relevant characteristics of an item" (DIN EN13306, p. 41). To enable a direct comparison between the initial state and the actual condition, the determination of the condition always has to take place under constant operating and environmental conditions. In addition, the scales and tolerances have to be specified in the same dimension as the initial state. Sub-measures of inspection include determining the condition of additional technical equipment, assessing the condition, or conducting error analyses (Matyas 2019, p. 35).

*Repair*

Repair covers the "physical action taken to restore the required function of a faulty item" (DIN EN13306, p. 44). Repair can be divided into the sub-measures of repair by processing the faulty item or replace by restoring the faulty item (Matyas 2019, p. 39; Strunz 2012, p. 68).

*Improvement*

Improvement describes the "combination of all technical, administrative and managerial actions, intended to ameliorate the intrinsic reliability and/ or maintainability and/ or safety of an item, without changing the original function" (DIN EN13306, p. 36). In this regard, the identification and elimination of weak points are important, since process

stability is affected and costs are increased. A weak point is a unit conspicuous by repeated functional failure. The prerequisite for the improvement of a weak point is the technical and economic feasibility (Strunz 2012, p. 70).

The planning and execution of maintenance measures require a systematic approach and the evaluation of relevant input information. The design of the processes is determined to a large extent by the selected maintenance strategy (Ryll and Freund 2010, p. 26).

### 2.2.1 Maintenance Strategy

The maintenance strategy is a "management method used in order to achieve the maintenance objectives" (DIN EN13306, p. 9). The maintenance strategy defines which maintenance tasks are performed for which maintenance objects, at what time and with what frequency. For the selection of the maintenance strategy the most important criteria are technical, safety, production-relevant, economic and object-specific criteria (VDI-Richtlinie2895, p. 26).

Maintenance strategies have evolved from a reactive to a proactive approach. The development of maintenance and its strategies are described based on the maturity model established by Mühlnickel *et al.* (2018, p. 353). The maturity model is illustrated in Figure 2.11.

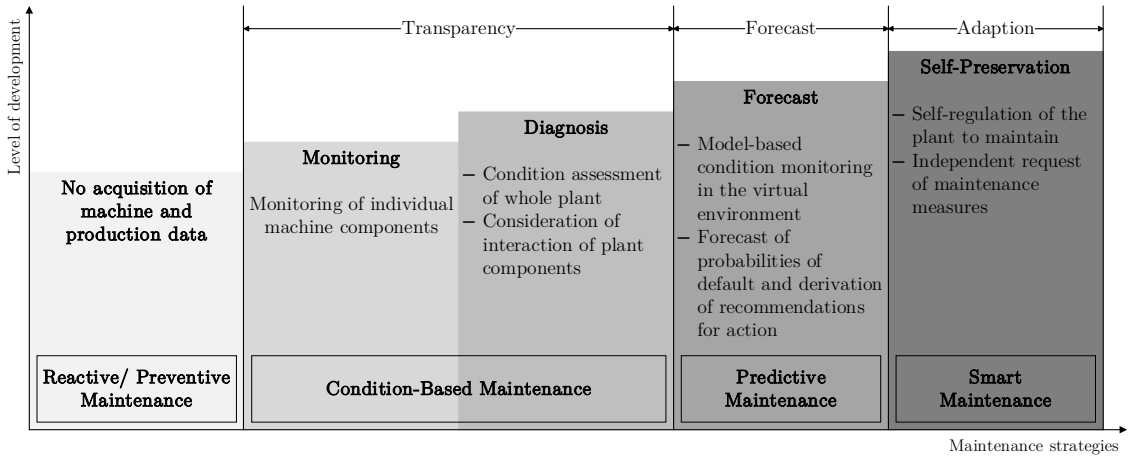



Figure 2.11: Development of maintenance strategies
Adopted from Mühlnickel *et al.* (2018, p. 353)

In the initial form of maintenance, no machine or production data are gathered. The two maintenance strategies, reactive and preventive maintenance can be distinguished (Mühlnickel *et al.* 2018, p. 352).

*Reactive Maintenance*

Reactive maintenance is also known as run-to-failure, failure-based or breakdown maintenance (Ryll and Freund 2010, p. 41; Starr *et al.* 2010, p. 11; Strunz 2012, p. 296). This type of maintenance is a reaction which follows only after the failure of an item or based on a defined damage limit. Intermediate maintenance measures are not performed (Leidinger 2017, p. 20). Since the item is operated until an event of damage, the wear margin can be utilised to its full extent. In addition, no planning effort is required, but the event of damage is a sudden and unplanned incident. Consequently, the necessary measures must be executed under time pressure and with a lot of resources such as personnel, spare parts or tools. Furthermore, consequential damage to other items may occur. In contrast to other maintenance strategies, reactive maintenance leads to the highest downtime and costs (Ryll and Freund 2010, p. 41). The concept of reactive maintenance is applied only in exceptional situations in the modern industrial environment, for instance if the respective items are redundant or of minor importance for the production process (Matyas 2019, p. 121).

*Preventive Maintenance*

In literature, preventive maintenance is also referred to as time-based maintenance (Matyas 2019, p. 122; Leidinger 2017, p. 16). The German Institute for Standardisation (DIN EN13306, p. 34) defines preventive maintenance as "maintenance carried out intended to assess and/or to mitigate degradation and reduce the probability of failure of an item". The objective is to reduce the failure rate by performing maintenance measures at periodic predefined intervals, regardless of the actual condition of the item (Starr *et al.* 2010, p. 12). The definition of the interval can be derived from the specific performance or output quantity of production. In contrast to reactive maintenance, the downtime is lower due to the lower probability of default and the ability to plan preparatory measures. However, the risk exists of replacing items too early and not using the wear margin efficiently. The implementation of preventive maintenance is useful if a failure of the item causes a high production loss or an increased hazard potential for people and the environment (Strunz 2012, pp. 296–297).

The next two stages of development, monitoring and diagnosis, can be summarised under the category of transparency. The core of both development stages is the accurate representation of the machine or the plant status. The development stage of condition-based monitoring aims to minimise machine failures and production downtime by implementing machine monitoring. In the third development stage, the diagnosis, the entire plant is considered, not individual components. Due to the increasing complexity of plants, the interdependencies between individual plant components have to be included. The principles of monitoring and diagnosis are the basis for the condition-based maintenance strategy (Mühlnickel *et al.* 2018, pp. 352–355).

*Condition-based Maintenance*

Condition-based maintenance is defined as a type of "preventive maintenance which includes assessment of physical conditions, analysis and the possible ensuing maintenance actions" (DIN EN13306, p. 35). Maintenance actions are initiated according to the wear margin of a maintenance object. Suitable monitoring and diagnostic systems are required to detect deviations from the required performance at an early stage. Thus, the maintenance intervals are adapted to the wear margin and optimally utilised. The main tool is the condition monitoring system. The manual form of condition monitoring is performed by maintenance personnel through regular inspections with recordings and evaluation of condition relevant parameters (Ryll and Freund 2010, p. 31).

In the automated form, sensors are used to monitor and evaluate individual or combined acoustic, mechanical, thermal or electrical measured variables. The application of automated condition monitoring systems is suitable for automated and interlinked production facilities with a high degree of complexity and a high probability of failure, as they have a greater need for reliability and availability (Matyas 2019, p. 128). Compared to reactive maintenance, condition-based maintenance offers the advantage of reducing the probability of failure, downtimes due to malfunctions and the risk of consequential damage. In addition, the wear margin is utilised to a high degree. In contrast to preventive maintenance, the condition-based strategy is more cost-effective, as damage caused by unnecessary replacement is avoided (Strunz 2012, p. 301).

The further development of maintenance involves the concept of forecasting. With the application of static analysis or simulation methods, a forecast of failure probabilities and the derivation of recommendations for maintenance measures is enabled. This type of strategy is termed predictive maintenance (Mühlnickel *et al.* 2018, p. 355).

*Predictive Maintenance*

Reactive, preventive and condition-based maintenance are often insufficient to ensure system reliability due to the increasing complexity and flexibility of production processes. Maintenance measures are initiated at incorrect and inopportune times since incomplete or delayed information about machine conditions prevent the optimum replacement of maintenance objects in terms of time and wear. Predictive maintenance provides a remedy by integrating the possibility of forecasting into the concept of condition-based maintenance (Nemeth *et al.* 2015, p. 570).

The main focus is the prediction of wear and its effect on the production process. For this purpose, sensor signals from condition monitoring systems, quality and machine data as well as historical data on the condition of the maintenance objective are acquired and evaluated. The data sets are used to derive probability models describing typical wear processes of the maintenance object (Siener and Aurich 2011, p. 16). In summary,

predictive maintenance can be described using the definition of the German Institute for Standardisation (DIN EN13306, p. 35) as "condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item".

The further development and the current stage of maintenance is self-preservation of plants and machines with the aim of ensuring process capability through self-regulation. Continuous adaptions of the maintenance strategy are performed based on current and expected loads. In the event of an imminent failure, measures to ensure the process capability are automatically requested. The concept of self-preservation is the core of smart maintenance (Mühlnickel *et al.* 2018, p. 355).

In the following section, smart maintenance is discussed in detail.

### 2.2.2 Smart Maintenance

Digitalisation introduced the beginning of Industry 4.0. The vision of Industry 4.0 is characterised by a comprehensive interlinking of machines and systems as well as the application of advanced automation and ICTs. Every material, product, production facility, tool, logistic system, conveyor, storage system as well as building is equipped with embedded systems, resulting in cyber-physical systems (Henke *et al.* 2019, p. 6; Kostolani *et al.* 2019, pp. 131–132). Those systems are microcomputers capable of capturing the physical world using sensors, evaluating the physical world with data and services available worldwide through the internet and influencing the physical world using actuators. Thus, cyber-physical systems interlink to establish autonomous, decentralised networks and to optimise themselves independently (Bauernhansl 2014, p. 16; Henke and Kuhn 2015, p. 11).

Despite the new developments, maintenance has to ensure its basic objectives of safety for personnel and environment, as well as the availability, reliability and value preservation of machines and plants at minimum cost. According to Lucke *et al.* (2017, pp. 76–77), maintenance therefore faces the challenges of a rising number of maintenance objects, growing technical complexity of systems, increasing technical and organisational interlinking of systems as well as higher safety and environmental requirements. As a result, the concept of maintenance has to adapt into what is referred to as smart maintenance.

In literature, no clear scientific definition of smart maintenance is established. To ensure uniform terminology, the definition developed by Henke *et al.* (2019, p. 11) is applied:

*"Smart Maintenance refers to a learning-oriented, self-regulated, intelligent maintenance with the objective of maximising the technical and economic effectiveness of maintenance measures taking into account the respective existing production system by using digital applications."*

Bokrantz *et al.* (2020, p. 11) see smart maintenance as a configured organisational composition of the following four interlinked and mutually supportive dimensions:

- Data-driven decision-making
- Human capital resource
- Internal integration
- External integration

The underlying dimensions of smart maintenance and its influencing factors are described in the following sections.

*Data-driven Decision Making*

Bokrantz *et al.* (2020, p. 11) define data-driven decision making as "the degree to which decisions are based on data". In maintenance, an essential part is the storage, access and further processing of existing data and the inclusion of new data in order to make decisions. However, the scope and handling of data has changed with the development of smart maintenance (Henke *et al.* 2019, p. 29). Figure 2.12 shows an overview of the factors for data-driven decision-making in smart maintenance.

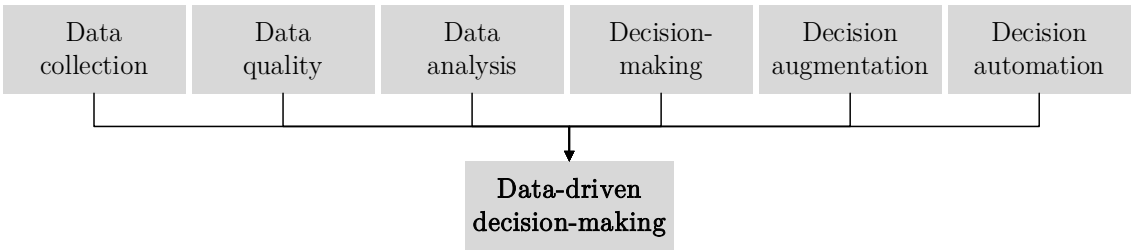



Figure 2.12: Factors influencing data-driven decision-making
Adopted from Bokrantz *et al.* (2020, p. 7)

In the process from raw data to real value, collection, quality and analysis of data as well as decision-making is essential. Without the collection of data, no decision is possible. The transformation of poor-quality data into valuable data is not possible using any algorithm and without the analysis of data, no conclusion can be drawn. However, gathering and evaluating high-quality data does not lead automatically to decision-making based on data. The aspects of decision automation and decision augmentation are crucial. In the context of decision automation, the task of decision-making previously performed by humans is substituted by advanced algorithms such as machine learning. Decision augmentation describes the value creation from the synergies between data respective algorithms and human judgement (Bokrantz *et al.* 2020, p. 7).

*Human Capital Resource*

The trend towards digitalisation and advances in technology lead to an increasingly complex range of maintenance tasks in smart maintenance (Henke *et al.* 2019, p. 15). In addition, a structural shift from labour-intensive to knowledge-intensive tasks is taking place (North 2016, p. 1). The consequence is a demand for highly qualified personnel with new skills (Bokrantz *et al.* 2020, p. 8; Mühlnickel *et al.* 2018, p. 358). The new skills can be divided into six categories as shown in Figure 2.13.

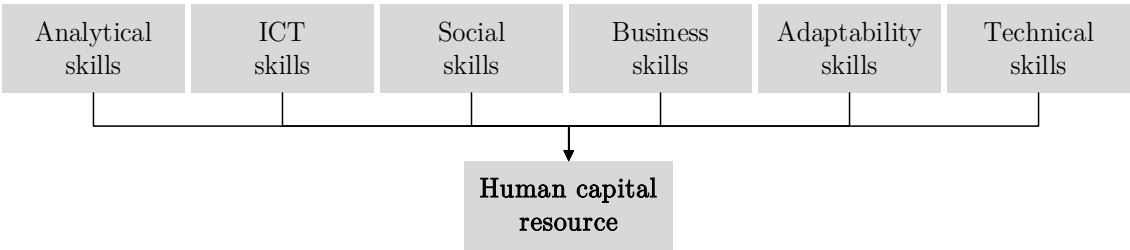



Figure 2.13: Factors influencing human capital resource
Adopted from Bokrantz *et al.* (2020, p. 7)

Analytical skills describe the ability to understand how to gather, analyse and use data as well as make decisions based on data. Skills in the field of ICTs include the capability to manage and implement information systems in maintenance. In addition, social skills cover interpersonal capabilities and business skills reflect the ability to understand the economic factors and impacts of maintenance. Adaptability skills are required for dynamic transition to embrace technical changes and new tasks. Furthermore, technical skills reflect the ability to perform fundamental maintenance tasks (Bokrantz *et al.* 2020, p. 8).

*Internal Integration*

Another underlying dimension of smart maintenance is the relation between the maintenance function and the internal plant organisation (Bokrantz *et al.* 2020, p. 9). The integration of maintenance into production and the rest of the organisation is divided into the categories shown in Figure 2.14.

In smart maintenance, digitalisation enables the ubiquitous access to data, information and knowledge which was previously stored locally or personally (Henke *et al.* 2019, p. 29). Sharing and combining data, information and knowledge allow establishing internal flows to other functions, thus optimising the maintenance function. Furthermore, internal integration requires cross-functional collaboration and joint decision-making between functions in order to achieve teamwork, better communication, closer connection and better coordination (Bokrantz *et al.* 2020, p. 9).

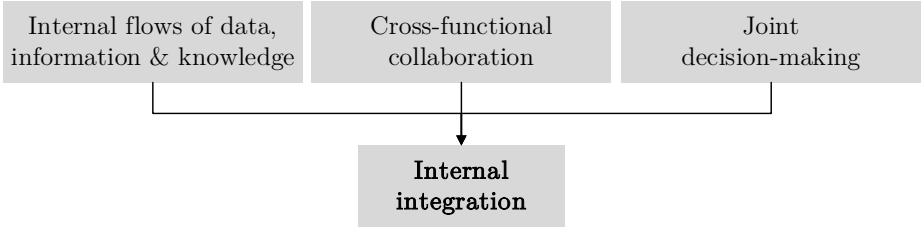



Figure 2.14: Factors influencing internal integration
Adopted from Bokrantz *et al.* (2020, p. 7)

*External Integration*

Besides the dimension of internal integration, the dimension of external integration plays an important role in smart maintenance. The interaction of the maintenance function with the external environment is divided into four categories, as shown in Figure 2.15.

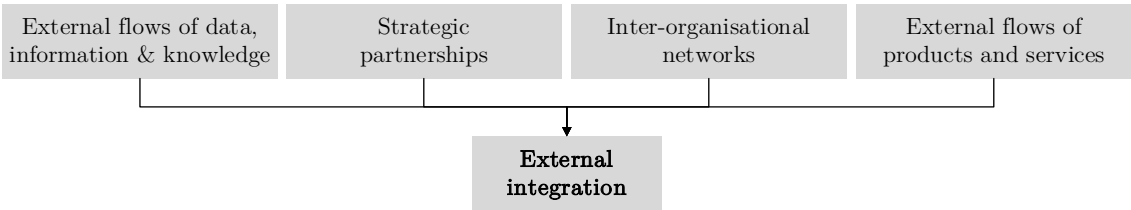



Figure 2.15: Factors influencing external integration
Adopted from Bokrantz *et al.* (2020, p. 7)

The ubiquitous access and flow of data, information and knowledge are not limited to the internal organisation but extended to the external environment. Thus, for example, the exchange with other plants, suppliers or partners is possible. In order to ensure the external flow and the access to the relevant resources, strategic partnerships and inter-organisational networks are essential. The closer relation and organisation of functions leads to the more efficient flow of products and services (Bokrantz *et al.* 2020, p. 10).

### 2.2.3 Asset Management in Maintenance

The International Organisation for Standardisation (DIN ISO55000, p. 35) defines an asset as an "item, thing or entity that has potential or actual value to an organization". The rather general definition is qualified with two notes concerning value and asset:

- Value can be tangible or intangible, financial or non-financial, and includes consideration of risks and liabilities. It can be positive and negative at different stages of the asset's life.

- Physical assets usually refer to equipment, inventory and properties owned by the organisation. Physical assets are the opposite of intangible assets, which are non-physical assets such as leases, brands, digital assets, use rights, licences, intellectual property rights, reputation or agreements.

Against this background, the International Organisation for Standardisation (DIN ISO55000:) defines asset management as the "coordinated activity of an organization to realize value from assets". The objective is to ensure effective control and management of assets to create value by balancing risk, performance and costs. The challenge of balancing these constraints is that risk as well as costs should be as low as possible and performance should be as high as possible. However, risk and costs increase if performance is improved and vice versa (Chattopadhyay 2016, p. 521; DIN ISO55000, p. 21).

In maintenance, asset management refers to the management of production facilities and systems (Weber and Reichel 2018, p. 35). In this context, risk of those physical assets is for example the risk of an error, which results from the hazard potential and the probability of an error. The error can pose a real danger to people and the environment. Thus, if the risk is reduced safety is increased. In addition, the maintenance performance is determined by the error rate and the maintenance costs resulting from the error. Therefore, if the risk for an error increases, the error rate and the costs resulting from the errors increase as well (Chattopadhyay 2016, p. 521; DIN15341, pp. 14–20; Matyas 2019, pp. 100–102).

Digitalisation enhances the complexity of asset management in maintenance. The focus is not solely on the value creation of the production system but also on the functional interaction of numerous digitalised components of the production system. In addition, digitalisation enables communication across value chains. The information received through communication has to be analysed properly and used profitably. Ultimately, the rising number of interfaces leads to an increasingly difficult assessment of the correlations between risk, performance and costs of assets (Weber and Reichel 2018, pp. 35–39).

## 2.3 Assistance Systems Based on Reality Technology in Maintenance

To evaluate the state of the art for ASs with RT in maintenance, a systematic literature review is conducted. Every literature review is supposed to be systematic, but reviews differ in the extent to which they are systematic and how explicitly their methods are reported. Systematic approaches are characterised by greater clarity, internal validity and auditability. The objective of a systematic literature review is the search, the appraisal, the synthesis and the analysis of the relevant publications for a specific field of research (Booth *et al.* 2016, pp. 19–23).

Since RT presents the umbrella term and to obtain specific information, the systematic literature review is conducted for ASs based on AR, MR and VR in maintenance. For the scope of AR, Palmarini *et al.* (2018) performed a systematic literature review. However, the review was carried out in 2017 and due to the rapidly evolving nature of the topic, an extension through a review for the years 2018 to 2020 is necessary. Furthermore, the method applied by Palmarini *et al.* (2018) is used for the systematic literature review in order to obtain a uniform and scientific basis. Nevertheless, the method was adapted to the scope of the thesis.

Figure 2.16 shows the steps used to carry out the systematic literature review. The individual steps and the respective methodologies are described in the following section.

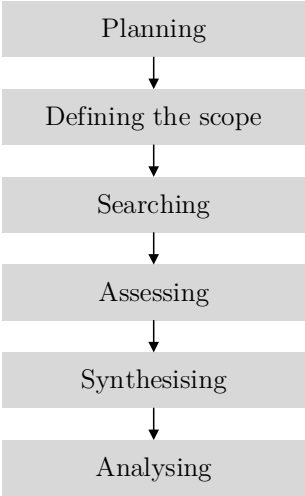



Figure 2.16: Steps of the systematic literature review
Adopted from Booth *et al.* (2016, pp. 2–3)

The initial step of the systematic literature review is planning. This step involves the identification of the database used for the literature search and the selection of the software used to manage the references. The second step aims to define the scope. Based on initial brainstorming and a literature search, a research question is formulated to be answered by the systematic literature review. In the following step, the searching, the search string is defined and the first literature search is carried out in the databases defined in first step. The fourth step involves the assessing. The objective is to narrow down the scope of the literature found in the research phase to a number of publications relevant for answering the research questions. For this purpose, inclusion and exclusion criteria are defined and a second three-phase literature search is applied to the results obtained in the fourth step. The first phase uses the search tools provided by the database; this is followed by reviewing the title and the abstract of each publication and finally the introduction and conclusion are reviewed. After this third phase, the collection of the publications is complete. In the

final two steps of the systematic literature review, the identified literature is synthesised and analysed in order to answer the research question.

In the following sections, the first four steps – planning, defining the scope, searching and assessing – of the systematic literature review are described. The final two steps – synthesising and analysing – are presented separately for AS based on AR, MR and VR. In addition, the results for AS based on AR are extended with the results conducted by Palmarini *et al.* (2018).

*Step 1 – Planning*

The selection of the databases is based on Palmarini *et al.* (2018, p. 216). The following databases are utilised for the systematic literature review:

- IEEE Xplore (https://www.ieee.org/)
- ScienceDirect (https://www.sciencedirect.com)
- Scopus (https://www.scopus.com)
- Google Scholar (https://scholar.google.com)

For the management of the references, the software from Citavi (https://www.citavi.com) is used. The benefit of Citavi is the integrated PDF viewer and the automatic citation add-in for Microsoft Word.

*Step 2 – Defining the Scope*

The definition of the research question results from the ideas of Palmarini *et al.* (2018, p. 216) as well as an iterative process of brainstorming and literature search. The research questions for ASs based on AR (RQ-AR), MR (RQ-MR) and VR (RQ-VR) in maintenance are defined as follows:

RQ-AR: What is the state of the art of ASs based on AR in industrial maintenance?

RQ-MR: What is the state of the art of ASs based on MR in industrial maintenance?

RQ-VR: What is the state of the art of ASs based on VR in industrial maintenance?

*Step 3 – Searching*

For the initial literature search, the strings ("Augmented Reality" AND "Maintenance"), ("Mixed Reality" AND "Maintenance") and ("Virtual Reality" AND "Maintenance") are applied separately in the selected databases. The Boolean operator "AND" is applied to reduce the number of returns in the first screening. Usually, strings are searched in the title, abstract and keywords. However, in this case the strings are only searched in the title. The argument for not searching in the title, abstract and keywords is that the number of returned documents is too high to examine thoroughly and scientifically within the scope of this thesis. Furthermore, the reason to search in the title is that in a preliminary literature search the conclusion was drawn that the documents containing the strings in

the title include the best quality and most relevant data to answer the defined research questions. The literature search for AR and MR was conducted on 7 August 2020 and for VR on 19 June 2020. Table 2.3 shows an overview of the results including the name of the database, the search field for the search string and the number of documents returned.

Table 2.3: Results of the initial literature search

| Name of Database | Search Fields | Returned Documents | | |
|---|---|---|---|---|
| | | AR | MR | VR |
| IEEE Xplore | Document TITLE | 52 | 5 | 22 |
| Science Direct | TITLE | 30 | 6 | 19 |
| Scopus | Article TITLE | 179 | 19 | 81 |
| Google Scholar | TITLE | 96 | 32 | 220 |
| | **SUM** | **357** | **62** | **342** |

*Step 4 – Assessing*

To narrow down the amount of literature found in the searching step to the number of documents relevant to answer the research question, specific inclusion and exclusion criteria are identified. The selection of the criteria is based on the ideas of Palmarini *et al.* (2018, p. 216) as well as an iterative process of brainstorming and literature search. The following inclusion criteria (IC) and exclusion criteria (EC) are defined:

Inclusion Criteria

IC1: Study that represents the use of ASs based on AR/ MR/ VR in maintenance

Exclusion Criteria

EC1: Not in English or German

EC2: Older than 1997

EC3: Not engineering or computer science field

EC4: Not related or applicable to industrial maintenance

Since Palmarini *et al.* (2018) conducted a systematic literature review for AR in maintenance in 2017, the second exclusion criteria (EC2) is adapted as follows for the extended literature search regarding AR:

EC2: Older than 2017

The criteria are utilised in the predefined databases and applied in three phases – through the searching tool, to the title and the abstract as well as to the introduction and the conclusion. Table 2.4 shows the results including the number of returned documents in the searching step and the included documents (ID) and excluded documents (ED) in each phase of the assessing step. The results for ASs based on AR are seven documents, for ASs based on MR four documents and for ASs based on VR eleven documents.

Table 2.4: Selection process and results of the searching and assessing step

| | **AR** | | **MR** | | **VR** | |
|---|---|---|---|---|---|---|
| | **ID** | **ED** | **ID** | **ED** | **ID** | **ED** |
| **Searching String** ("Augmented Reality"/ "Mixed Reality"/ "Virtual Reality" AND "Maintenance") | 357 | - | 62 | - | 342 | - |
| **Phase 1** IC & EC applied through database searching tools | 100 | 257 | 62 | 0 | 255 | 87 |
| **Phase 2** IC & EC applied to title and abstract | 20 | 80 | 18 | 44 | 45 | 210 |
| **Phase 3** IC & EC applied to introduction and conclusion | **7** | 13 | **4** | 14 | **11** | 34 |

*Step 4 and Step 5 – Synthesising and Analysing*

The documents identified in the assessing step are synthesised and analysed in order to answer the predefined research question. Based on brainstorming, a literature search and with regard to the development of the framework, the following aspects are considered during the review of the documents:

- Maintenance operation
- Hardware and software
- Requirements and instructions for implementation
- Costs
- Advantages and disadvantages

The first aspect refers to the area of the maintenance environment in which the AS based on RT is applied. In addition, information about the utilised hardware and software are collected during the review. The hardware is categorised according to input device, output device and tracking device. The decisive factors for the selection of hardware are relevant in this context as well. Another aspect concerns the requirements and general measures to be considered for the implementation of ASs based on RT in maintenance. Furthermore, information about the costs regarding the hardware, software or implementation is gathered. The final aspect includes the advantages and disadvantages of ASs with RT in the maintenance environment.

In the following sections, the synthesising and analysing step are discussed separately for ASs based on AR, MR and VR in maintenance.

### 2.3.1 Augmented Reality

The assessing step for ASs based on AR in maintenance resulted in seven documents. The identified documents and the relevant documents of the systematic literature review on AR in maintenance done by Palmarini *et al.* (2018) are outlined in the following sections.

Two of the seven documents identified introduce tools and requirements for the implementation of ASs based on AR. The remaining documents address the application in the line of execution. Furthermore, Palmarini *et al.* (2018, pp. 220–222) discuss the use of AR systems in the line of execution and training.

*Implementation Guideline for ASs Based on AR in Maintenance*

Amo *et al.* (2018, p. 362) introduce a design support tool to consider user-centred criteria for the selection of an AS based on AR in maintenance. The ASs are classified into visual, aural and haptic solutions. The tool is shown in Figure 2.17.

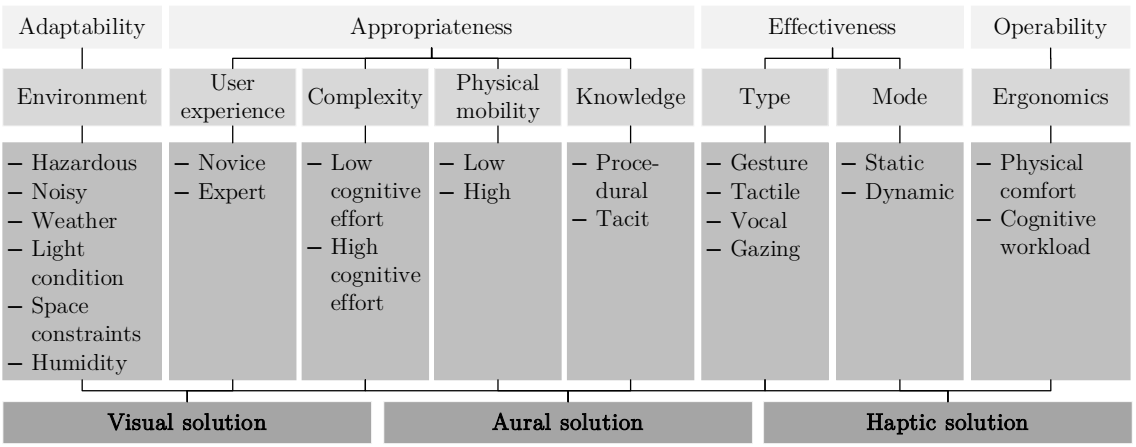



Figure 2.17: Design support tool for the selection of ASs based on AR

Adopted from Amo *et al.* (2018, p. 365)

Amo *et al.* (2018, pp. 363–365) divide the user-centred criteria in the first level into adaptability, appropriateness, effectiveness and operability. The first criterion, adaptability, depends on the environment in which the AR application is implemented. The environment is affected by physical properties, which are measured by the risk level, noise level, weather conditions, visibility level, working space and humidity level. The second criterion, appropriateness, is determined by user experience, the maintenance task and required information. The user is required to have either no previous knowledge or expert knowledge. The maintenance task requires either a low or high cognitive effort as well as a low or high physical mobility. The required information is either based on procedural or tacit knowledge. The third criterion, effectiveness, is based on the interaction with the AR-based application. The interaction can be required once or several times and can involve gesture, haptic, speech or eye movements. The last criterion, operability, includes the ergonomic aspects either regarding physical comfort or cognitive workload.

Similar to the findings of Amo *et al.*, Lorenz *et al.* (2018, p. 151) summarise the requirements of AR-based support systems for maintenance workers. The authors claim that although the benefits of ASs based on AR for maintenance are proven, the implementation often fails due to the industrial requirements. Therefore, Lorenz *et al.* (2018, p. 152) present an overview and distinguish user requirements, technical requirements as well as environmental and regulative requirements. Examples are shown in Table 2.5.

Table 2.5: Industrial requirements for the implementation of ASs based on AR (Lorenz *et al.* 2018, p. 152)

| Requirement | Example |
|---|---|
| User requirement | – Workflow guidance with the help of 3D animations<br>– Hands-free operation |
| Technical requirement | – Data connection at all locations of use – preferred wireless<br>– Operation time of at least 4h |
| Environmental and regulative requirement | – Usable with hard hats, noise protection, safety glasses and gloves – alongside or integrated into the equipment<br>– The protective measures should not impede the functionality of the device |

*Application of ASs Based on AR in the Line of Execution in Maintenance*

Koteleva *et al.* (2020, p. 1623) compared the application of an AS based on AR with traditional methods for servicing oil pumps. The evaluation is conducted with four groups. The first group uses a traditional method in the form of paper instructions. The other groups use a mobile AR-based AS to receive instructions (second group); remote support through an expert (third group); or instructions and, if necessary, remote support (fourth group). As a result, Koteleva *et al.* (2020, pp. 1626–1627) conclude AR-based ASs reduce the time and thus improve the efficiency of the maintenance of oil pumps. The results show that the first group performs worse compared with the other groups. Moreover, the usage of instructions provided by the AR application in the second group is the most efficient method. Although the third group completed the tasks in the same length of time, the support through instructions is cheaper compared to an expert.

Similar to Koteleva *et al.*, Obermair *et al.* (2020, p. 944) evaluate an AR-based AS for remote support in comparison to paper-based instructions in maintenance. The AS consists of a smartphone which is connected to an expert in a support centre. The maintenance technician can communicate with the expert through visual or verbal exchange or in case of a noisy environment using a text chat. The conclusion drawn by Obermair *et al.* (2020, p. 947) is that the error rate is significantly decreased through the AR-based application compared with the paper-based instructions. However, the time required to complete the maintenance process is similar for both methods.

Gatullo *et al.* (2019, p. 174) developed an HHD based on AR for the inspection of a milling machine. The HHD illustrates real-time data from the milling machine as well as its components and processes in order to support the maintenance technician. For the assessment, Gatullo *et al.* (2019, p. 178) compared the AR application of the HHD with a paper-based instruction through a user study. The results indicate that the time required to complete the maintenance with the AR application is reduced compared with the paper-based method. However, no differences in the error rate are shown. Regarding the usability, the users prefer the AR application although they are more familiar with the paper-based instructions. Furthermore, Gatullo *et al.* (2019, pp. 178–179) tested the AR application with a smartphone and a tablet. The results show no improvement in user performance regarding time, error rate or usability.

Aromaa *et al.* (2018, p. 119) present an AR-based AS for the maintenance of an elevator hydraulic control unit. The aim is to support the technician by visualising the maintenance steps of the control unit with 3D models and describing the process in text form. The AS consists of a tablet with the Windows operating system and the Unity development platform as well as visual tags located on the control unit for tracking. For the evaluation of the AR-based AS, Aromaa *et al.* (2018, p. 124) conducted a study to examine the impacts especially on ergonomics and user experience. The results show that, from an

ergonomic point of view, the users adopted poor posture when using the AR-based AS, but not over a long period of time. The well-being of the users is therefore not affected in a negative way. Furthermore, the overall user experience was positive and the users accepted the AR-based ASs well. However, the users expressed concern for implementing tablets in harsh environments.

Sabarinathan *et al.* (2018, p. 614) introduce an AS in the form of a smartphone for machine maintenance. The technician can point the smartphone with the camera at the machine and view its components, description and technical features. In addition, the technician has the option of viewing a demonstration video that illustrates the execution of the maintenance task. A prerequisite for this AS is a stable internet connection. As a result, Sabarinathan *et al.* (2018, p. 617) conclude that the overall performance of the machine maintenance is improved. The costs and the time for performing the maintenance task are significantly minimised. Furthermore, Sabarinathan *et al.* (2018, p. 617) emphasise the additional benefits for the training of maintenance technicians and that novices can carry out maintenance tasks with the minimum of knowledge.

*Systematic Literature Review Conducted by Palmarini et al. (2018)*

Palmarini *et al.* (2018, p. 220) conclude the most common maintenance task for AR in maintenance is assembly and disassembly. In 1997, Azuma (1997, pp. 379–380) noted that the assembly process could be simplified compared with traditional user manuals by overlaying 3D animation drawings. Westerfield *et al.* (2015, p. 158) state AR as the ideal tool for "situations which require manipulation of objects, such as manual assembly". Moreover, Yuan *et al.* (2008, p. 1745) consider the greatest potential for application of AR to be in the field of assembly. A practical example of using AR in assembly is provided by Sanna *et al.* (2015, p. 178) and the user interface is shown in Figure 2.18. The description of the task is illustrated as a text at the bottom of the display to support the user. In addition, arrows allow the user to navigate backwards or forwards through the procedure steps.

Webel *et al.* (2013, p. 399) present another example of using AR in assembly. In Figure 2.19, the user interface is shown. The user is supported during the task by overlaying virtual 3D animations and texts on top of the real environment. The level of guidance can be adjusted based on the knowledge of the user. The 'strong' guidance is for inexperienced users requiring help with every step and the 'soft' guidance is for experienced users requiring only top-level information.

Furthermore, AR is applied in repair, inspection and diagnosis as well as training operations. Palmarini *et al.* (2018, p. 221) point out that all three operations are different types of maintenance tasks, but each AR application developed by the authors of the identified documents includes assembly and disassembly procedures. In general, repair

operations include the regeneration and replacement of faulty components or devices, which could be supported by AR-based applications (Wójcicki 2014, p. 45).

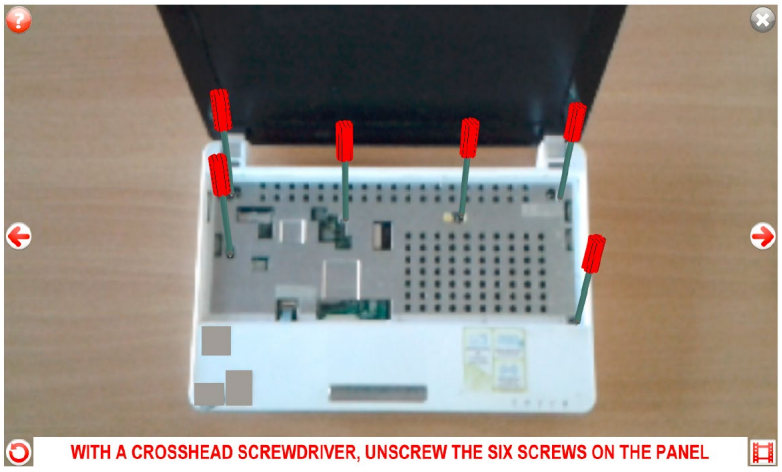



Figure 2.18: Step-by-step support for assembly procedures
(Sanna *et al.* 2015, p. 178)

(a) (b)

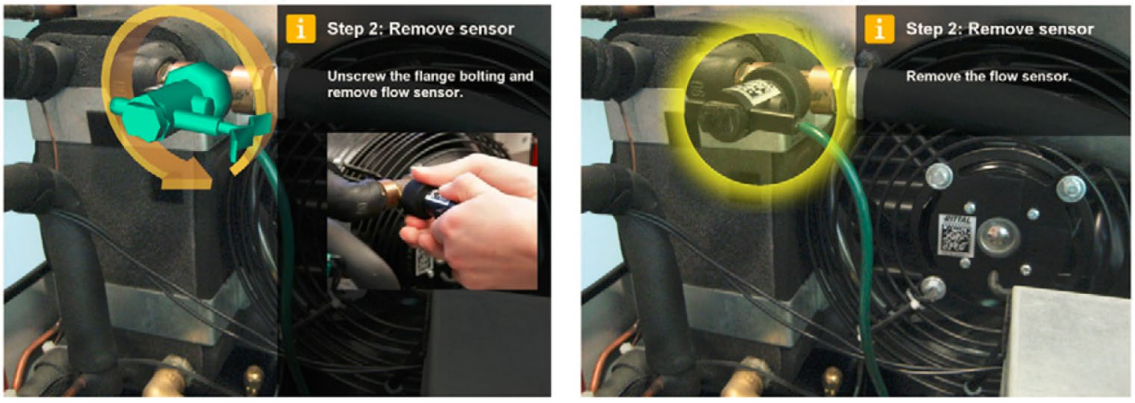



Figure 2.19: Support of disassembly process at (a) strong guidance level and (b) soft guidance level
(Webel *et al.* 2013, p. 440)

Inspection and diagnosis operations include the maintenance measures for evaluating the current condition of an object and analysing the reason for its deterioration and functional deficits (Takata *et al.* 2004, p. 650). For the increasingly complex systems of today, information and initial diagnoses are provided through embedded sensors, which are accessed by computers. The process can be enhanced with the implementation of AR by displaying the relevant information directly on the maintenance object (Regenbrecht *et al.* 2005, pp. 49–50).

Training operations are performed either on the job or offline depending on the industry (Webel *et al.* 2013, pp. 400–401). For example, hands-on training is highly accepted in the construction industry and Wang *et al.* (2004, pp. 2–3) developed an AR-based application for this purpose. The technical information is virtually overlaid on real construction vehicles such as loaders or excavators in order to train the user. Neumann and Majoros (1998, p. 5) found that AR is an efficient way to retrieve information from memory. This supports the statement by Navab (2004, p. 17) that AR training applications "offer the advantages of VR systems without immersing users into a virtual space[.]".

### 2.3.2 Mixed Reality

The assessing step for ASs based on MR in maintenance yielded a total of four documents. Many documents were excluded because MR is interpreted ambiguously. MR is a relatively new technology and in literature, no uniform definition or delimitation has been established. Several authors therefore equate MR with AR or consider MR as an umbrella term for AR and VR. Thus, documents are included if the definition of MR concurs with the definition stated at the beginning of section 2.1 or if the applied devices are declared to be MR devices by the manufacturer.

The resulting four documents are described in the following sections. In summary, ASs based on MR are applied in the identified documents either in the line of execution or for training.

*Application of ASs Based on MR in the Line of Execution in Maintenance*

Piedimonte and Ullo (2018, pp. 559–560) established an MR-based AS for preventive and corrective maintenance tasks of military systems. The status quo is that the maintenance tasks are either performed by on-site experts or by external experts depending on the degree of technical complexity. Piedimonte and Ullo (2018, pp. 559–560) suggest implementing the Microsoft HoloLens to enable on-site experts to perform technical complex tasks. An external expert can guide and assist the on-site expert through remote support. Thus, the maintenance task can be executed at a lower cost and with improved efficiency. Furthermore, Piedimonte and Ullo (2018, p. 560) underline the benefits for the training of maintenance personnel. By using the Microsoft HoloLens, training sessions are possible without real systems and can be performed at any location. Thus, costs are reduced and flexibility is increased.

Fonnet *et al.* (2017, pp. 1–2) present a MR-based solution for preventive maintenance tasks related to historical and cultural buildings. The reason for a new solution is that the maintenance tasks are currently carried out by an inspector using paper, camera and laptop, which allows collecting the required information, but in an inefficient way. The requirements for the MR device are to be a mobile and hands-free application as well as to be able to take pictures, display information extracted directly from the database and store

observations made by the inspector. Based on those required features, the Microsoft HoloLens is selected. Fonnet *et al.* (2017, pp. 6–7) underline the benefit of presenting the complex information required for the maintenance task in an efficient and simple user interface. Thus, the inspector can interact with the relevant data while concentrating on the task at hand. However, the limits set by the processing power of the Microsoft HoloLens must be considered.

Silva *et al.* (2018, p. 50) propose an MR-based approach for repairs and preventive tasks within building maintenance. Thereby the main problem of locating in order to check or repair faulty infrastructure components can be solved. The reason for the difficulties is based on the lack of the required data or its poor quality. By using the Microsoft HoloLens, Silva *et al.* (2018, pp. 53–54) conclude that the relevant information can be presented through the MR technology to simplify the localisation of faulty infrastructure components. Thus, the maintenance tasks are performed faster and more accurately.

*Application of ASs Based on MR for Training in Maintenance*

Aitken and Ross (2019, pp. 7–8) developed an MR-based training AS for the routine vehicle maintenance tasks performed by automotive technicians in the military. The aim is to evaluate the performance impacts as well as the potential benefits of using MR in training. In the scope of a study, the MR-based training using the Microsoft HoloLens is compared to the paper-based training using maintenance manuals. Qualitative and quantitate data are gathered during the study. The qualitative data is obtained through pre-training and post-training surveys. In addition, feedback regarding user experience is collected through workshops. The quantitative data is derived from video recordings and error rates. Aitken and Ross (2019, pp. 11–19) made the following conclusions from the results of the study:

- No significant improvement in performance
- Lower error rate
- Easier to use

The implementation of an MR-based AS did not significantly alter the performance of the participants during the maintenance tasks. In fact, some participants needed to be reminded to exploit the additional information provided by the Microsoft HoloLens. However, Aitken and Ross (2019, p. 20) note that if the information were better presented, more participants would probably use the additional features. In addition, the MR-based training leads to fewer errors. The conclusion is that the Microsoft HoloLens allows a structured and comprehensive overview of the maintenance task and ultimately reduces the potential for re-work. Furthermore, the participants state that the MR-based training is easier compared with the paper-based training. In particular, the training of new employees can benefit from the application of the Microsoft HoloLens. However, the need for qualified staff will not be substituted. Regarding the user experience, Aitken and Ross,

p. 19 (2019, p. 19) summarise the advantages and disadvantages shown in Table 2.6 in using the HoloLens for training. From the summary it can be seen that the advantages concern the optimisation of the execution of the maintenance task and the disadvantages the obstacles caused by the hardware itself.

Table 2.6: Advantages and disadvantages of using a MR-based HMD for training (Aitken and Ross 2019, p. 19)

| Advantages | Disadvantages |
|---|---|
| – Instructions are easy to follow<br>– Photo and video training aids are helpful<br>– Navigation through training task is easy<br>– Anyone with any skill level can use this technology<br>– MR allows user to concentrate on the task at hand instead of looking away and reading instructions | – Headset difficult to attach to the head – re-adjustments necessary<br>– Concerns about damaging the device due to the high price<br>– Long-term use leads to eye strain and fatigue<br>– Headset too bulky and heavy for long-term use<br>– Potential safety risk since headset obscured peripheral vision and vision above the line of sight |

### 2.3.3 Virtual Reality

The assessing step for ASs based on VR in maintenance resulted in eleven documents. The identified documents are discussed in the following sections. Overall, ASs based on VR are utilised in some of the identified documents in the line of execution but primarily for training.

*Application of ASs Based on VR in the Line of Execution in Maintenance*

Eschen *et al.* (2018, p. 159) present a VR-based solution for the inspection of aircraft engines during maintenance. The status quo concept involves digitising the surface of the engine for automatic evaluation followed by manual verification to avoid errors. The manual verification is performed on a conventional desktop PC. Since no human-object interaction is required, Eschen *et al.* (2018, p. 159) propose as a new solution an HMD capable of creating VR with a game controller as an input device. As a result, no benefits can be identified. However, Eschen *et al.* (2018, p. 159) indicate that modifying the conditions by optimising the digitisation and using a tracked controller as an input device can lead to advantages.

Linn *et al.* (2017, p. 2) established a VR-based AS for virtual remote inspection. The approach is based on a 360-degree camera that captures real-time videos of the maintenance object. The videos can be viewed by the technician as a virtual live stream on an HMD capable of creating VR. The HMD presents a complete overview of the object and its surroundings with additional relevant information. Thus, the technician is able to detect and investigate faults or irregularities without being on-site. According to Linn *et al.* (2017, p. 5), the VR-based application offers three main advantages. First, it is possible to carry out a fast and inexpensive inspection of systems, areas or machines that are not easily accessible. Second, the real-time and non-invasive method enables visual inspections during the operation of systems and machines. Third, the immersive experience and the enrichment through virtual information provides the full context of the situation and support for the maintenance technician. However, Linn *et al.* (2017, p. 5) mention technical challenges regarding the application and handling of the 360-degree camera and the streaming of the video.

*Application of ASs Based on VR for Training in Maintenance*

Shen *et al.* (2012, pp. 524–527) discuss desktop-based VR training for equipment maintenance. The benefits are shorter training periods and higher efficiency compared with traditional training methods. In addition, the knowledge required for the training can be stored and shared through the VR application and therefore the dependency on employees and their know-how is reduced. Furthermore, the training session can be adapted better and faster to new processes or machines in maintenance. Thus, maintenance costs are reduced and flexibility is increased.

Shamsuzzoha *et al.* (2018, pp. 1896–1897) add that the VR-based training enables a learning-by-doing approach that is not feasible in a real-world environment due to constraints such as safety, time and costs. Safety and cost restrictions are the main reasons for Arendarski *et al.* (2008, pp. 485–487) developing a VR-based training method for electrical power systems and García *et al.* (2016, pp. 27–29) doing the same for power distribution systems. In the electricity industry, safety is the top priority. The potential for minor or fatal injuries to maintenance technicians can be eliminated through virtual training. In addition, the training for electrical power systems, as well as power distribution systems is very expensive. Furthermore, Duan *et al.* (2012, p. 1396) underline the fact that the use of real equipment is further restricted due to quality as well as availability and that it also leads to high wear and therefore poor quality. The availability of the required training resources is not always ensured if new equipment is implemented.

Li *et al.* (2012, p. 72) present a VR-based AS for the training of multiple maintenance operators for large-scale and complex equipment. The problem is that the equipment and its maintenance processes are becoming increasingly complex and difficult. Cooperation with different departments is necessary to execute the maintenance tasks. Therefore, the

training methods have to be adapted in order to train more than one maintenance technician at the same time. For this purpose, Li *et al.* (2012, p. 80) suggest a semi-immersive VR system based on a standard desktop PC and a stereoscopic projection system. The desktop PC is utilised to create the simulation, which is displayed in 3D through the projection systems. The input devices are data gloves and a space mouse as well as tracking equipment to identify hand action as well as the position and the orientation of the users. As a result, Li *et al.* (2012, pp. 83–84) observe that the training time is significantly reduced and thus, the collaborative training session improves the maintenance efficiency of complex equipment.

Gavish *et al.* (2015, pp. 781–784) compared uncontrolled and controlled VR-based and AR-based training methods for maintenance technicians. The uncontrolled VR training system is based on a desktop PC, which displays the maintenance task in 3D and provides audio information through embedded speakers. The trainee can interact with the virtual environment through a tactile device in the form of a controller. The controlled VR-based training approach includes an instructional video, which the trainees watch as training. The uncontrolled AR training system consists of a tablet with a touch screen and a tactile bracelet as input devices, which the trainees use for guidance during the training on real equipment. The controlled AR-based training approach is based on an instructional step-by-step video, which the trainees view while performing the maintenance task on the physical equipment. Gavish *et al.* (2015, pp. 792–794) state as a result that the controlled VR and AR training methods require more time. One reason may be that most of the trainees are not familiar with the new technology and therefore long-term advantages can be expected. In addition, the trainees performed well with the uncontrolled VR system but not significantly better compared with the uncontrolled VR method.

Bailey *et al.* (2017, pp. 2–4) evaluated the effectiveness of a traditional training method compared with a VR-based training approach. The aim is to assess whether the effectiveness depends on the level of immersion or the amount of interaction. To assess the level of immersion, desktop-based training is compared with HMD-based VR training. To assess the degree of interaction, the input is a PC mouse in the desktop-based method and a voice or gesture command in the VR-based method. As a result, Bailey *et al.* (2017, pp. 9–10) conclude that VR training in 3D requires more time but improves performance compared with the desktop-based training in 2D. In addition, the VR-based training with voice command takes as much time as with gesture command. However, the voice input improves the performance. The reason is not that fewer mistakes are made in the execution of the maintenance task, but because of interaction problems with the gesture command such as using the wrong gesture.

McNamara *et al.* (2016, p. 623) developed a low-cost, immersive VR-based AS for maintenance training. The AS consists of an HMD capable of creating VR, an input device

for motion tracking, a game engine and a desktop PC. The trainee can view the virtual presentation of the training situation through the HMD. The trainee's movements are tracked using the input device and processed by the game engine on the desktop PC in order to render the virtual environment on the HMD accurately. McNamara *et al.* (2016, pp. 630–631) conclude that VR-based AS enables large-scale training applications. However, the application should not require small gestures due to limitations of the motion-tracking system.

### 2.3.4 Application Characteristics and Implementation Requirements

From the systematic literature review, several conclusions can be drawn regarding the application characteristics and implementation requirements of ASs based on RT in maintenance.

Regarding the application characteristics, factors concerning environment, user experience, complexity of the task, level of physical mobility, type of knowledge, type of interaction, type of presentation of virtual content and type of support are considered decisive for the selection of visual, auditive or tactile ASs based on AR. In addition, requirements concerning the application and implementation are further factors identified for the selection of ASs based on AR in maintenance and these are differentiated between user requirements, technical requirements as well as environmental and regulative requirements. Since the stated selection criteria are not specifically defined for ASs based on AR, the conclusion can be drawn that the criteria are also suitable for the selection of ASs based on MR and VR and thus generally of ASs based on RT.

ASs based on AR are utilised on the one hand in the execution of maintenance. Regarding the advantages and disadvantages in contrast to traditional methods such as paper-based instructions, the results are diverse. The mentioned advantages are reduced time, costs and error rates, improved efficiency and overall performance, positive user experience as well as no long-term negative ergonomic impacts. However, in some of the literature, no improvements in time and error rates are recorded, and higher costs and concern about the application of ASs based on AR in harsh environments are being identified. On the other hand, ASs based on AR are employed for training in maintenance. The advantages compared to traditional training methods include the possibility that novices can carry out maintenance tasks on site and thus, only a minimum of knowledge is required. In addition, ASs based on AR enable a simplified representation of training material, thus increasing the efficiency of training.

ASs based on MR are applied for training but primarily to carry out maintenance. The assessment compared with traditional training methods indicated that costs and error rates are reduced, flexibility is increased and usage is simplified but performance is not significantly improved. Furthermore, the evaluation compared with traditional methods in

the line of execution resulted primarily in benefits: reduced time and costs as well as improved accuracy, efficiency and performance. In particular, the possibility of presenting complex information in a simple and efficient user interface is emphasised. A single drawback is mentioned that the processing power of the output devices is insufficient.

ASs based on VR are employed in the line of execution but primarily for training in maintenance. For the execution of maintenance tasks with VR compared with traditional methods, it is determined that costs and time are reduced but that technical challenges can arise due to ASs based on VR. For the application of ASs based on VR for training, the advantages compared to traditional training methods are diverse. In some documents, a reduction in time and an improvement in performance is reported and in other documents, the opposite is the case. Other benefits include increased efficiency, flexibility and safety as well as the possibility to train several people at the same time. Further disadvantages are not identified.

Furthermore, the conclusion is made that ASs based on RT generally offer three types of support. First, the provision of information, that is specifically designed for the user, the maintenance task and the maintenance object. Second, enabling communication with an expert who is not on site, using remote support. Third, carrying out documentation, for example, during the performance of a maintenance task without any effort for the user.

Regarding the implementation requirements, factors concerning employees, costs, technology are identified as essential for the implementation of ASs based on RT in maintenance. In terms of employees, the important aspects are that the employees accept and are able to use the new technology. Moreover, a company is required to have sufficient financial resources to invest in an ASs based on RT. Furthermore, three different aspects are relevant in terms of technology. First, the technologies and machines employed in the intended maintenance environment are required to have a certain level of maturity for the successful use of ASs based on RT. Second, a certain degree of digitalisation is essential for the digital ASs. Third, the data used for ASs based on RT must be secured appropriately. Thus, the following implementation requirements for ASs based on RT in maintenance are derived:

- Acceptance of employees
- Skills of employees
- Financial resources
- Maturity of technologies and machines
- Degree of digitalisation
- Data security

## 2.4 Concluding Summary

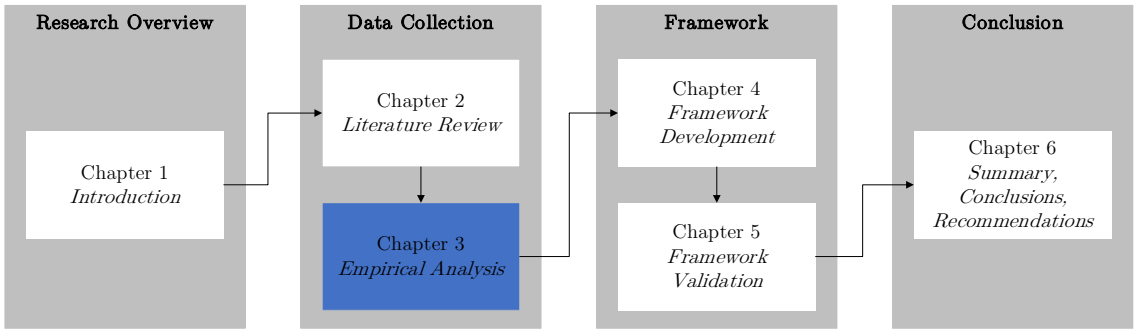
In this chapter, the relevant literature for this research is reviewed. The first part of the chapter covers a background literature review on ASs based on RT. The different types of RT are AR, MR and VR. The main elements of ASs based on RT are an output device, an input device, a tracking device and a development platform. Output devices can be divided according to the way virtual content or the virtual world is presented in visual, auditive and tactile devices. Visual output devices can be subdivided according to the type of display in HMDs, HHDs, screen-based displays or projector-based displays. Auditive output devices are headphones or loudspeakers and tactile devices are vibrotactile bracelets. Analogous to the output devices, input devices are differentiated into visual, auditive or tactile devices depending on the way information is transferred to the output device. Visual input devices are cameras and auditive input devices are microphones. Tactile output devices are PC mice, keyboards, buttons, touch surfaces or screens, joysticks, controllers, data gloves and vibrotactile bracelets. Regarding the tracking devices, tracking is either based on sensors or cameras. For sensor-based tracking, electromagnetic, acoustic, inertial, optical or mechanical sensors can be applied. Camera-based tracking can be subdivided in marker-based and vision-based tracking. Regarding the development platform, specific programming languages, game engines, software platforms or SDKs can be employed.

The second part of the chapter consists of a background literature review on maintenance. The basic measures of maintenance are service, inspection, repair and improvement. The planning and execution of the maintenance measures depend primarily on the maintenance strategy. Depending on the maintenance strategy, reactive, preventive, condition-based, predictive or smart maintenance can be differentiated. Smart maintenance is the current development status. Maintenance has evolved from a labour-intensive to a knowledge-intensive field, which impacted the qualification requirements of maintenance personnel. In addition to technical knowledge, knowledge in the field of ICT is required. Furthermore, assets are evaluated in maintenance by considering their impact on the balanced set of risk, performance and costs.

The third part of the chapter concludes with a systematic literature review on ASs based on RT in maintenance. Regarding the application characteristics, the environment of the maintenance application is decisive for the selection of an AS based on RT. In addition, according to the literature, the application in maintenance of ASs based on AR is in the line of execution and training, ASs based on MR primarily in the line of execution and ASs based on VR primarily for training. Furthermore, ASs based on RT offer support by providing targeted information, enabling communication with technical experts via remote support and carrying out documentation. Regarding the implementation requirements,

requirements concerning employees, costs and technology are crucial for the successful implementation of ASs based on RT in maintenance.

# Chapter 3
# Empirical Analysis of Assistance Systems Based on Reality Technology in Maintenance




The objective of this chapter is to conduct an empirical analysis as a further method of data collection for this research. Using the empirical analysis, the relationship between application characteristics of ASs based on RT and maintenance activities (RO5) as well as the requirements for the successful implementation into maintenance (RO6) are investigated and thus, answers for SRQ3 provided.

## 3.1 Conditions for the Empirical Analysis

The empirical analysis is conducted through interviews. The utilisation of interviews as a further method of data collection for this research is motivated by three reasons. First of all, Jabareen (2009, p. 53) proposes to employ several types of data collection including interviews for the development of a conceptual framework. Second, insufficient information is available in the literature on the topic of ASs based on RT in general and in the field of maintenance in particular. Third, the aim of the thesis is to develop a pragmatic as well as a practical framework and therefore, gathering experiences and knowledge from the industry is beneficial.

The interviews were conducted with nine participants. The selection strategy of the participants was based on including subject matter experts in maintenance representing

different industries and countries as the purpose of the interviews is to gather generic data. The participants are engineers, directors or consultants of maintenance management in the following sectors: consulting; healthcare; the petrochemical industry, the liquid beverage industry and the electricity industry with a focus on traditional and renewable energy sources. In addition, the experts are from South Africa as well as the United Kingdom and represent national as well as international companies.

A brief description of the research project, an interview guideline and a written consent form were sent to the participants in advance by e-mail. The interview guideline is designed according to the ethics requirement of Stellenbosch University and approved by its research ethics committee. The notice of approval from the research ethics committee, the consent form and the interview guideline are attached in Appendix A.

The interviews were conducted either by telephone or in person on the premises of Stellenbosch University or the respective company. The duration of the interviews ranged between half an hour and one hour. Furthermore, the interviews were recorded with the consent of the participants to ensure an accurate and efficient evaluation of the answers. The recordings of the interviews are available on request for examination purposes.

The design of the expert interviews is based on the approach of so-called semi-structured interviews. The objective is to obtain information and new insights through a conversation with one respondent at a time. In semi-structured interviews, the interviewer follows an interview guideline that contains a blend of open-ended and closed-ended questions (Adams 2015, p. 493). On the one hand, the open-ended questions offer the opportunity to discuss a topic in more detail with follow-up questions if the respondent has more knowledge on the topic. In this way, the interviewer can deviate from the interview guideline and orient the interview based on the knowledge of the expert. The advantage is that the conversation is as natural as possible under the given circumstances. On the other hand, the partial standardisation facilitates the comparability of the interviews. Therefore, the use of semi-structured interviews provides a scientific basis for data collection through detailed, differentiated and specific research on a topic or problem.

## 3.2 Structure of the Guideline

The questions of the interview guideline are derived from the background literature reviews and the systematic literature review conducted in chapter 2. The interview guideline is divided into four parts. The first part covers the introduction to the interview and the remaining parts address ASs based on RT in maintenance. The second part covers the application characteristics, the third part handles the implementation requirements and the final part presents the benefits and challenges.

At the beginning of the interview, the first question ascertains the area of expertise of the respondent as a maintenance expert. In addition, general sub-questions are raised about the maintenance process employed in the respondent's company. The questions in the first part serve as an introduction to the interview for the expert and at the same time provide the interviewer with a basic context for the expert's answers to the remaining questions.

The second part addresses the application characteristics of ASs based on RT in maintenance. First, a question is posed as to whether the respondent is generally familiar with reality technologies. Regardless of the answer, an explanation about reality technologies is given with brief definitions of AR, MR and VR. In this way, on the one hand, an explanation is provided to the respondents who are unfamiliar with the topic. On the other hand, a definition is given to ensure that the interviewer and the respondent have the same understanding of the topic and to ultimately avoid any inconsistencies. Thus, the comparability of the interviews is facilitated. With the next question, the maintenance processes in which ASs based on RT can be integrated are discussed and in addition, whether any maintenance problems can be simplified or even be solved through RT. The following question focuses on how ASs based on RT can be integrated into the maintenance processes. Subsequently, the next two questions examine which type of RT and which output device are suitable for maintenance. The final question in the second part is about how ASs based on RT can support maintenance. Based on the systematic literature review, the following three types of support are defined:

- Providing targeted information
- Enabling communication with technical experts via remote support
- Carrying out documentation

The respondents are asked to choose one or more types of support that in their opinion are valuable for maintenance and to justify the choice.

The third part of the interview deals with the requirements for the implementation of ASs based on RT in maintenance. The following six implementation requirements are derived from the systematic literature review:

- Acceptance of employees
- Skills of employees
- Financial resources
- Maturity of technologies and machines
- Degree of digitalisation
- Data security

The respondents are asked to rank the requirements according to their relevance for implementation in maintenance and to justify the decision. In addition, the respondents

are invited to add further implementation requirements that, in their opinion, are important.

The final part of the interview discusses the benefits and challenges of ASs based on RT for maintenance. First, the benefits of ASs based on AR, MR and VR for maintenance are addressed. The respondents are asked to select one or more of the following benefits, which are derived from the systematic literature review, and explain their decision:

- Optimisation of maintenance training
- Optimisation of maintenance planning
- Optimisation of maintenance processes
- Optimisation of occupational health and safety
- Optimisation of process reliability
- Optimisation of availability of machines and systems
- Support in case of shortage of skilled employees
- Other benefit
- No Benefit

At the end of the interview, the challenges caused by ASs based on AR, MR and VR as well as RT in general for maintenance are addressed.

## 3.3 Results of the Empirical Analysis

Since the questions in the first part of the guideline served as an introduction to the interview and the answers are not relevant for the development of the framework, the following sections discuss the remaining parts.

### 3.3.1 Application Characteristics

The following sections present the results of the second part of the interview on application characteristics. The results are structured according to the questions in the second part on knowledge about RT, optimisation of maintenance processes, integration possibilities, type of RT, type of output device as well as type of support.

*Knowledge about RT*

In general, RTs are well known, since eight of the nine respondents state that they are familiar with the topic. The majority of them had heard or read about RT, while a few of them already used or integrated ASs based on RT in maintenance. Furthermore, four of them did not know the differences between the types of reality technologies. In addition, AR and VR are better known than MR.

*Optimisation of Maintenance Processes*

None of the experts believe that certain problems can solely be solved with support through ASs based on RT. However, the majority of experts agree that specific maintenance processes can be simplified. Particular emphasis was given to the ability to display critical information in real time and the possibility of remote support that facilitates the performance of increasingly complex maintenance tasks against the background of a growing shortage of skilled workers.

*Integration Possibilities*

Most of the experts comment that to integrate ASs based on RT requires wireless technology. Thus, the maintenance technician is more flexible in terms of movement and able to concentrate better on the task itself.

Furthermore, one expert emphasises the crucial relevance of device management. In particular, thorough back-end support with a support office, servers, databases and sufficient connectivity throughout the work area has to be established and ensured.

*Type of RT*

The respondents decide which type of RT to choose based on the desired application area in maintenance. AR and MR are favoured by the majority of respondents for the execution of maintenance tasks, while VR is preferred by the majority of respondents for planning or training tasks in maintenance.

In general, the experts see the greatest potential for maintenance in AR due to its simple and in most cases cost-effective implementation. In contrast to this, the majority of the experts see the least benefit for maintenance using MR on the grounds that the technology is rather immature or that they are not familiar with MR and therefore unable to identify any advantage.

*Type of Output Device*

Overall, the respondents favour visual output devices in from of HHDs or HMDs. Other types of output devices are not mentioned. The result is shown in Figure 3.1. The absolute numbers are indicated in brackets in this and the following figures.

Five of the experts generally prefer HHDs in form of smartphone and tablets, but for different reasons. One of the reasons is that the employees are familiar with smartphones and tablets from their daily life and are therefore more open as well as better able to handle this kind of technology. Another reason is that HHDs are in some cases already employed in the maintenance environment and the ASs would only be utilised, for example, for irregular activities. Thus, using the available hardware is the simplest and most cost-effective solution. Furthermore, according to the opinion of two respondents, HHDs are more mature and provide better visualisation of virtual content compared to HMDs. In

most cases, the batteries of HMDs do not last an entire work shift and the FOV of HMDs is rather small. In this context, one respondent compares the size of the FOV with the size of a coin.

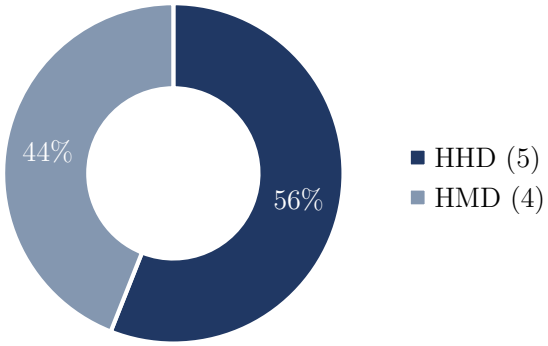



Figure 3.1: Suitable output devices for the application in maintenance according to the subject matter experts (n = 9)

Four of the experts generally see more benefits in using HMDs. This decision is based on the nature of the application. Either the ASs are intended for on-site maintenance activities that require the operator to have his hands free and therefore, HMDs capable of AR are most suitable. Alternatively, the field of application is in the area of training for maintenance personnel for which HMDs capable of VR are best qualified.

*Type of Support*

The experts consider the possibilities offered by AS based on RT to provide targeted information, enable communication with technical experts via remote support or carry out documentation equally beneficial for maintenance, which is shown in Figure 3.2.

The possibility to present information customised to the operator, the maintenance task and the system through the AS based on RT can be of particular help in the maintenance of highly complex systems. According to three experts, the operator is able to use the targeted information to identify more easily which object has to be maintained and how this is to be done. Thus, the time and error rate for the maintenance process can be significantly reduced.

The possibility to use remote support to employ the assistance of a specific expert who is not on site offers the advantage that the employees' knowledge is enhanced by the experience of the expert. However, one respondent of the interview stresses that training a novice is easier than directly utilising an unskilled employee with the help of remote support. In addition, another respondent comments that calling an expert and waiting for

his arrival within three or four hours is in some cases more profitable than using remote support.

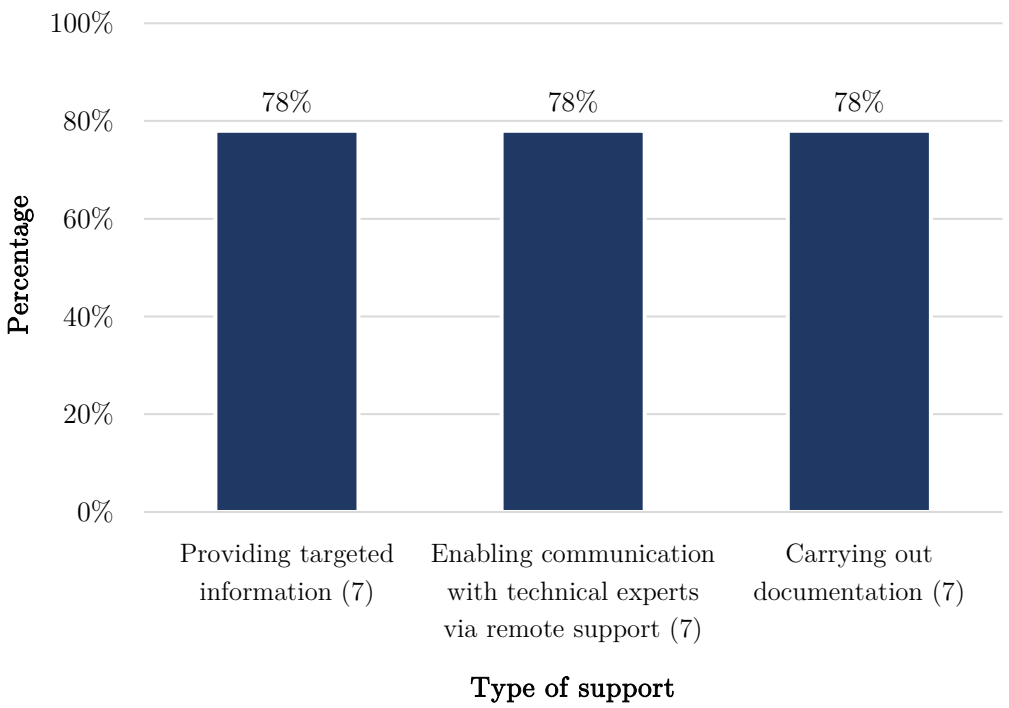



Figure 3.2: Beneficial type of support from AS based on RT in maintenance according to the subject matter experts (n = 9)

The automatic documentation of maintenance processes is in particular valuable for the evaluation of conducted maintenance processes, rarely performed maintenance processes and the training of novices. In this context, one respondent adds that the ASs can capture passive data such as working routes and working hours of the employees as well as can perform measurements and calculations. However, ethical standards must be considered for capturing passive data. Furthermore, one respondent emphasises that documentation is in some cases already carried out in an electronic form, which is usually sufficient.

### 3.3.2 Implementation Requirements

The following sections outline the results of the third part of the interview on the requirements for the implementation of ASs based on RT in maintenance.

In addition to the six requirements listed in the question, some experts add a requirement concerning safety. In general, the experts assess the relevance of the requirements rather differently. The reason for the divergent assessments is identified as the different backgrounds of the experts, which are determined by the type of industry as well as the size and type of company in which they work. However, a conclusion can be drawn that

generally, some implementation requirements are more important than others. Thus, the following sequence of decreasing relevance is derived:

1. Skills of employees
2. Financial resources
3. Acceptance of employees
4. Maturity of technologies and machines
5. Degree of digitalisation
6. Data security
7. Additional requirement: Safety

Most of the experts agree that the employees' skills are a crucial prerequisite for implementation. One expert justifies the relevance by stating that if all conditions for the introduction are given, but the employees are unable to use the ASs based on RT, the whole project is pointless. In addition, the effort involved depends on the size and resources of the company. One expert points out that due to the size and structure of his company, the training of the employees would be rather complicated, time-consuming and expensive.

Financial resources are considered by most experts to be another essential requirement for implementation. The decision of a company whether and to what extent to invest in an AS based on RT depends on the one hand, logically, on the financial resources available to the company. On the other hand, the benefits resulting from the investment for the company regarding maintenance are decisive. In this context, one expert mentions that his company has to train its maintenance staff abroad and by using ASs based on RT, the training could be carried out on-site, thus saving significant costs. Therefore, the decision to invest in ASs based on RT has to be based on the comparison between costs and benefits. However, one expert stresses in this regard the risk of uncertainty as in most cases the calculation of costs and the assessment of benefits are based on assumptions.

Most of the experts identify the acceptance by employees as another important requirement. Some experts state that in rather traditional companies, the employees are in most cases sceptical and reluctant to adapt to new technologies. The reasons given are that employees prefer to work with the technologies and equipment which they are used to and that adapting to new technologies and equipment involves significant effort. However, several experts see the chance to gain more acceptance and support for the application of ASs based on RT if the benefits to the employees in their daily work are demonstrated.

The majority of experts rate the maturity of technologies and machines as a less important prerequisite. The argument is not based on the fact that mature technologies and machines are not essential for the effective use of ASs with RT, but that the technological infrastructure is already established in their maintenance environment. Accordingly, the

experts who consider the level of maturity of the machine and technologies in their company to be insufficient ranked the requirement as more important.

Degree of digitalisation is identified by most of the experts as another less essential requirement for implementation. The justification for the decision is analogous to that used to assess the requirement concerning maturity of technologies and machines. The experts acknowledge the relevance, but consider the existing degree of digitalisation in their maintenance environment as sufficient for the implementation of ASs based on RT.

Most of the experts classify data security as another less crucial requirement for the implementation. The justification for the classification is the same as for the requirements concerning the maturity of technologies and machines as well as the degree of digitalisation. In addition, some experts comment that a high standard of data protection for the application of ASs based on RT is generally not necessary, since in most cases no sensitive or confidential data are involved.

Furthermore, some experts introduce the aspect of safety as a further requirement. The reason given is that a safety standard is required to ensure that the AS based on RT does not pose any danger to the user or the environment. However, as most companies have a sufficient safety standard and only minor adjustments may be necessary for the implementation of ASs based on RT, the requirement is considered to be less important.

### 3.3.3 Benefits and Challenges

The following sections present the results of the final part of the interview on the benefits and challenges of ASs based on RT for maintenance. The results are structured according to the questions in the final part on benefits or challenges through AR, MR or VR as well as RT in general.

*Benefits of ASs Based on AR in Maintenance*

Figure 3.3 shows the benefits of implementing ASs based on AR in maintenance according to the respondents.

Most of the respondents consider a benefit of ASs based on AR to be the optimisation of maintenance processes in the line of execution. The arguments are that with the information provided by ASs based on AR, processes can be simplified, saving time and costs. In addition, ASs based on AR can serve as quality control which reduces error rates and ultimately improves occupational safety. Moreover, accuracy is increased, because the right maintenance process is carried out and documented for the right object. Furthermore, accurate documentation enables consistency for a high level of data quality. Nevertheless, one expert points out that the risk exists that employees may rely completely on the technology instead of on their senses and experiences. Thus, ASs based on AR should support the employee and not substitute their abilities and expertise.

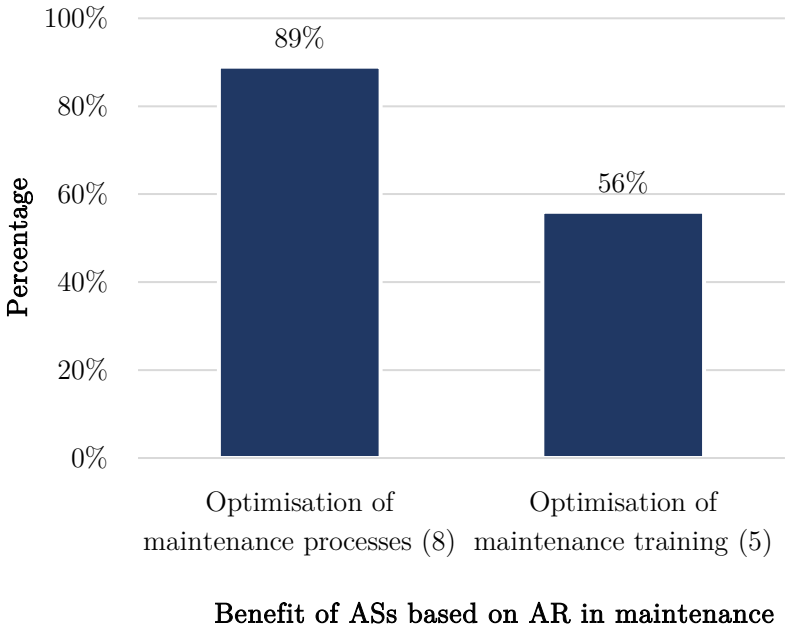



Figure 3.3: Benefits of ASs based on AR in maintenance according to the subject matter experts (n = 9)

Five experts claim that ASs based on AR have an advantage in the area of maintenance training. The reason given is that new maintenance workers can be trained directly on site, which makes training easier and more effective. In this context, however, one expert points out that AR-based training is in most cases more expensive than traditional training methods. Thus, the benefits have to be considered to determine whether the investment in ASs based on AR for maintenance training is profitable.

*Benefits of ASs Based on MR in Maintenance*

The advantages of employing ASs based on MR in maintenance according to the experts are shown in Figure 3.4.

The opinions of the experts on the greatest benefits of ASs based on MR are quite diverse. The reasons given are that most experts are not familiar with the technology and therefore, uncertain whether the application of ASs based on RT in the maintenance environment offers an advantage. In addition, some of the experts consider MR to be immature for implementation in their industry.

Five respondents indicate the advantage of remote support through ASs based on MR in performing complex tasks and in case of a shortage of skilled employees. For example, the visualisation through an MR-based HMD is better than an AR-based HMD since the FOV of the MR-based HMD is broader. In addition, four respondents state that the application of ASs based on MR in the area of training is possible, but see no further advantage in not using ASs based on AR. Moreover, two respondents argue that ASs based on MR offer

advantages for planning tasks by enabling interaction with virtual content. The planning of maintenance is improved by virtually intervening in maintenance processes or modifying maintenance equipment without affecting the real world. Furthermore, two experts currently see no benefit through ASs based on MR, since the technology is too immature for practical implementation in the industry.

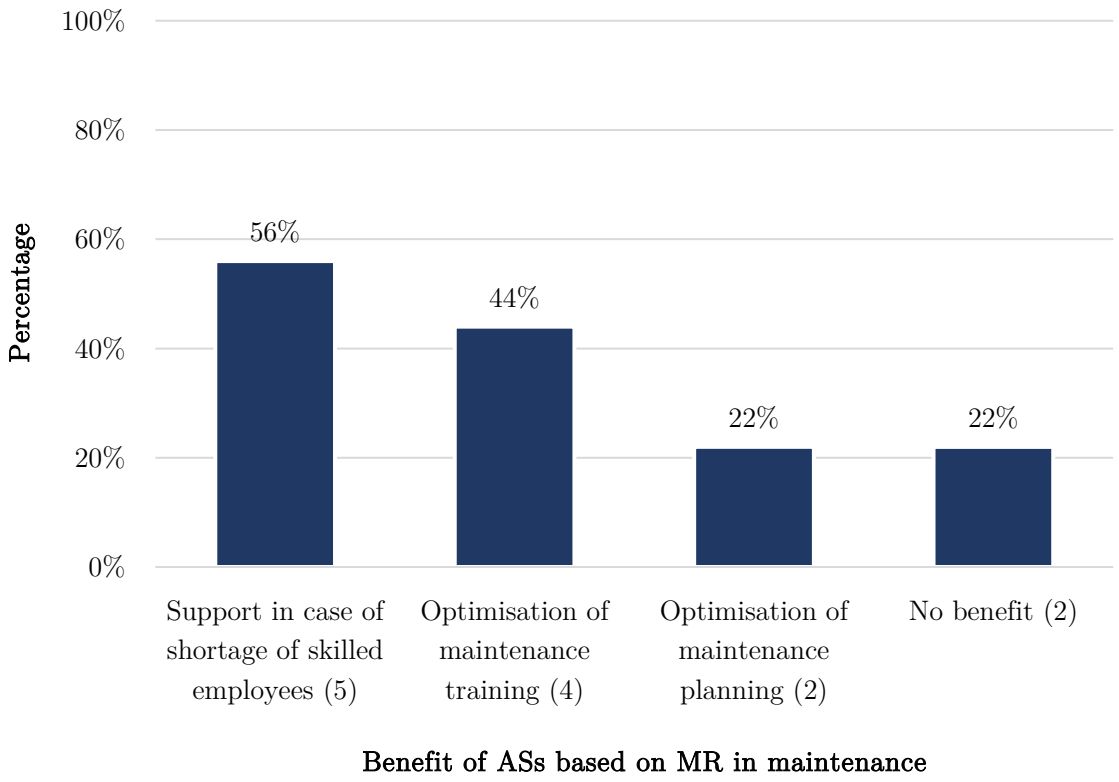



Figure 3.4: Benefits of ASs based on MR in maintenance according to the subject matter experts (n = 9)

*Benefits of ASs Based on VR in Maintenance*

The advantages of using ASs based on VR in maintenance, in the opinion of the experts, are shown in Figure 3.5.

The majority of the respondents see a main benefit of ASs based on VR in the area of maintenance training. The statement is justified on aspects concerning either safety or costs. Training for maintenance tasks that have to be carried out in hazardous environments such as high-voltage lines or in substations can be simulated in VR and thus be practised in a safe environment without real risk. In this context, one expert points out that the simulation of one-off incidents is not profitable and that the focus should be on regularly encountered high-risk conditions. Furthermore, from an economic perspective, costs could be reduced as training requires no physical equipment which is very expensive

in most cases. In addition, costs can be minimised as training can be performed on-site. For one respondent, the training concerned the maintenance of wind turbines for which the training has to be relocated. In this case, safety aspects play an important role as well. For another respondent, the training for the maintenance of machines had to be carried out overseas, since not the company itself but the machine manufacturer had the necessary knowledge and therefore provided the training courses. In this case, VR-based training enables the company to reduce a significant amount of time and costs.

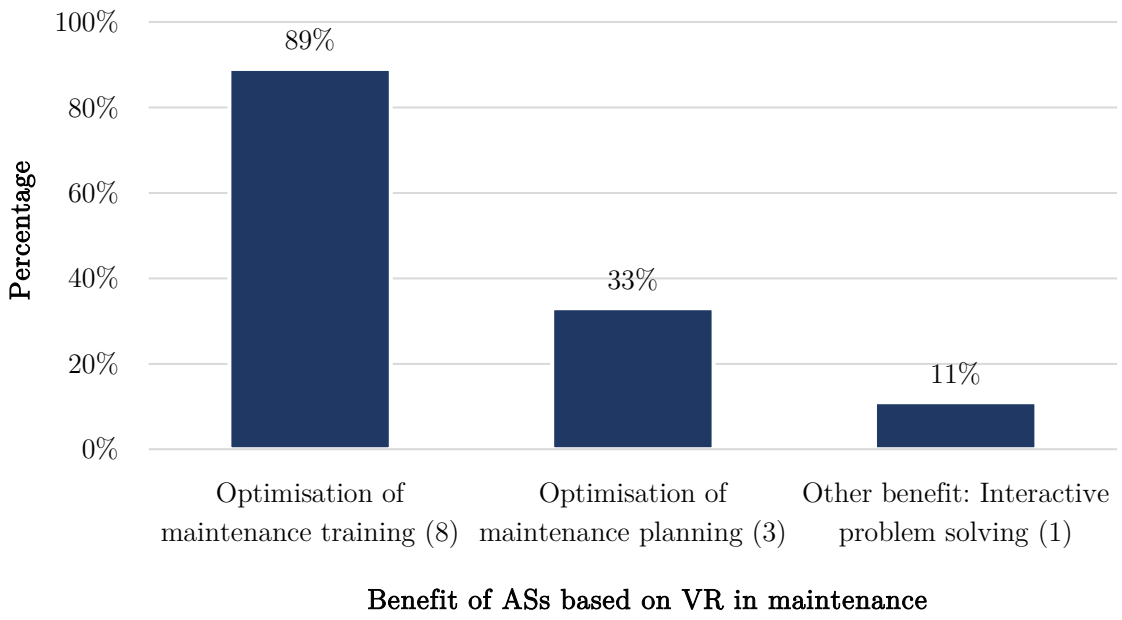



Figure 3.5: Benefits of ASs based on VR in maintenance according to the subject matter experts (n = 9)

Three respondents state that a major advantage of ASs based on VR in maintenance is in the area of planning. The argument is based on the fact that a lot and various kinds of resources are wasted in the process of planning which can be avoided with the application of ASs based on VR. Furthermore, one expert mentions that ASs based on VR can be utilised as a tool for interactive problem solving. For instance, the maintenance technician is able to simulate a machine generating errors, which simplifies and accelerates the identification of actual problems such as faulty items.

*Challenges of ASs Based on RT in Maintenance*

The evaluation of the results shows that although the experts mentioned challenges regarding a certain type of RT, these challenges are also applicable to the other types of RT. Thus, the identified challenges are summarised for RTs in general. In summary, the

experts mention challenges related to costs, technical implementation, risks of distraction as well as risks of dependency and deskilling. An overview is shown in Figure 3.6.

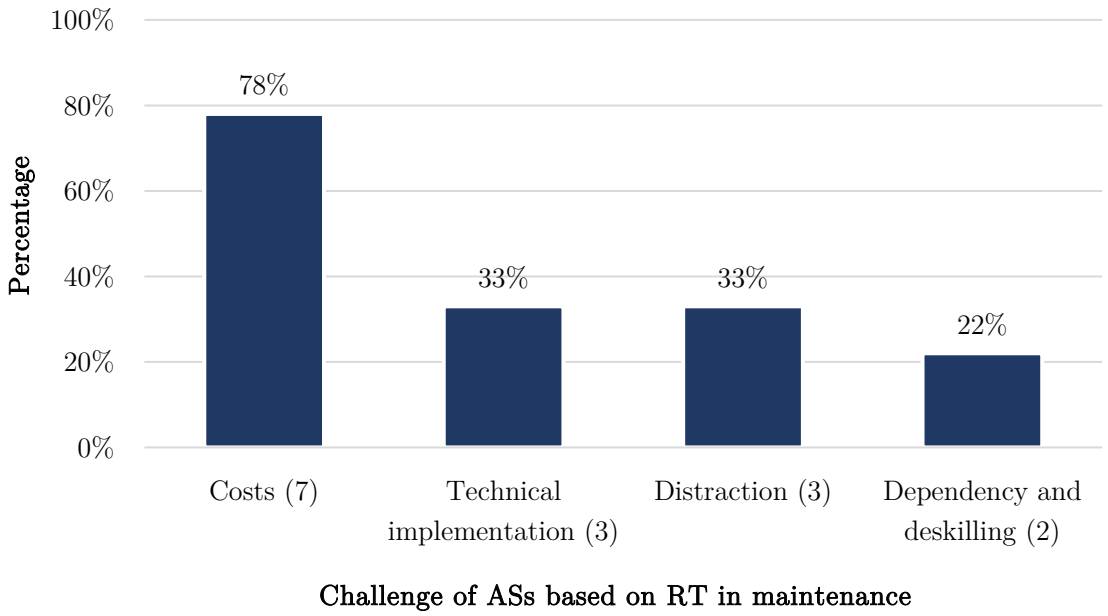



Figure 3.6: Challenges of ASs based on RT in maintenance according to the subject matter experts (n = 9)

The majority of the experts identify costs as the main challenge. The application of ASs based on RT involves direct costs for hardware and software. In this context, one expert points out that technological obsolescence for ASs based on RT is at a very high rate and therefore the upkeep of technology is very expensive. A further cost factor is the setup of a technical infrastructure, which is necessary for the application of ASs based on RT. One expert underlines in this context that a stable internet connection is essential for the effective use of digital ASs. However, setting up a network in remote, restricted, difficult to access or unusual environments such as mines is rather challenging. Moreover, new capacities need to be created, which leads to further costs. For the implementation, a project team is required for the organisation of the application. In addition, one expert states that a certain level of knowledge is required for the implementation, which is obtained by training existing employees or by hiring new specialists. Regarding the application, three experts underline the challenge of integrating ASs with a sustainable and long-term approach. For example, capacities for the maintenance of the AS itself have to be ensured. In general, the experts' answers indicate concerns as to whether the benefits outweigh the costs and efforts caused by the application of ASs based on RT. In this context, one expert raises the question of how practical ASs based on RT are in the maintenance environment.

Furthermore, three experts see challenges relating to the technical implementation. The problem of which data is transmitted to the AS for which purpose and how has to be addressed. One expert points out that if maintenance is based on analogue methods, the data has to digitised for the application of ASs based on RT, which involves a massive effort. Moreover, concerns are expressed about health and safety in the use of ASs based on RT. The digital devices can distract both easily and quickly, thus posing a risk for employees and the environment. In addition, two experts emphasise the risk of dependency and deskilling. The possibility exists that employees rely too much on the AS and neglect their senses or experience to think critically. In the event of an error in the system, consequences may arise that could easily have been avoided.

### 3.3.4 Empirical Analysis of Application Characteristics and Implementation Requirements

Based on the results of the interviews, various conclusions can be drawn regarding the application characteristics and the implementation requirements for ASs based on RT in maintenance.

Regarding the application characteristics, the type of RT is selected based on the nature of the application. AR and MR are preferred for the execution of maintenance tasks, while VR is favoured for maintenance training or planning tasks. The selection of an output device depends on the nature of the application as well as the characteristics of the output device. The preferred output devices are visual output devices in the form of HHDs or HMDs. The decision to select HHDs in form of smartphones or tablets is either because these devices are well known to maintenance workers from their daily life and therefore the adaption to use them would be easy or because HHDs are already integrated into the maintenance environment and therefore would be the most cost-effective solution. In addition, the technical advantages such as better visualisation, larger FOV or better battery life are decisive for the selection of HHDs over HMDs. However, HHDs are preferred if an AS is required that does not have to be carried by hand, because, for example, a maintenance worker is required to perform maintenance tasks. Furthermore, the possibilities offered by ASs based on RT to provide targeted information, to enable communication with technical experts via remote support and to carry out documentations are considered to be valuable for maintenance.

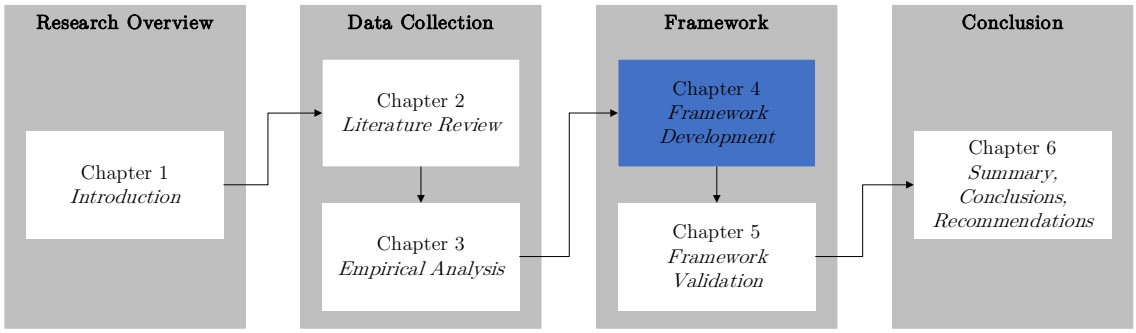
Regarding the implementation requirements, the results of interviews show that the requirements concerning skills of employees, financial resources, acceptance of employees, maturity of technologies and machines, degree of digitalisation, data security and safety play a role for the implementation of ASs based on RT in maintenance. In terms of financial resources, the conclusion is drawn that in addition to the costs, the benefits of using ASs based on RT in maintenance have to be taken into account. Thus, the costs have to be

weighed up against the benefits to make a profound decision on whether the investment in ASs based on RT is profitable. Furthermore, the individual circumstances of the maintenance department or the company determine which requirements are more important than others. Thus, a generally valid sequence for the relevance of the implementation requirements cannot be derived.

## 3.4 Concluding Summary

In this chapter, an empirical analysis on ASs based on RT in maintenance is performed. Semi-structured interviews are utilised as a method and the participants in the interviews are nine subject matter experts. Based on the results of the interviews, the following conclusions can be drawn. Regarding the application characteristics, the nature of the application and the features of the output device are decisive for the selection of an AS based on RT. Regarding the implementation requirements, the requirements concerning skills of employees, financial resources, acceptance of employees, maturity of technologies and machines, degree of digitalisation, data security and safety are relevant to the implementation into maintenance. However, the sequence of the relevance has to be determined individually according to the given circumstances.

# Chapter 4
# Development of the Decision Support Framework for Reality Technologies in Maintenance




The objective of this chapter is the development of a framework that assists companies with the identification, selection and implementation of ASs based on RT in maintenance (RO7), thus providing the first part of the answer for the PRQ. At the beginning of this chapter, the design requirements for the framework are defined and based on this, the structure and the steps of the framework are presented.

## 4.1 Design Requirements

The development of the design requirements is based on the proposal given by Jabareen (2009, p. 52) to draw theories from the data collection. Thus, six design requirements are derived for the proposed framework from the results identified through the background literature reviews and the systematic literature review in chapter 2 as well as the interviews in chapter 3. In addition, the research questions and the delimitations of the thesis are further influencing factors for the design of the proposed framework.

The design requirements are classified either as a layout requirement (LR) or a content requirement (CR). LRs indicate how the proposed framework is to be structured in general, while CRs specify the subject areas to be covered within the proposed framework. Table 4.1 shows an overview.

Table 4.1: Overview of design requirements for the proposed framework

| Requirement | | Description |
|---|---|---|
| Layout | LR1 | User-friendly handling |
| | LR2 | No previous knowledge about reality technology required |
| Content | CR1 | Overview of hardware and software |
| | CR2 | Overview of the implementation requirements |
| | CR3 | Feasibility Study |
| | CR4 | Guideline for implementation |

The following sections discuss in more detail the reasons for defining the design requirements and outline their implications for the proposed framework.

The requirement for user-friendly handling (LR1) is derived primarily from the delimitation of the thesis to design a generic framework that can be used by any person regardless of their position in the company. In addition, as a result of the PRQ, the emphasis is on the fact that the framework is intended to support companies in the industry and therefore, to be practical. Thus, the degree of detail is crucial to ensure that the proposed framework is comprehensive and covers the relevant topics while being concise and well structured.

The requirement which implies that no knowledge about RTs is necessary to apply the framework (LR2) is concluded on the one hand from the delimitations of the thesis that the framework can be employed by any person regardless of their level of knowledge. On the other hand, the results of the interviews indicate that the majority of users do not have fundamental knowledge about RT. The proposed framework is therefore to be structured in such a way that the users only require to know for which maintenance application the AS based on RT is intended, but the information about the AS based on RT is provided through the framework.

The requirement for an overview of hardware and software (CR1) resulted from the background literature review on AS based on RT and the interviews. The background literature review demonstrates that a broad range of hardware, which includes output devices, input devices and tracking devices as well as software, which includes the development platform, is available for practical use. However, the interviews point out that especially for the output devices only visual output devices in form of HMDs or HHDs are known. Thus, the proposed framework is required to provide a comprehensive overview of hardware and software to determine the optimal solution for the intended maintenance application of the user from a technical perspective.

The requirement for an overview of the necessary conditions for the implementation (CR2) of an AS based on RT into maintenance is derived from the systematic literature review and the interviews. The results show that various requirements concerning employees, technology and safety have to be considered. Consequently, the proposed framework has to incorporate the implementation requirements in a manner that users are informed about the conditions that are crucial for the successful application in their specific case.

The requirement for a feasibility study (CR3) is concluded from the delimitations of the thesis and the interviews. The delimitation of this research to develop a practical framework for industry implies the consideration of the economic aspects as well. For a company, the application of an AS based on RT represents a viable option only if the investment is profitable. In addition, the results of the interviews underline the significance of economic considerations. Therefore, the proposed framework has to include the economic assessment of the application of ASs based on RT in maintenance.

The requirement for an implementation guideline for ASs based on RT into maintenance is defined from the PRQ and the systematic literature review. The PRQ includes besides the identification and selection also the implementation of ASs based on RT. Furthermore, the results of the interviews indicate that thorough implementation planning is crucial for a sustainable and long-term application of new systems in maintenance. Thus, the proposed framework is required to provide a form of support for the implementation of ASs based on RT in maintenance.

## 4.2 Structure of the Framework

Against the background of the four CRs, the following four steps are derived for the proposed framework:

1. Context analysis
2. Implementation requirements analysis
3. Cost-benefit analysis
4. Implementation guideline

In the first two steps support is provided for identification, in the third step for selection and in the final step for implementation of ASs based on RT in maintenance. Therefore, the proposed framework is referred to as *Decision Support Framework for Reality Technologies in Maintenance* (**DSF-RTM**).

The two LRs shaped the structure of the DSF-RTM. The structure is shown using a flow chart in Figure 4.1. The flow chart applies elements of a programming flow chart: A rectangle with rounded corners indicates the start or the stop, an arrow connects an element with the following element, a rectangle represents an operation and a rhombus symbolises a decision (DIN66001, pp. 3–6).

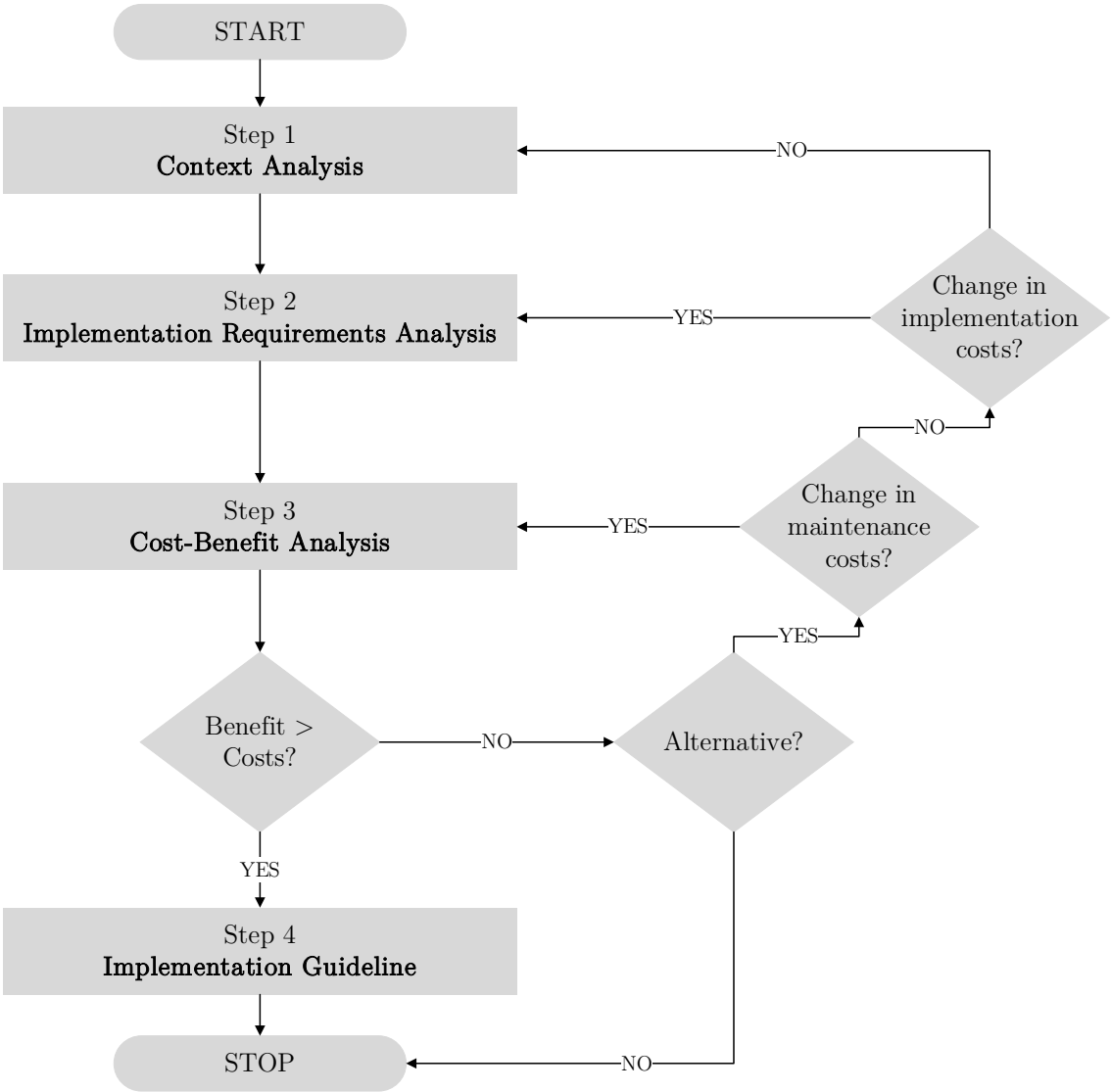



Figure 4.1: Flow chart of the DSF-RTM

The following sections describe the structure as well as outlining the steps and their objectives of the DSF-RTM.

The start of the DSF-RTM is the context analysis as a first step. In the context analysis, the optimal AS based on RT for the intended maintenance application of the user is identified. In addition, the costs for the identified AS based on RT are assessed. The objective of the first step is the identification of the suitable AS based on RT with the respective costs.

The second step of the DSF-RTM involves the analysis of the implementation requirements. In this step, the environment of the intended maintenance application of the user is examined to determine what adjustments are necessary to achieve the implementation requirements. In addition, the costs of the identified adjustments are

assessed. The objective of the second step is the identification of the adjustments for implementation with the respective costs.

The cost-benefit analysis is the third step of the DSF-RTM. For the assessment of the costs, the acquisition and operating costs are considered. The acquisition costs cover the hardware costs identified in the first step and the implementation costs identified in the second step. The operating costs include the software costs identified in the first step and the maintenance costs identified in this step. For the assessment of the benefits, the benefits for maintenance resulting from the application of an AS based on RT are determined. The objective of the third step is to weigh up the costs against the benefits and depending on the outcome, to decide whether to select the identified AS based on RT or not.

In the case that the costs outweigh the benefits, a decision has to made whether to investigate an alternative solution or to end the framework because the identified AS based on RT is nevertheless acceptable or no suitable solution is available. In the case that an alternative solution is to be investigated, the next decision is to determine whether the cost for the hardware and software, the implementation or the maintenance are to be adjusted. Consequently, three possibilities arise. First, in the case that the hardware and software costs are to be adjusted, the next step is once again the context analysis. Second, in the case that the implementation costs are to be adjusted, the next step is once again the implementation requirements analysis. Third, in the case that the maintenance costs are to be adjusted, the next step is once again the cost-benefit analysis. Thus, the objective is to identify and select the optimum solution for the user in an iterative process.

In the case that the benefits outweigh the costs, an implementation guideline is provided as the final step of the DSF-RTM. The guideline presents an overview of the phases and details to be considered for the long term and the sustainable implementation of ASs based on RT into the maintenance environment. The objective of the fourth step is to provide support within the framework for the implementation phase in addition to the identification and selection phase.

## 4.3 Decision Support Framework for Reality Technologies in Maintenance

In the next sections, the four steps and the respective methods utilised for the DSF-RTM are discussed in more detail.

### 4.3.1 Context Analysis

The objective of the context analysis is the identification of the optimal AS based on RT for the user's intended maintenance application with the respective costs. For the identification of the AS based on RT, the components output device, input device, tracking

device and development platform have to be determined. The decisive element of the AS based on RT is the output device and therefore the context analysis starts with the identification of the output device.

Based on that, the context analysis is structured in four sub-steps. First, the identification of the output device. Second, the identification of the costs for the hardware. Third, the identification of the costs for the software. Fourth, the calculation of the costs for the identified hardware and software.

*Sub-step 1.1 – Identification of Output Device*

Against the background of LR1 and LR2, the type of output device is to be identified with a simple tool that requires no prior knowledge of RT. Consequently, the tool cannot be developed from the point of view of the AS based on RT. However, the point of view of the intended maintenance application of the user can be used as a starting point.

From the systematic literature review it can be derived that the definition of the application environment is possible using physical conditions. Since output devices are divided into visual, auditive and tactile devices or distinguished into mobile or stationary devices in the background literature review, the physical conditions concerning light, noise and working space are relevant. Thus, the indications shown in Table 4.2 can be derived for the environment of the application.

Table 4.2: Indications on the environment of the application

| Condition | Indication |
|---|---|
| Lighting conditions | Dark or bright environment |
| Noise level | Quiet or noisy environment |
| Working Space | Open or closed environment |

In addition, from the background literature review it can be derived that the nature of the application can be determined through further distinguishing characteristics of output devices. The distinguishing characteristics for output devices in general are whether and how the device is worn as well as the type of RT that the device provides. In addition, the size of the display in particular for visual output devices. A distinction is made between small-, medium- and large-size displays. In this thesis, the display of a smartphone is defined as small-size, the display of a tablet as medium-size and any display equal to or larger than the display of a laptop or desktop PC as larger-size. In summary, the indications shown in Table 4.3 can be derived for the nature of the application.

Table 4.3: Indications on the nature of the application

| Characteristic | | Indication |
|---|---|---|
| Required transportation | | Mobile or stationary application |
| Way of transportation | | Application does or does not require the user to be hands-free |
| Type of RT | AR | Application does or does not require the real world with overlaid virtual content |
| | MR | Application does or does not require the real world with overlaid virtual content and the interaction with the virtual content |
| | VR | Application does or does not require the virtual world without the real world |
| Size of display | Small | Application does or does not require a small-size display |
| | Medium | Application does or does not require a medium-size display |
| | Large | Application does or does not require a large-size display |

Against the background of the defined indications, a flow chart is established for the identification of the suitable output device for the intended maintenance application of the user. The flow chart is presented in three parts in the following sections to provide a clear and simplified explanation. A comprehensive overview of the flow chart is shown in Appendix B. For the flow chart, the elements of a programming flow chart are utilised. In addition, different colours are applied to indicate the type of output device: visual output devices using green, auditive output devices using blue and tactile output devices using orange.

The flow chart starts with the decision about whether a hands-free device is required, as this requirement is the decisive factor to distinguish most output devices. Figure 4.2 shows the part of the flow chart for the case that a hands-free output device is necessary. For the further identification of a hands-free output device, the next decision determines whether the real world is necessary for the application. In the case that the real world is not required to be present and thus only the virtual world, a visual solution in form of a VR-based HMD is proposed. In the case that the real world is required to be present, the next question queries whether a noisy environment is prevalent. Irrespective of the result, the following question checks whether a bright environment is present. This results in four possibilities: First, in the case of a non-noisy and bright environment, an AR-based auditive solution in form of headphones or loudspeakers is presented. Second, in the case of a non-noisy and non-bright environment, the option is to choose between loudspeakers, headphones, AR-

based HMD, MR-based HMD or a vibrotactile bracelet. The user can decide this based on their own preferences or the costs which are provided within the framework. Third, in the case of a noisy and bright environment, an AR-based tactile solution in form of vibrotactile bracelets is suggested. Fourth, in the case of a noisy and non-bright environment, a visual solution in form of a HMD is recommended. If the application requires an interaction with the virtual content a MR-based model is suitable, otherwise an AR-based model.

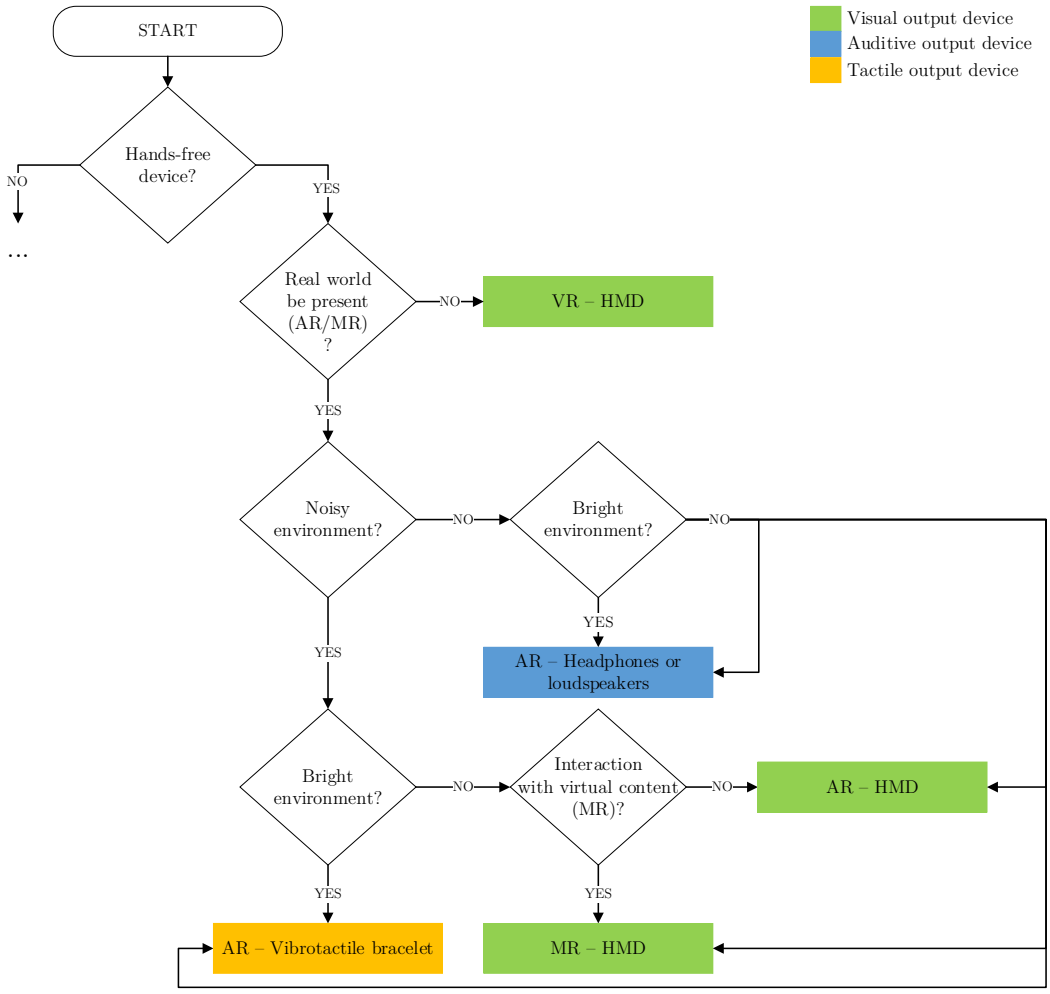



Figure 4.2: Part of the flow chart in which hands-free output devices are identified

Figure 4.3 shows the part of the flow chart for the case that not a hands-free and not a mobile output device but a stationary output device is required. For the further identification of a stationary output device, the following question asks whether an AR-based visual solution is suitable. In the case that an AR-based solution is suitable, a distinction is made whether a screen-based solution in form of a desktop PC or a laptop and a projector-based solution in the form of an SAR display is recommended. In the case that a VR-based solution is required, three options are possible: For a screen-based solution

a desktop PC or laptop is required, whereas for a closed environment a CAVE or otherwise a stereoscopic projection system is suitable.

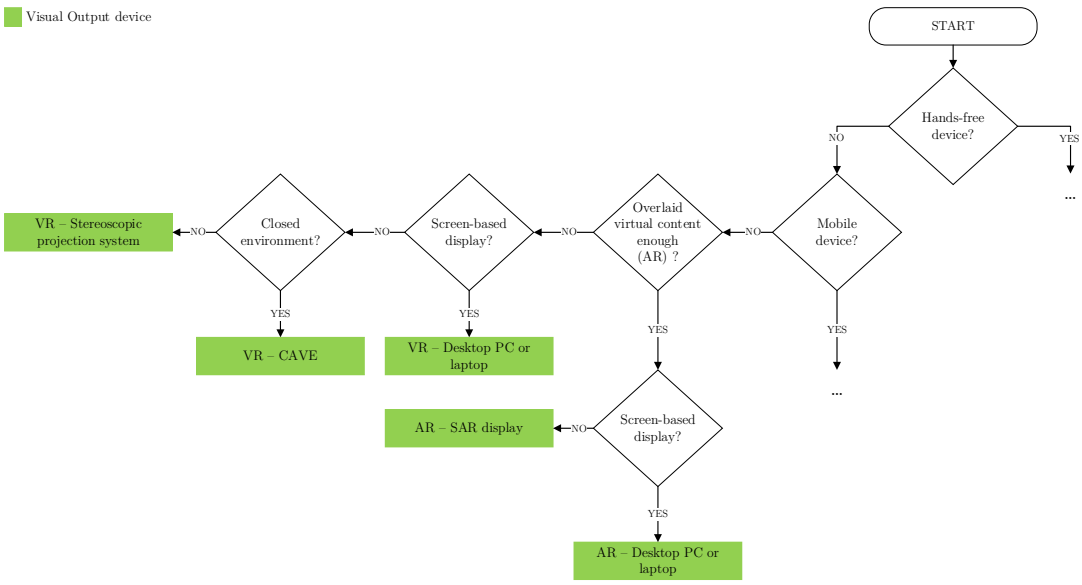



Figure 4.3: Part of the flow chart in which stationary output devices are identified

Figure 4.4 shows that part of the flow chart for the case where not a hands-free but a mobile output device is required. For the further identification of a mobile device, the next question asks whether the intended environment is noisy. In the case of a noisy environment, an AR-based auditive solution in form of headphones or loudspeakers is proposed. In the case of a non-noisy environment, the following decision determines whether a bright environment is prevalent. This results in two possibilities: First, in the case of a bright environment, no output device is available as a suitable solution. Second, in the case of a non-bright environment, a visual output device in form of an HHD is suggested. Since several types of HHDs can be distinguished based on the type of RT presented or the size of the display, a distinction is made whether an AR-based or a MR-based smartphone or tablet is recommended.

*Sub-step 1.2 – Identification of Hardware Costs*

Following the identification of the suitable output device based on its technical characteristics for the intended maintenance application of the user, the respective costs are considered. Since several cost assessments are performed within the DSF-RTM, to ensure their comparability, the cost metric and respective rating shown in Table 4.4 are defined as a standard for the DSF-RTM. The definition of the ranges is based on the analysis of the identified costs throughout the framework for the lowest and highest costs as well as in which range the most costs are identified.

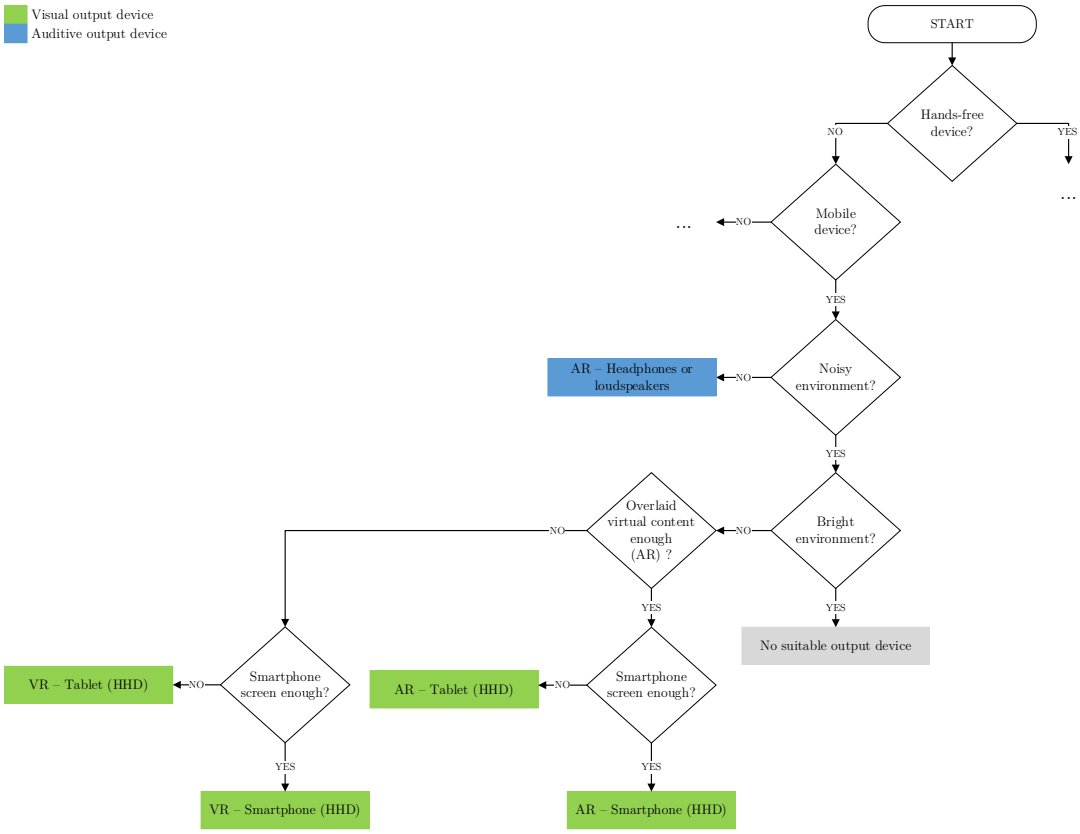



Figure 4.4: Part of the flow chart in which mobile output devices are identified

Table 4.4: Cost metric applied throughout the DSF-RTM

| Range of Costs | Cost Metric | Rating |
|---|---|---|
| X > 5.000€ | High | 5 |
| 1.000€ < X <= 5.000€ | Medium | 3 |
| X <= 1.000€ | Low | 1 |
| X = 0 | None | 0 |

The cost assessment of the currently available hardware of ASs based on RT – output device, input device and tracking device – is based on a price analysis carried out on 19 October 2020. For the analysis, prices are obtained either from the website of the manufacturer, a price enquiry to the manufacturer or from literature. The references for the price analysis are listed in Appendix C.

An overview of the cost assessment of currently available output devices is shown in Table 4.5. In addition, the respective input devices embedded in the output devices are listed.

The reason is to provide the user with the possibility to determine whether the embedded input devices are sufficient or whether additional input devices are required.

Table 4.5: Overview of output devices with respective embedded input devices and the classification of the respective costs

| Output Device | Embedded Input Device | Costs | Rating |
|---|---|---|---|
| AR-HMD | Camera, microphone, buttons, touch surface | Medium | 3 |
| MR-HMD | Camera, microphone, buttons, touch surface | Medium | 3 |
| VR-HMD | Camera, microphone, buttons, touch surface | Medium | 3 |
| Smartphone | Camera, microphone, buttons, touch screen | Medium | 3 |
| Tablet | Camera, microphone, buttons, touch screen | Medium | 3 |
| Laptop | Camera, microphone, touch surface/ screen | Medium | 3 |
| Desktop PC | Camera, microphone | Medium | 3 |
| SAR display | – | Medium | 3 |
| Stereos. proj. syst. | – | High | 5 |
| CAVE | – | High | 5 |
| Headphone | Microphone, buttons, touch surface | Low | 1 |
| Loudspeaker | Buttons, touch surface | Low | 1 |
| Vibrot. bracelet | Buttons, touch surface | High | 5 |

In sub-step 1.2, the first decision is whether and which type of additional input devices are required for the user's intended maintenance application. In the case that no additional input devices are necessary or the input devices embedded in the identified output devices are sufficient, no further costs arise at this point. In the case that no input devices are integrated into the identified output device or the embedded input devices are insufficient, one or more additional input devices can be identified depending on the identified output device, the requirements of the intended maintenance application, the costs or the user's own preferences. Table 4.6 shows an overview of the cost assessment of the currently available input devices.

Subsequently, a decision has to made whether and which type of tracking devices are required for the user's intended maintenance application. In the case that no tracking devices are required, no additional costs arise at this point. Otherwise, one or more types of tracking devices can be identified depending on the identified output and input devices,

the intended maintenance application, the costs and the user's own preferences. An overview of the cost assessment of the currently available tracking devices is shown in Table 4.7.

Table 4.6: Overview of additional input devices with the classification of the respective costs

| Additional Input Device | Costs | Rating |
|---|---|---|
| Camera | Low | 1 |
| Microphone | Low | 1 |
| PC mouse/ space mouse | Low | 1 |
| Keyboard | Low | 1 |
| Joystick | Low | 1 |
| Controller | Low | 1 |
| Data glove | Medium | 3 |
| Vibrotactile bracelet | High | 5 |

Table 4.7: Overview of tracking devices with the classification of the respective costs

| Tracking Device | | Costs | Rating |
|---|---|---|---|
| Sensor-based tracking | Electromagnetic sensor | Low | 1 |
| | Acoustic sensor | Low | 1 |
| | Inertial sensor | Low | 1 |
| | Optical sensor | Low | 1 |
| | Mechanical sensor | High | 5 |
| Camera-based tracking | Marker-based tracking | Low | 1 |
| | Vision-based tracking | Low | 1 |

*Sub-step 1.3 – Identification of Software Costs*

After identifying the hardware of the AS based on RT, the software has to be determined. The software for ASs based on RT is either included in the price of the output device, has to be purchased with a licence or is available free of charge. In Table 4.8, an overview of the cost assessment of the currently available development platforms is shown. The price

analysis for the development platforms was carried out on 10 October 2020. For the analysis, the prices were obtained from the website of the manufacturer. The references of the price analysis for the development platforms are listed in Appendix C.

Table 4.8: Overview of development platforms with the classification of the respective costs

| Development Platform | License | Costs per Year | Rating |
|---|---|---|---|
| Programming Language | Free | None | 0 |
| Game Engine | Proprietary | None (Included in hardware price) | 0 |
| | Commercial | Medium | 3 |
| | Free | None | 0 |
| Software Platforms | Proprietary | None (Included in hardware price) | 0 |
| | Commercial | Medium | 3 |
| | Free | None | 0 |
| SDK | Proprietary | Medium | 3 |
| | Commercial | None (Included in hardware price) | 0 |
| | Free | None | 0 |

*Sub-step 1.4 – Calculation of Hardware Costs and Software Costs*

In the final sub-step of the context analysis, the costs for hardware and software are calculated. For the hardware, the ratings for the output device, input device and tracking device identified in sub-step 1.2 are summed, which is shown in equation 4.1. In the case that multiple devices are determined for input or tracking, these ratings are added. The following abbreviations are applied for the clear presentation of the equation: rating (R), hardware costs (HC), output device (OD), input device (ID) and tracking device (TD).

$$R_{HC} = R_{OD} + R_{ID} + R_{TD} \tag{4.1}$$

Table 4.9 shows the cost metric utilised to classify the hardware costs as low, medium or high costs and indicates the respective rating.

Table 4.9: Cost metric and rating of hardware costs

| Range of Rating | Cost Metric | New Rating |
|---|---|---|
| X > 18 | High | 5 |
| 8 < X <= 18 | Medium | 3 |
| X <= 8 | Low | 1 |
| X = 0 | None | 0 |

For the software costs, the rating identified in sub-step 1.3 is to be considered since the costs for the development platform are the only cost factor for the software.

### 4.3.2 Implementation Requirements Analysis

Following the identification of the optimal AS based on RT in the first step, the objective of the second step is to identify the adaptations to fulfil the implementation requirements for the AS based on RT into the maintenance environment and the respective costs. The implementation requirements derived from the systematic literature review and evaluated for relevance in the interviews are used as a basis. The result of the evaluation in the interviews is as follows in decreasing order of relevance:

1. Skills of employees
2. Financial resources
3. Acceptance of employees
4. Maturity of technologies and machines
5. Degree of digitalisation
6. Data security
7. Safety

The reason why financial resources are defined as a requirement is that the implementation of AS based on RT is only feasible if the investment is economically profitable. As CR3 requires that a feasibility study is conducted within the framework, a cost-benefit analysis is applied in the third step to determine whether the investment of an AS based on RT is profitable. Therefore, the requirement for financial resources is not taken into account in the context of the implementation requirements analysis.

The implementation requirements analysis consists of three sub-steps. First, the evaluation of the weighting of the requirements according to their relevance. Second, the identification of the adjustments and resulting costs for the fulfilment of the requirements. Third, the calculation of the costs for implementation.

*Sub-step 2.1 – Weighting of Requirements*

The evaluation of the implementation requirements in the interviews resulted in a certain ranking. However, this also indicated that the level of importance of the requirements differed among the experts based on their circumstances. Thus, the ranking is not applicable in general. Against the background of LR1 and to enable the evaluation of the requirements to be performed based on individual circumstances, a template for a pairwise comparison is provided. The template is shown in Figure 4.5.

| Compared to requirement / Requirement | Acceptance of employees | Skills of employees | Maturity of technologies and machines | Degree of digitalisation | Data security | Safety | **SUM** |
|---|---|---|---|---|---|---|---|
| Acceptance of employees | | | | | | | |
| Skills of employees | | | | | | | |
| Maturity of technologies and machines | | | | | | | |
| Degree of digitalisation | | | | | | | |
| Data security | | | | | | | |
| Safety | | | | | | | |

Figure 4.5: Template for pairwise comparison

The pairwise comparison allows the evaluation of each requirement against the other requirements to determine how important each of them is. The method by which the pairwise comparison is conducted consists of using the number zero, one or two if the row value is less important (0), equally important (1) or more important (2) compared to the column value. In the end, the row value is added up and divided by the total sum (Drews and Hillebrand 2007, pp. 132–135). Thus, the relevance of the order of the individual requirements is determined. Subsequently, the requirements are weighted depending on the determined order. Since the total number of requirements is six, the first requirement is weighted with six, the second requirement with five and onwards.

*Sub-step 2.2 – Identification of Adjustments*

Following the evaluation of the weighting of the requirements, the second sub-step includes determining the adjustments and associated costs necessary to achieve the requirements.

Since each user has to apply individual adjustments for the intended maintenance application, three general possibilities and the respective costs are provided for each requirement. The idea behind the general possibilities is that a requirement is either fulfilled or not. In the case where a requirement is fulfilled, no further adjustments are necessary. In the case where a requirement is not fulfilled, either the current features can be changed or new features can be integrated.

Against the background of LR1 to establish a user-friendly framework, a description is necessary to define if a requirement is or is not fulfilled. The description is intended to serve as a brief definition, but at the same time not be too detailed and to be generally valid, as the framework is to be applied independently of the industry.

In the following sections, the possible adjustments for the implementation requirements are outlined.

The requirement regarding the acceptance of employees includes that the employees are willing to use the AS based on RT. Thus, the following definition for this requirement is developed:

*"The employees must accept the assistance system based on reality technology or at least be open to integrate it into their working environment."*

In case the level of acceptance is sufficient or insufficient, Table 4.10 shows the possible adjustments with the respective costs. If the acceptance of the employees is not sufficient, the most suitable solution is to show the advantages of the AS based on RT for the daily working life through training. As an expensive but rather unlikely alternative, new employees can be hired who are willing to use the new technology.

Table 4.10: Adjustments for the requirement "acceptance of employees"

| Status | Adjustment | Costs | Rating |
|---|---|---|---|
| Sufficient level of acceptance | None | None | 0 |
| Insufficient level of acceptance | Training of existing employees | Low | 1 |
| | Recruiting of new employees | Medium | 3 |

The requirement concerning the skills of employees describes the necessity for the implementation that the employees are well versed with the AS based on RT on a technological basis. The employees are required to know how to successfully integrate the hardware and software into the maintenance environment. In addition, the knowledge for

sustainable usage must be available, including the maintenance of the AS based on RT itself. Therefore, the following definition for this requirement is established:

"*Employees must be well versed with the hardware including the output, input and tracking devices as well as with the respective software to enable a successful implementation and sustainable usage in maintenance.*"

Table 4.11 shows the possible adjustments with the respective costs in the case where the result is a sufficient or insufficient level of skills according to the definition. In the case that there is an insufficient level of knowledge, but the employees are interested in the topic and the company offers the opportunity, the employees can be trained to the required level of knowledge. The cost of training is considerably lower than recruiting new employees specialised in the field of AS based on RT.

Table 4.11: Adjustments for the requirement "skills of employees"

| Status | Adjustment | Costs | Rating |
|---|---|---|---|
| Sufficient level of skills | None | None | 0 |
| Insufficient level of skills | Training of existing employees | Low | 1 |
| | Recruiting of new employees | Medium | 3 |

The requirement concerning the maturity of technologies and machines includes that a technological basis must be given to ensure the implementation and long-term usage of the AS based on RT. Depending on the nature of the application, different maturity levels are required. For instance, if the AS based on RT is intended as a digital guide for maintenance tasks, a lower maturity level is necessary than if the AS based on RT is intended to be able to retrieve data from machines automatically. The following definition is therefore provided for this requirement:

*"Technologies and machines that are part of the maintenance must be mature enough depending on the intended application for the successful implementation and sustainable usage of the assistance system based on reality technology in maintenance."*

An overview of the possible adjustments in case of a sufficient or insufficient level of maturity is shown in Table 4.12 . If the maturity level is insufficient and depending on the nature of the application of the AS based on RT, a decision can be made whether an upgrade of the installed technologies and machines is enough or whether new equipment must be procured.

Table 4.12: Adjustments for the requirement "maturity of technologies and machines"

| Status | Adjustment | Costs | Rating |
|---|---|---|---|
| Sufficient level of maturity | None | None | 0 |
| Insufficient level of maturity | Upgrade of existing technologies and/or machines | Low | 1 |
| | Purchase of new technologies and/or machines | Medium | 3 |

The requirement regarding the degree of digitalisation implies the necessity for a digital network to enable the implementation and sustainable usage of the AS based on RT. For example, if an analogue method of data storage is used, the relevant data has to be digitised for the successful implementation of the AS based on RT. Furthermore, if the application requires the AS based on RT to retrieve data from the machine in real-time, a stable internet connection is crucial at the point of use. However, if the application requires the AS based on RT to retrieve data not in real time but once a day, it is not essential to have a stable internet connection at the point of use. The data can be retrieved at a location where a stable internet connection is available. Thus, the following definition for this requirement is established:

*"The degree of digitalisation must be sufficient depending on the intended application to ensure the successful implementation and sustainable usage of the assistance system based on reality technology in maintenance."*

Table 4.13 shows the possible adjustments in case of a sufficient or insufficient degree of digitalisation. In the case of an insufficient degree of digitalisation as well as depending on the intended application and the circumstances, a decision must be made whether an upgrade of the existing standard is suitable or a new standard is required.

Table 4.13: Adjustments for the requirement "degree of digitalisation"

| Status | Adjustment | Costs | Rating |
|---|---|---|---|
| Sufficient degree of digitalisation | None | None | 0 |
| Insufficient degree of digitalisation | Upgrade of existing digitalisation standard | Low | 1 |
| | Development of a new digitalisation standard | Medium | 3 |

The data security requirement includes the necessity for secure handling of the data employed for the usage of the AS based on RT. Depending on how sensitive the utilised data is, a lower or higher level of data security is required. Therefore, the following definition for this requirement is presented:

*"The level of data security must be sufficient depending on the intended application to prevent third parties from accessing, modifying or stealing confidential data."*

An overview of the possible adjustments in case of a sufficient or insufficient level of data security is shown in Table 4.14. In case of an insufficient level of data security and depending on the degree of how sensitive the utilised data is, a decision must be made whether the existing data security standard is enough or a new standard has to be developed.

Table 4.14: Adjustments for the requirement "data security"

| Status | Adjustment | Costs | Rating |
|---|---|---|---|
| Sufficient level of data security | None | None | 0 |
| Insufficient level of data security | Upgrade of existing data security standard | Low | 1 |
| | Development of a new data security standard | Medium | 3 |

The safety requirement defines the necessity to ensure that no danger to the user or the environment can be posed by AS based on RT. The AS based on RT can distract the user quickly and easily and thus cause avoidable risks. Depending on the type of intended application and the circumstances, the level of the safety standard has to be chosen. Thus, the following definition of this requirement is developed:

*"The level of the safety must be sufficient depending on the intended application and the circumstances to ensure that the assistance system based on reality technology at no time poses any risk to people or the environment."*

In case the level of safety is sufficient or insufficient, Table 4.15 shows the possible adjustments with the respective costs. In case of a sufficient level of safety and depending on the application and circumstances, either an upgrade of the existing safety standard or development of a new safety standard is required.

Table 4.15: Adjustments for the requirement "safety"

| Status | Adjustment | Costs | Rating |
|---|---|---|---|
| Sufficient level of safety | None | None | 0 |
| Insufficient level of safety | Upgrade of existing safety standard | Low | 1 |
| | Development of a new safety standard | Medium | 3 |

*Sub-step 2.3 – Calculation of Implementation Costs*

In the final sub-step of the requirements analysis, the costs for implementation of the AS based on RT into maintenance identified in step 1 are calculated. The basis is the weighting determined in sub-step 2.1 and the rating of the costs for the implementation adjustments defined in sub-step 2.2. For the calculation, the weighting is multiplied by the rating of the respective requirements and the results are then added together, which is shown in equation 4.2. The following abbreviations are applied for the clear presentation of the equation: weighting (W), rating (R), implementation costs (IC), skills of employees (SE), acceptance of employees (AE), maturity of technologies and machines (MTM), degree of digitalisation (DD), data security (DS) and safety (S).

$$R_{IC} = W_{SE} \times R_{SE} + W_{AE} \times R_{AE} + W_{MTM} \times R_{MTM} + W_{DD} \times R_{DD} + \\ + W_{DS} \times R_{DS} + W_S \times R_S \tag{4.2}$$

The cost metric, shown in Table 4.16, is utilised to classify the implementation costs as low, medium or high costs with the respective rating.

Table 4.16: Cost metric and rating of implementation costs

| Range of Rating | Cost Metric | New Rating |
|---|---|---|
| X > 42 | High | 5 |
| 21 < X <= 42 | Medium | 3 |
| X <= 21 | Low | 1 |
| X = 0 | None | 0 |

### 4.3.3 Cost-Benefit Analysis

The objective of the cost-benefit analysis, the third step of the framework, is to compare the total costs and total benefits that arise from the implementation and application of the AS based on RT in maintenance. Based on the outcome of this step, a decision is to be made whether to select the AS based on RT and complete the framework with step 4 or to return to step 1, step 2 or step 3 to choose alternative hardware or software, implementation adjustments or maintenance plans.

The cost-benefit analysis is based on three sub-steps: First, the calculation of total costs, second, the assessment of total benefits and third, the comparison of total costs and total benefits.

*Sub-step 3.1 – Calculation of Total Costs*

Total costs consist of acquisition costs and operating costs. The acquisition costs include the one-off costs for hardware and implementation determined in the first two steps. The operating costs cover the annual costs for software identified in step 1 and maintenance. The annual maintenance costs are to be estimated by the user of the framework on the basis of the defined cost metric. The maintenance costs consist of the maintenance effort for the hardware and software as well as the implementation requirements including the preservation of the digitalisation standard, data security standard and safety standard. In addition, the costs for maintenance personnel are covered. Furthermore, the user of the framework has to define the period of time after which the investment in the AS based on RT in maintenance is supposed to be profitable. The period of time is to be defined in years. In summary, the total costs result from the rating of the hardware and implementation costs as well as the rating of the annual software and maintenance costs for the defined period of time, as shown in equation 4.3. For the clear presentation of the equation, the following abbreviations are utilised: rating (R), total costs (TC), hardware costs (HC), implementation costs (IC), software costs (SC), maintenance costs (MC) and time (T).

$$R_{TC} = R_{HC} + R_{IC} + (R_{SC} + R_{MC}) \times T \tag{4.3}$$

*Sub-step 3.2 – Assessment of Total Benefits*

Against the background of LR1 to design a user-friendly, practical and industry-independent framework, a simple and generally applicable method is established for the assessment of the benefits. The criteria risk, performance and costs are the basis of the method, as they are defined in the background literature review on maintenance as a

balanced set of criteria for the evaluation of assets in maintenance. The aim is to estimate whether the implementation and application of the AS based on RT has a small, medium or high positive impact on the risk, performance and cost level of maintenance. According to LR1, examples of the impact on the chosen maintenance criteria are provided.

The maintenance costs can be minimised and maintenance performance can be improved by reducing downtime. In the event of an unplanned machine failure, the AS based on RT can provide targeted information about the machine to support the maintenance worker in identifying and solving the cause of the breakdown. In addition, the identification and solving of the cause can be automatically documented by the AS based on RT without any effort on the part of the maintenance worker. The documentation can be utilised as a guideline for future breakdowns. Furthermore, maintenance risk can be reduced by minimising the probability of a breakdown. The AS based on RT can serve as an early warning system by processing real-time data from the machine to detect potential failures.

A further possibility to reduce maintenance costs is through remote support. In case of a total breakdown of a machine, in most cases, an external expert has to be called to solve the problem. With the use of an AS based on RT, a maintenance technician on site can communicate digitally with the external expert through remote support and thereby solve the problem. Thus, the problem can be solved in less time and the expert is not required to travel to the site, which saves a significant amount of costs.

Another possibility to improve maintenance performance and minimise maintenance risk is to reduce the error rate. During the execution of maintenance tasks such as repairs, the maintenance technician can be supported as the AS based on RT provides the relevant information for the tasks. In addition, the AS based on RT can serve as quality control and realise if the maintenance technician makes a mistake. Thus, the probability of the maintenance technician making a mistake is reduced. Furthermore, the avoided errors prevent consequential damage, which ultimately saves maintenance costs.

Based on the examples, the user of the framework should estimate to what extent the intended application of the AS based on RT identified in step 1 has an impact on the risk, performance and cost level of maintenance. The impact is to be estimated on an annual basis. For the estimation, the impact metric with the respective rating shown in Table 4.17 is provided.

In summary, the assessment of total benefits is based on the rating of the annual impact on the risk, performance and cost level of maintenance for the period of time defined by the user of the framework in the calculation of total costs, as shown in equation 4.4. For the clear presentation of the equation, the following abbreviations are applied: rating (R), total benefits (TB), risk benefits (RB), performance benefits (PB), cost benefits (CB) and time (T).

Table 4.17: Impact metric and rating of total benefits

| Impact Metric | Rating |
|---|---|
| High | 5 |
| Medium | 3 |
| Low | 1 |
| None | 0 |

$$R_{TB} = (R_{RB} + R_{PB} + R_{CB}) \times T \tag{4.4}$$

*Sub-step 3.3 – Comparison of Total Costs and Total Benefits*

In sub-step 3.3, the rating of the total costs determined in sub-step 3.1 is compared with the rating of the total benefits determined in sub-step 3.2. The purpose is to evaluate if the investment in the AS based on RT is profitable or not. In the case that the total benefits outweigh the total costs, the investment is considered to be profitable and the framework can be completed with the fourth step. In the case where the total costs outweigh the total benefits, the investment is considered to not be profitable. A decision has to be made whether a suitable alternative is to be investigated or whether the conclusion is drawn that the investment is nevertheless profitable or no suitable AS based on RT is available for the intended maintenance application and the framework is thus ended. In the case that an alternative is to be investigated, three options are possible to reduce the total costs and thus make the investment profitable. First, the costs for the AS based on RT can be reduced by identifying a less expensive output device, input device, tracking device or development platform. Second, the implementation costs can be reduced by making compromises in the adjustments to fulfil the implementation requirements. Third, the maintenance costs can be reduced by making compromises in the maintenance plan for the application of the AS based on RT.

### 4.3.4 Implementation Guideline

In the final step of the DSF-RTM, an implementation guideline is presented. The objective is to provide support for the identification and selection also for the implementation of the AS based on RT into maintenance.

As a basis for the implementation guideline, literature from the field of project management with a focus on technical projects is utilised. In general, five phases are defined for technical projects: initial phase, definition phase, development phase, realisation phase and conclusion phase (Felkai and Beiderwieden 2015, pp. 18–20; Meinholz and Förtsch 2019,

pp. 441–444). Against the information gathered through the background literature reviews, the systematic literature review and the interviews, the implementation guideline is established. An overview is shown in Figure 4.6.

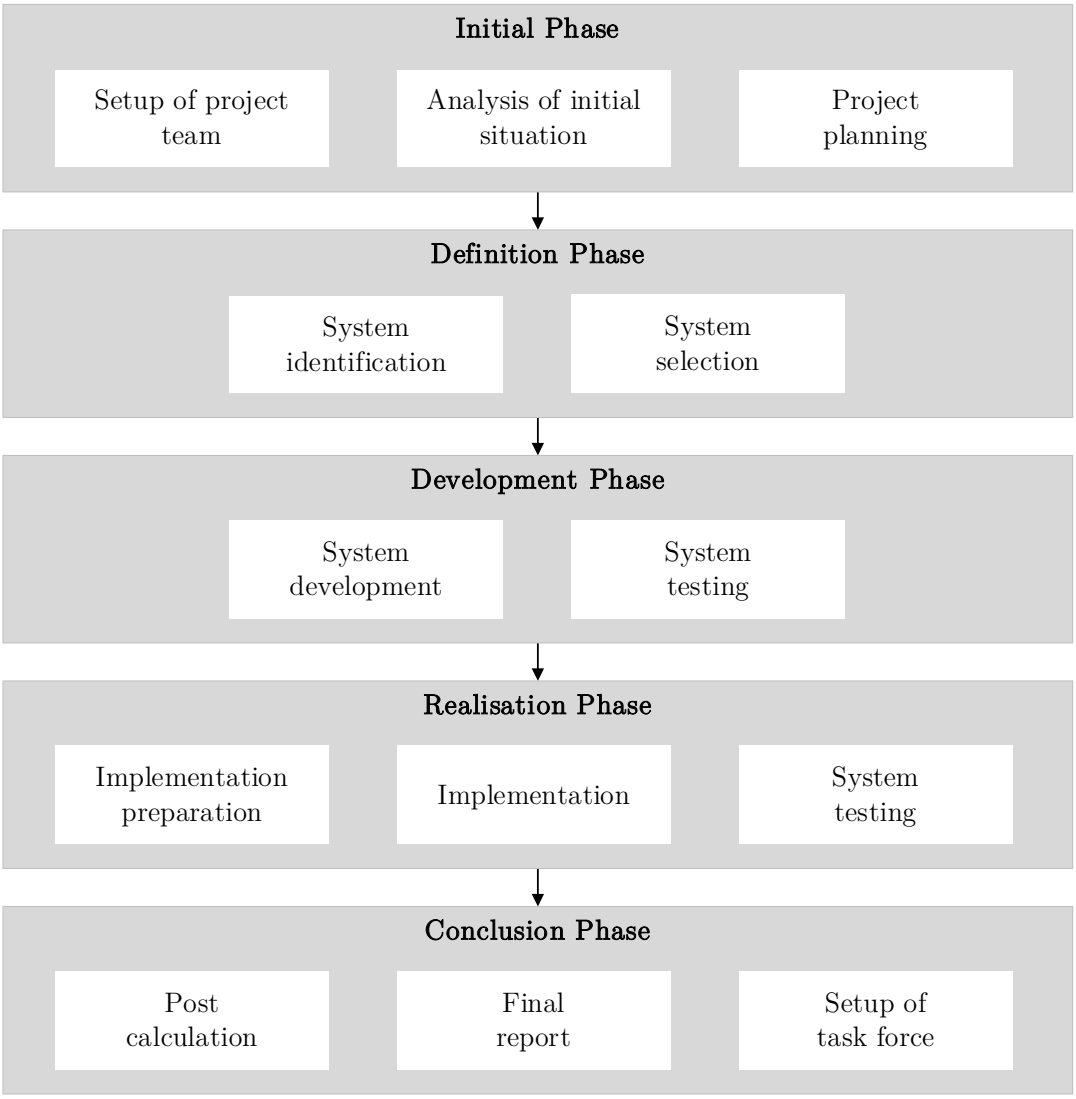



Figure 4.6: Implementation guideline

The initial phase includes the preparation of the project. Initially, a project team is to be set up. In addition, the initial situation is to be analysed to define the objectives and based on that the tasks of the project. The defined tasks are to be assigned to the members of the project team. Furthermore, the remaining phases are to be planned in terms of content and time.

The definition phase consists of the identification and the selection of the AS based on RT. The first two steps of the DSF-RTM, the context analysis and the implementation

requirements analysis, are to be utilised for the identification and the third step of the DSF-RTM, the cost-benefit analysis, is to be applied for the selection.

The development phase involves the development or purchase of a prototype of the selected AS based on RT and the testing of the prototype for its usability in the intended maintenance application. In the case that the results of the testing are not satisfactory, a decision has to be made whether to identify and select another system in the definition phase or to stop the project. In the case that the results of the testing are satisfactory, the next phase is to be conducted.

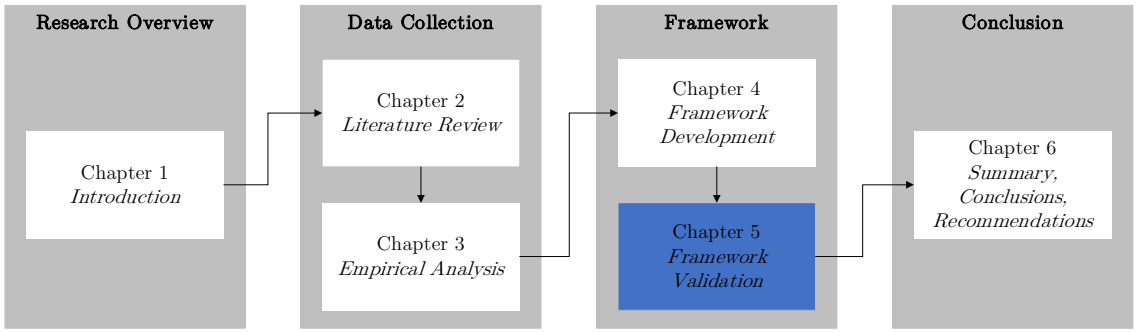
The realisation phase includes the preparation and implementation of the selected and tested AS based on RT into the intended maintenance application. For the preparation, the adjustments defined in the second step of the DSF-RTM are to be realised to fulfil the requirements of the implementation. After the requirements are fulfilled, the AS based on RT can be employed in the intended maintenance application. Following the realisation, a final usage analysis is to performed to identify possible weak points of the AS based on RT or the application conditions and based on this, to implement improvements.

The conclusion phase consists of a post-implementation calculation to compare the target costs and the actual costs as well as a final report on the project. Furthermore, a task force is to be established for the usage and maintenance of the AS based on RT.

## 4.4 Concluding Summary

In this chapter, the DSF-RTM is developed. The DSF-RTM is designed to be a user-friendly framework that requires no prior knowledge about RT. It is structured in four steps: context analysis, implementation requirements analysis, cost-benefit analysis and implementation guideline. In the context analysis, the optimal AS based on RT for the user's intended maintenance application is identified and based on that, the respective costs are determined. In the implementation requirements analysis, the adjustments and the respective costs necessary to fulfil the requirements of a successful implementation of the AS based on RT in maintenance are identified. The costs for the AS based on RT and the implementation are compared in the cost-benefit analysis with the benefits that arise for maintenance. In the case that the costs outweigh the benefits, a decision has to be made whether an alternative AS based on RT is to be selected or the DSF-RTM is to be ended. In the case that the benefits outweigh the cost, the DSF-RTM concludes with an implementation guideline.

# Chapter 5
# Validation of the Decision Support Framework for Reality Technologies in Maintenance




The objective of this chapter is the validation of the DSF-RTM (RO8), thus providing the second part of the answer to the PRQ. At the beginning of the chapter, the conditions of the validation are outlined. The validation is then carried out in the scope of a case study for two use cases. Finally, conclusions are drawn for the DSF-RTM with regard to the usability as well as the degree of fulfilment of the LRs and CRs defined in chapter 4.

## 5.1 Conditions of the Validation

O'Leary *et al.* (1990, p. 51) describes validation as the process of determining whether the framework represents the real-world system in a particular domain. Validation covers two dimensions: verification and substantiation (O'Leary *et al.* 1990, p. 51). Verification refers to the process of ensuring that the developed framework corresponds with the conceptual design and thus represents what the scientist intends to develop (Miser 1993, p. 212). Substantiation is defined as the demonstration that the framework "within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application" of the framework (Balci and Sargent 1981, p. 190).

Following the approach of Jabareen (2009, p. 54) to validate a conceptual framework in terms of its usability, the DSF-RTM is validated using a case study. The case study is

conducted in Werk150, the learning factory of the ESB Business School at Reutlingen University. Werk150 provides a realistic production environment in which current topics of applied research as well as new methods, technologies and tools related to Industry 4.0 and smart maintenance are applied and tested. Thus, Werk150 presents a suitable infrastructure to validate the DSF-RTM.

In Werk150, 3D printing and laser cutting are employed for the manufacture of components that are utilised, for example, in the construction of infrastructure as well as demonstrators. As an extension to the portfolio of manufacturing technologies, a new milling machine was purchased. Figure 5.1 shows the milling machine, which is a PC-controlled vertical machining centre and is designed for processing by milling and drilling of machinable metals and plastics. The objective of the case study is to use the DSF-RTM to determine the optimal RT-based solution for the maintenance of the new milling machine at Werk150.


Figure 5.1: Milling machine at Werk150

The case study was carried out with the help of a research associate at Werk150 to obtain information about the milling machine and its application as well as about Werk150 as an application environment.

## 5.2 Case Study for the Maintenance of a Milling Machine

At the beginning of the case study, the question was clarified whether the AS based on RT is intended for training, planning or in the line of execution for maintenance of the milling machine.

The nature of the maintenance tasks for the milling machine do not require intensive and long-term training. In addition, the planning of the maintenance tasks consists of knowing when each maintenance task has to be performed, which can be accomplished by setting a simple reminder on a mobile phone, laptop or directly on the machine. Thus, an AS based on RT is not necessary for training or planning.

As different types of maintenance tasks are required for the milling machine, the application of an AS based on RT could be useful in the line of execution. In this context, a distinction can be made if scheduled maintenance tasks which are defined in the maintenance plan of the machine or unscheduled maintenance tasks such as in the case of a total breakdown have to be conducted. Therefore, the framework is applied to investigate the first use case for scheduled maintenance activities and the second use case for unscheduled maintenance activities in the scope of the case study.

The two use cases are discussed in the following sections.

### 5.2.1 Scheduled Maintenance Activities

For the use case of scheduled maintenance activities, the maintenance plan of the milling machine is considered. The maintenance plan defines performing a visual inspection, oil lubrication or oil change, grease lubrication and exchange of components at intervals of eight hours, 40 hours, 200 hours, 1000 hours, one year, five years or as required. Table 5.1 shows an overview of these intervals, how frequently the maintenance activities should be carried out and which type of inspection or service measure is required.

Table 5.1: Required scheduled maintenance measures of the milling machine at Werk150

| Interval | Maintenance Measure with Frequency |
|---|---|
| 8 hours | 3x inspection |
| 40 hours | 4x inspection; 3x cleaning; 1x oil |
| 200 hours | 3x inspection; 3x cleaning; 1x oil; 2x grease; 1x exchange |
| 1000 hours | 3x inspection; 1x exchange |
| One year | 1x oil; 1x grease; 1x exchange |
| Five years | 1x exchange |
| As required | 1x cleaning |

The application of an AS based on RT could lead to various benefits such as simplifying the execution and reducing the time required for the scheduled maintenance tasks defined in the maintenance plan of the milling machine. The DSF-RTM is therefore applied to

investigate if the application of an AS based on RT is profitable for the scheduled maintenance activities.

The steps of DSF-RTM are discussed for this use case in the following sections.

*Step 1 - Context Analysis*

At the beginning of the context analysis, the most suitable output device for the scheduled maintenance activities of the milling machine at Werk150 is identified using the flow chart given in the DSF-RTM. The first decision of the flow chart is whether the output device can be carried manually or not. The maintenance plan for the milling machine defines measures such as cleaning, oil or grease lubrication and exchange of components, which are measures that have to be performed manually. Therefore, the decision is made to choose a hands-free output device. Figure 5.2 shows the part of the flow chart for hands-free output devices. In addition, the further decisions taken for this use case are marked in red.

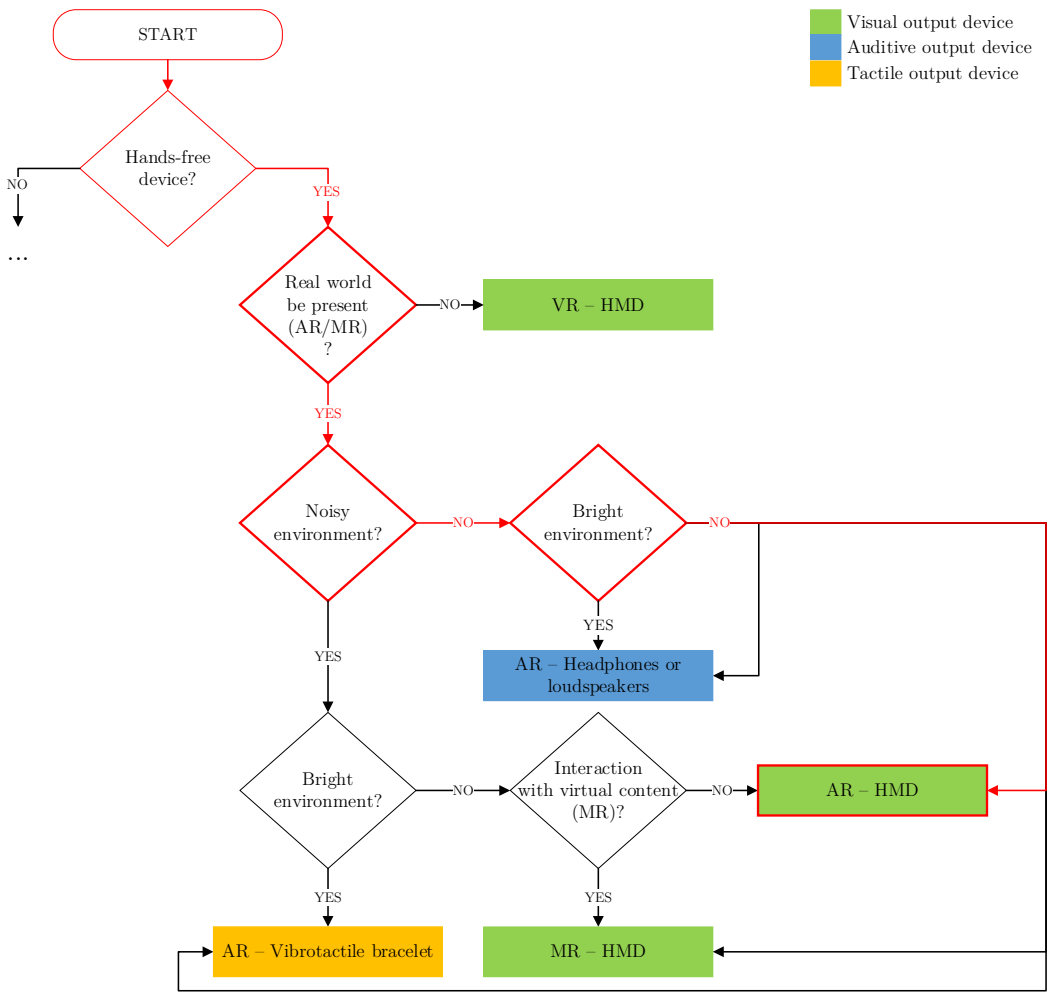



Figure 5.2: Identification of the output device for scheduled maintenance activities

The next decision concerns whether the real or the virtual world has to be present. For the execution of the scheduled maintenance task the real world has to be seen. In this context, the research associate comments that the presence of the real world would not be necessary if sensors were used to virtually display the machine through a digital twin. However, the development of a digital twin is too expensive and time-consuming for the kind of maintenance required for the milling machine. Thus, the decision is made that the real world has to be present.

The final two decisions query the noise and light conditions in the application environment. In terms of noise conditions, although the infrastructure for production is set up in Werk150, this is not carried out most of the time. In addition, the production process itself is not noisy. In terms of lighting conditions, the Werk150 has large windows on the walls and ceiling, which allow a lot of daylight to enter. However, content on a digital screen of a laptop, for example, can be seen without difficulty. Therefore, no high noise level or bright lighting conditions are present in Werk150, which allows a choice to be made between an auditive output device in the form of headphones or loudspeakers, a tactile output device in the form of a vibrotactile bracelet, or a visual output device in the form of an AR-based or an MR-based HMD.

The research associate selects an AR-based HMD and would prefer the model M300XL from Vuzix, which is shown in Figure 5.3. The reason is that the research associate has previously used the M300XL and is therefore familiar with the technology. In addition, the research associate appreciates that the model from Vuzix is comfortable to wear. Furthermore, AR is sufficient as a type of RT, as the research associate only requires top-level information to perform the maintenance tasks. An alternative such as the Microsoft HoloLens would be more suitable if the research associate did not have enough experience and knowledge and therefore required more detailed information to conduct the maintenance tasks.


Figure 5.3: Vuzix M300XL
(Vuzix 2020a)

After choosing a suitable output device for the scheduled maintenance task of the milling machine, the other two elements – the input device and the tracking device – have to be identified. In terms of input devices, the M300XL is equipped with a camera, a microphone, buttons and a touch surface. The embedded input devices are sufficient for the required scheduled maintenance tasks and therefore no additional input devices are required. In terms of tracking devices, no tracking is necessary to perform the required scheduled maintenance tasks.

In addition to the hardware, compatible software has to be identified. The research associate prefers the commercially available software platform from Frontline. The reason is that he used Frontline when he previously used the M300XL and so he is familiar with the software. In addition, the user interface is simple and well structured and the software is generally easy to handle.

In summary, Table 5.2 shows an overview of the identified hardware and software with the respective cost assessment and rating for the scheduled maintenance activities for the milling machine at Werk150.

Table 5.2: Identified AS based on RT for scheduled maintenance activities

| AS based on RT | | | Costs | Rating |
|---|---|---|---|---|
| Hardware | Output device | AR-based HMD | Medium | 3 |
| | Input device | Not required | None | 0 |
| | Tracking device | Not required | None | 0 |
| Software | Development platform | Software platform – commercially available | Medium | 3 |

The total costs for the hardware do not have to be added together since no costs incurred for input and tracking devices. Therefore, the context analysis for the use case of scheduled maintenance activities of the milling machine at Werk150 results in medium costs with a rating of three for both hardware as well as software.

*Step 2 – Implementation Requirements Analysis*

The basis for the second step of the DSF-RTM is the six requirements defined in the DSF-RTM as crucial for the successful implementation of ASs based on RT in maintenance. Initially, the requirements are ranked according to their relevance using a pairwise comparison and thus weighted. The pairwise comparison for the use case of scheduled maintenance tasks for the milling machine at Werk150 is shown in Figure 5.4.

| Compared to requirement / Requirement | Acceptance of employees | Skills of employees | Maturity of technologies and machines | Degree of digitalisation | Data security | Safety | SUM |
|---|---|---|---|---|---|---|---|
| Acceptance of employees | | 2 | 2 | 2 | 2 | 0 | **8** |
| Skills of employees | 0 | | 0 | 2 | 2 | 0 | 4 |
| Maturity of technologies and machines | 0 | 2 | | 2 | 2 | 0 | **6** |
| Degree of digitalisation | 0 | 0 | 0 | | 2 | 0 | **2** |
| Data security | 0 | 0 | 0 | 0 | | 0 | **0** |
| Safety | 2 | 2 | 2 | 2 | 2 | | **10** |

Figure 5.4: Pairwise comparison of implementation requirements for scheduled maintenance activities

The research associate considers the safety requirement to be the most important prerequisite. Safety measures have to be considered to ensure that the use of the AR-based HMD does not pose any danger to the user and other persons who are currently in Werk150. Another important requirement is a sufficient skill level of the employees. The employees of the Werk150 have to be familiar with the M300XL from Vuzix and the software platform from Frontline in order to ensure a successful implementation as well as sustainable and long-term usage including the maintenance of the hardware and software. The research associate values the requirement concerning the maturity of technologies and machines as a further important criterion. The technological infrastructure of Werk150 has to be mature enough to implement the AR-based HMD. The requirements regarding the acceptance of employees, degree of digitalisation and data security are considered to be of minor relevance. The research associate explains this decision with the fact that the maintenance tasks for the milling machine do not require these prerequisites or the requirements are already fulfilled in Werk150. Thus, the outcome is the ranking and weighting of the implementation requirements shown in Table 5.3.

As a next part in the second step of the DSF-RTM, the adjustments necessary to fulfil the implementation requirements are identified. The research associate considers the level of safety in Werk150 to be sufficient to ensure a safe application of the AR-based HMD. Every person must attend safety training to work or remain for a lengthy period of time in Werk150. In addition, laboratory regulations as well as safety equipment such as safety shoes and glasses are available. Thus, no adjustment is necessary to fulfil the safety

requirement. The requirement for sufficient skills levels of the employees is also given as most of the employees of Werk150 have already used and are therefore familiar with the M300XL from Vuzix and the software platform from Frontline. Furthermore, the technologies and machines are in generally mature enough for the application of AR-based HMD. However, the data relevant for performing the maintenance tasks have to be transferred from the maintenance plan to the AS. Thus, small adjustments tasks which include a low-cost effort have to be carried out to fulfil this requirement. In terms of acceptance, the research associate comments that the employees of Werk150 are all researchers and therefore interested as well as open-minded towards new technologies. Moreover, the degree of digitalisation at Werk150 is sufficient as further projects related to Industry 4.0 and smart maintenance are applied and tested there. In addition, no real-time data is required during the performance of the scheduled maintenance tasks and therefore no WIFI connection is necessary directly at the milling machine. In terms of data security, the research associate considers the standard in Werk150 to be sufficient for two reasons. First, the data employed for the maintenance of the milling machine is not highly sensitive. Second, Werk150 has its own WIFI network which is protected with a password.

Table 5.3: Ranking and weighting of implementation requirements for scheduled maintenance activities

| Ranking | **Implementation Requirement** | **Weighting** |
|---|---|---|
| 1 | Safety | 6 |
| 2 | Skills of employees | 5 |
| 3 | Maturity of technologies and machines | 4 |
| 4 | Acceptance of employees | 3 |
| 5 | Degree of digitalisation | 2 |
| 6 | Data security | 1 |

In summary, out of the six implementation requirements, an adjustment is only necessary to fulfil the requirement concerning the maturity of technologies and machines. The adjustment involves a low-cost effort and according to the cost metric defined in the DSF-RTM, it is therefore given a rating of one. Accordingly, no costs are incurred for the remaining requirements since no adjustments are necessary.

The second step of the DSF-RTM concludes with the calculation of the total costs for implementation. For the calculation, the respective defined weighting and rating of the costs for the adjustment are multiplied for each requirement and finally the results are

summed up. Since no costs incurred for five of the requirements and costs with a rating of one are incurred for one requirement, the calculation shown in equation 5.1 is applied.

$$6 \times 0 + 5 \times 0 + 4 \times 1 + 3 \times 0 + 2 \times 0 + 1 \times 0 = 4 \tag{5.1}$$

The result is a rating of four and according to the cost metric defined in the DSF-RTM the total costs for implementation are therefore identified as low costs and given a rating of one.

*Step 3 – Cost-Benefit Analysis*

In the third step of the DSF-RTM, the total costs are weighed against the total benefits that arise from the application of the AS based on RT in maintenance. For the assessment of the total costs, the rating for the acquisition costs and the rating for the operating costs are considered. An overview of the ratings for the cost factors is shown in Table 5.4.

Table 5.4: Total costs for scheduled maintenance activities

| Cost Factor | | Costs | Rating |
|---|---|---|---|
| Acquisition costs | Hardware costs | Medium | 3 |
| | Implementation costs | Low | 1 |
| Operating costs | Software costs | Medium | 3 |
| | Maintenance costs | Low | 1 |

The rating for the hardware, implementation and software costs are adopted from the first two steps. The maintenance costs are estimated to be low. The reason for the estimation is that rather few maintenance tasks are necessary for the hardware as well as software and only one person is required to perform them. In addition, the upkeep of the implementation requirements including the preservation of the digitalisation standard, data security standard and safety standard is not associated with a great effort. Furthermore, a period of three years is defined until the investment is expected to be profitable. The reason for this decision is that the technical obsolescence rate of ASs based on RT is currently very high and after a short time a new investment is probably necessary and worthwhile. In summary, the rating of total costs is 16, as shown in equation 5.2.

$$3 + 1 + (3 + 1) \times 3 = 16 \tag{5.2}$$

The evaluation of the total benefits consists of the sum of ratings determined for the positive impacts resulting from the application of the AR-based HMD for the scheduled maintenance activities of the milling machine with regard to risk, performance and costs. An overview of the ratings for the benefit factors is shown in Table 5.5.

Table 5.5: Total benefits for scheduled maintenance activities

| Benefit Factor | Impact | Rating |
|---|---|---|
| Risk | Low | 1 |
| Performance | Low | 1 |
| Costs | Low | 1 |

In terms of maintenance risk, the research associate states that a reduction in error rate is expected. The AR-based HMD can serve as a digital quality control that prevents the user from making a mistake or forgetting a step or an entire maintenance task for the milling machine. Since no further risk advantages are expected, the impact for maintenance risk is assessed to be small. In terms of maintenance performance and risk, the time required to carry out the scheduled maintenance tasks can be reduced, thus improving performance and saving costs. However, the research associate stresses in this context that the maintenance tasks of the milling machine, which have to be carried out at intervals of eight hours and are therefore the most frequent, are visual inspections. These inspections are generally not associated with much effort and therefore the reduction of maintenance time through an AR-based HMD would be minimal. Thus, the impact for both maintenance performance and costs is classified to be low. In summary, with the assumption that the period is three years, a rating of nine results for the total benefits, as shown in equation 5.3.

$$(1 + 1 + 1) \times 3 = 9 \tag{5.3}$$

The third step of the DSF-RTM concludes with a comparison of the total costs and total benefits. For this use case, the total costs are evaluated with a rating of 16 and the total benefits with a rating of nine. Thus, the total costs outweigh the total benefits and therefore

the application of the identified AS based on RT for the scheduled maintenance tasks of the milling machine at Werk150 is considered to not be profitable.

Based on the outcome a decision has to be made whether an alternative solution should be identified by repeating the context analysis and the implementation requirements analysis or whether the DSF-RTM is to be ended. The research associate decides to end the DSF-RTM because he is not convinced that a profitable solution is available for the scheduled maintenance task for the milling machine at Werk150. The decision is based on three reasons. First, an RT-based solution is generally too expensive for the type of maintenance tasks required by the milling machine. Second, the use of the AR-based HMD is associated with too much effort. The research associate mentions the visual inspection as an example. The AR-based HMD would be kept in a storage place in Werk150. The time required to walk to the storage place to pick up the AR-based HMD and walk to the milling machine would be longer than the time required to perform the visual inspection itself. In addition, the visual inspection is possible without an AS based on RT. Third, the usage of the AR-based HMD would be rather low. The maintenance tasks that have to be performed most frequently are visual inspections and are therefore simpler activities. The more complicated tasks have to be carried out at larger intervals and therefore more rarely.

Since the DSF-RTM is ended after the third step, the final step is not considered for the use case of scheduled maintenance tasks for the milling machine at Werk150.

### 5.2.2 Unscheduled Maintenance Activities

For the use case of unscheduled maintenance activities, the maintenance tasks required in a case of a total breakdown of the milling machine at Werk150 are considered. The current plan in case of a total breakdown is that an external expert is called to solve the problem, because the employees of Werk150 do not have the necessary knowledge. However, the application of an AS based on RT would enable one of the employees of Werk150 to communicate via remote support with the external expert who is not on site, and thereby solve the problem. Thus, the DSF-RTM is applied to investigate whether the possibility of remote support enabled through an AS based on RT is profitable or not.

In the following sections, the steps of the DSF-RTM are discussed for this use case.

*Step 1 – Context Analysis*

Initially, the most suitable output device for the unscheduled maintenance tasks for the milling machine is identified using the flow chart defined in the DSF-RTM. For the first decision on the flow chart the decision is made that a hands-free device is necessary. The use of remote support requires that the device is not to be carried by hand to allow the user to perform the maintenance task while communicating with the expert. The part of

the flow chart for the identification of hands-free output devices with the further decision made for this use case marked in red is shown in Figure 5.5.

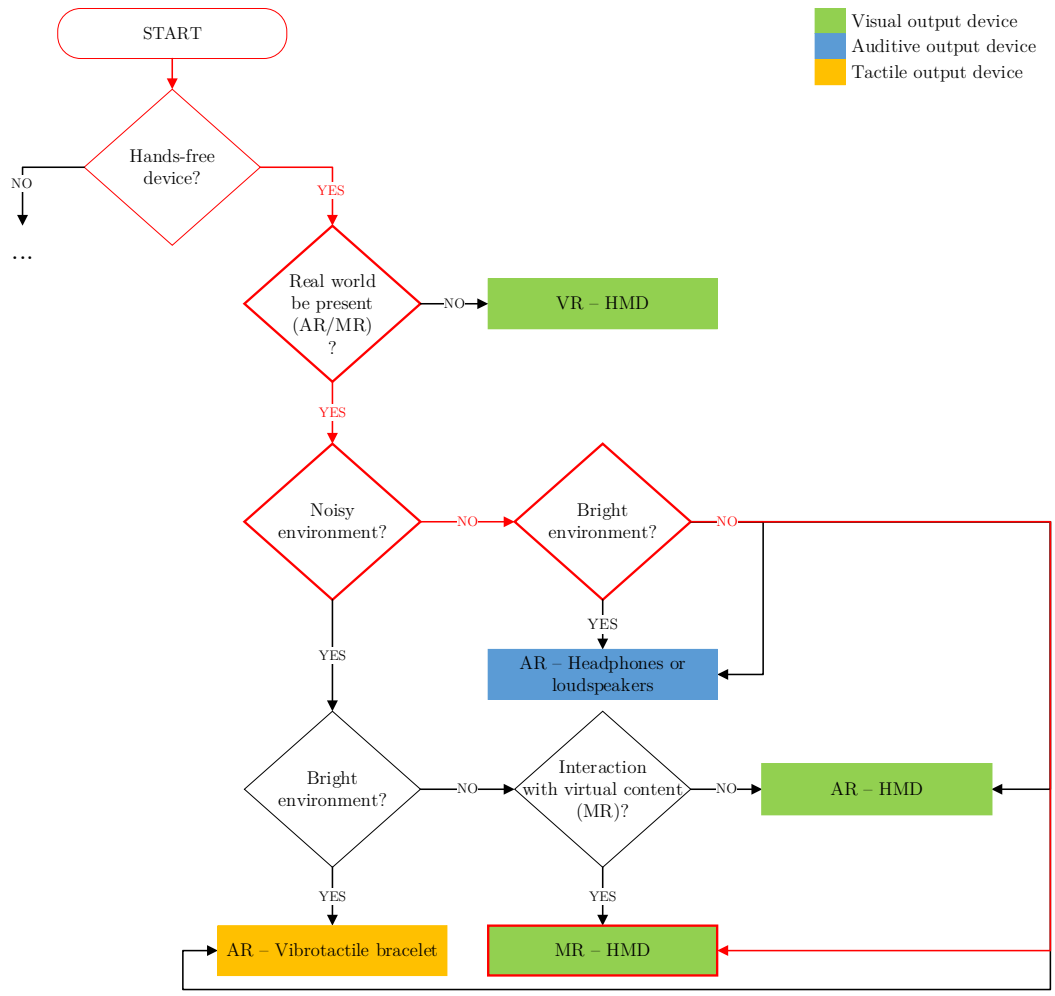



Figure 5.5: Identification of the output device for unscheduled maintenance activities

The subsequent question of whether the real world has to be present is answered in the affirmative. The maintenance worker should see the real machine for the execution of the maintenance tasks and virtual information provided by the external expert should be superimposed on top of the view. The final questions regarding a noisy and bright application environment are answered as for the use case of scheduled maintenance activities since the application environment is also Werk150. Since no noisy or bright environment is present in Werk150, the choice is between auditive, tactile or visual output devices. The decision is made in favour of visual output devices for three reasons. First, visual output devices have embedded cameras. In order to enable remote support in the first place, a camera is required to record a live video for the external expert. Second, visual

output devices have embedded headphones and microphones. The maintenance worker has to hear and talk to the external expert for efficient communication. Third, visual output devices provide a display, that enables the expert to illustrate the information that is relevant to the maintenance task and helpful for the maintenance worker. Ultimately, either an AR-based HMD or a MR-based HMD can be identified as a visual output device. The research associate would prefer an MR-based HMD for this use case and would choose the Microsoft HoloLens, which is shown in Figure 5.6. The reason for the preference is that the camera, microphone, headphones and wide display of the HoloLens are suitable for remote support. In addition, the research associate has used the HoloLens before and is therefore familiar with the HMD.

Figure 5.6: Microsoft HoloLens
(Piedimonte and Ullo 2018, p. 561)

After identifying a suitable output device, the input devices and tracking devices required for this use case are determined. The embedded input devices of the HoloLens are a camera, microphone, buttons and touch surface. In addition, the HoloLens is equipped with sufficient tracking sensors. Thus, no additional input devices and tracking devices are required for the unscheduled maintenance activities for the milling machine.

Subsequently, the compatible software for the defined hardware of the AS based on RT has to be identified. Since the Microsoft HoloLens is identified, the respective development platform from Microsoft is chosen. In addition, the research associate is familiar with the software from Microsoft since he has used the HoloLens before. Therefore, Table 5.6 shows the costs and rating for the identified hardware as well as software.

Since no costs are incurred for input or tracking devices, the context analysis for the use case of unscheduled maintenance activities for the milling machine at Werk150 results in medium costs with a rating of three for both hardware as well as software.

Table 5.6: Identified AS based on RT for unscheduled maintenance activities

| AS based on RT | | | Costs | Rating |
|---|---|---|---|---|
| Hardware | Output device | MR-based HMD | Medium | 3 |
| | Input device | Not required | None | 0 |
| | Tracking device | Not required | None | 0 |
| Software | Development platform | Software platform – commercially available | Medium | 3 |

*Step 2 – Implementation Requirements Analysis*

The ranking and weighting of the six implementation requirements as well as the identification and assessment of necessary adjustments can be adopted from the use case of scheduled maintenance activities because the unscheduled maintenance tasks have the same conditions and the application environment is again Werk150. Thus, the only necessary adjustment is to fulfil the requirement concerning the maturity of technologies and machines. Accordingly, in this case, the relevant data for the unscheduled maintenance task has to be transferred to the MR-based HMD. The costs for the adjustment are considered to be low, which represents a rating of one. Since no costs are incurred for the other requirements and the requirement concerning the maturity of technologies and machines is weighted with a one, the rating for the total costs for implementation is four. Thus, the outcome of the implementation requirements analysis is that the implementation of the identified AS based on RT is associated with low costs which represents a rating of one.

*Step 3 – Cost-Benefit Analysis*

At the beginning of the cost-benefit analysis, the total costs for the application of the identified AS based on RT are evaluated. The costs assessment includes the rating for the acquisition costs and the operating costs. Table 5.7 shows an overview of the ratings for the cost factors.

The assessment of the hardware, implementation and software costs are derived from the first two steps. The maintenance costs are estimated to be medium. The estimation is based on the fact that in the case of a malfunction in remote support, the maintenance is expected to be more complicated and time-consuming than for the use case of scheduled maintenance activities. Furthermore, a period of three years is defined on the grounds of the high technical obsolescence rate of ASs based on RT as in the use case for scheduled maintenance activities. In summary, the resulting rating for the total costs is 22, as shown in equation 5.4.

Table 5.7: Total costs for unscheduled maintenance activities

| Cost Factor | | Costs | Rating |
|---|---|---|---|
| Acquisition costs | Hardware costs | Medium | 3 |
| | Implementation costs | Low | 1 |
| Operating costs | Software costs | Medium | 3 |
| | Maintenance costs | Medium | 3 |

$$3 + 1 + (3 + 3) \times 3 = 22 \tag{5.4}$$

For the assessment of the benefits, the positive effects resulting from the application of the MR-based HMD for the unscheduled maintenance activities for the milling machine in terms of risk, performance and costs are considered and the respective ratings are summed. Table 5.8 shows an overview of the ratings for the benefit factors.

Table 5.8: Total benefits for unscheduled maintenance activities

| Benefit Factor | Impact | Rating |
|---|---|---|
| Risk | Low | 1 |
| Performance | Medium | 3 |
| Costs | High | 5 |

In terms of maintenance risk, an improvement in the error rate can be expected. The maintenance tasks no longer involve only the external expert but also the employee on-site in Werk150. In addition, the HoloLens can provide crucial information and serve as quality control. Thus, although the risk of making a mistake is reduced, the impact on the overall maintenance risk is estimated to be low. In terms of maintenance performance and costs, a rather significant improvement is expected. The external expert is not required to travel to Werk150 and work on site, thus saving time and costs. For an evaluation of the improvement, the time and costs saved are estimated. The following values are assumed based on the information provided by the research associate for the estimation:

- Travel rate: 0,89 €/km
- Distance service company: 200km

- Hourly rate for maintenance tasks: 96 €/h
- Hourly rate for programming tasks: 118€/h

The cost of the outward and return journey between the service company and Werk150 is 356€. Assuming that the external expert requires four hours to execute the maintenance tasks and four hours for programming tasks, the result is 856€. If the application of the HoloLens enables the expert to complete the maintenance tasks and programming tasks in one hour less each time, then in addition to the eliminated travel costs a total of 570€ and approximately four hours can be saved. These savings are classified as having a medium impact on performance and a high impact on costs. In summary, a rating of 27 results for the total benefits based on the defined assumption that the period is three years, as shown in equation 5.5.

$$(1 + 3 + 5) \times 3 = 27 \tag{5.5}$$

Finally, the total costs and total benefits are compared. Since the total costs are rated with 22 and the total benefits with 27, the application of the identified AS based on RT is considered to be profitable for the unscheduled maintenance tasks of the milling machine at Werk150.

*Step 4 – Implementation Guideline*

The DSF-RTM concludes with the implementation guideline. The project is proposed to be implemented in the following five phases:

1. Initial phase
2. Definition phase
3. Development phase
4. Realisation phase
5. Conclusion phase

In the initial phase, a project team is to be set up to carry out the implementation. The project team should preferably consist of two employees of Werk150 who have knowledge of the milling machine and its maintenance as well as ASs based on RT. Furthermore, the process as well as the maintenance tasks to be performed in case of a breakdown of the milling machine are to be identified and analysed. In addition, Werk150 has to be evaluated as an application environment. At the end of the initial phase, the remaining phases are to be planned. The project should be implemented in three months. The planned schedule is two weeks for the definition phase, one month each for the development and realisation phase and two weeks for the conclusion.

In the definition phase, the most suitable system for the unscheduled maintenance tasks of the milling machine are to be identified and selected. For this purpose, the results of the first three steps of the DSF-RTM can be adopted. The selected AS based on RT consists of the Microsoft HoloLens and a compatible development platform from Microsoft. For the implementation, the software has to be installed and the relevant information for the performance of the maintenance task has to be transferred.

The development phase covers the system development as well as testing. The Microsoft HoloLens and the development platform from Microsoft have to be purchased. The members of the project team should familiarise themselves with the new device and its software. Finally, the first tests should be carried out to investigate if the HoloLens functions for remote support with an external expert. If problems occur, these should be investigated and solutions should be developed.

If testing is successful, the realisation phase can be initiated. First, the adjustments determined in the definition phase have to be carried out. The data relevant for the user and the performance of the maintenance task has to be transferred to the HoloLens. Subsequently, the HoloLens should be implemented and utilised in the case of a total breakdown of the milling machine. The application should be examined to identify and improve potential weak points.

Finally, the conclusion phase is carried out. A post-calculation is to be performed to identify the actual costs of the project in terms of hardware, software and implementation. Furthermore, the relevant information concerning the milling machine and its maintenance in case of a total breakdown, as well as the HoloLens, its software and its application in the Werk150 should be summarised in a final report. To conclude the project, a task force is to be set up to ensure a sustainable and long-term application. One member of the project team or another employee of Werk150 should be responsible for the maintenance of the HoloLens and its software.

## 5.3 Usability of the framework

First of all, in terms of verification, the intention to develop a framework that provides support in the identification, selection and implementation of ASs based on RT in maintenance is verified through the case study. The DSF-RTM enables it to be concluded that no suitable RT-based solution is available for the use case of scheduled maintenance tasks and the Microsoft HoloLens is a suitable solution for the use case of unscheduled maintenance tasks.

In terms of substantiation and in order to draw further conclusions, the case study is examined whether the DSF-RTM fulfils the design requirements defined at the beginning of chapter 4. The design requirements are divided into two LRs and four CRs.

The first LR is to create a user-friendly framework, which is generally fulfilled with the DSF-RTM. The proposed framework is well structured and supports the decision-making process without being complicated and detailed. The research associate had no problems in following the logic of the DSF-RTM. However, the research associate suggested as an optimisation proposal to introduce norms or standards as a reference in the second step. The argument is that norms or standards could be helpful as an objective reference for assessing whether and to what extent adjustments are necessary to fulfil the implementation requirements. The reason why general definitions are provided and thus a subjective assessment by the user is necessary in the second step is that each application has different requirements. As an example, the requirement concerning the degree of digitalisation is mentioned. If the maintenance task requires the AS based on RT to display information only to the user, no WIFI is necessary at the point of use. However, if the AS based on RT is required to retrieve real-time information, WIFI is necessary at the point of use. Both cases require a different level of digitalisation. Therefore, no generally valid statement can be made as to which standards or norms are necessary.

The second LR is that no knowledge of RT is necessary to apply the framework, which is fulfilled with the DSF-RTM. The research associate had no difficulty in identifying and selecting the output device, input device, tracking device and development platform as well as in assessing the impact concerning risk, performance and costs of the AS based on RT on maintenance. However, it has to be noted in this context that the research associate has used an AR-based and MR-based HMD before. Therefore, a validation with maintenance workers who have no experience with RT is necessary to make a valid statement as to whether the DSF-RTM fulfils the second LR. The extended validation of the DSF-RTM is further discussed as a recommendation for future research in chapter 6.

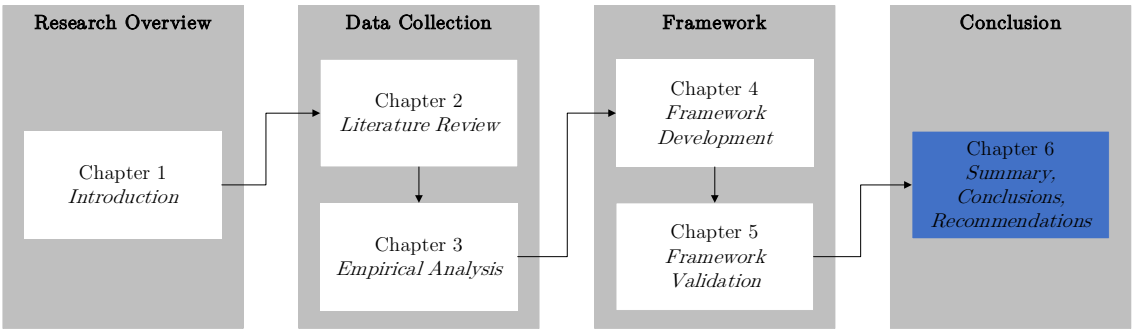
The four CRs which require an overview of hardware and software as well as implementation requirements, a feasibility study and an implementation guideline are satisfied. The DSF-RTM provides in the first step an overview of the currently available and for the maintenance application suitable output devices, input devices and tracking devices as well as development platforms. In the second step, the requirements for a successful implementation of AS based on RT in maintenance are considered. The third step includes the economic considerations of the application and the fourth step provides support to realise the implementation.

## 5.4 Concluding Summary

In this chapter, the DSF-RTM is validated. The DSF-RTM is applied in the scope of a case study to determine a RT-based solution for the maintenance of the milling machine at Werk150. The case study is divided into the use cases of scheduled and unscheduled maintenance activities. The result of the use case of scheduled maintenance activities is

that no profitable solution is identified. The outcome of the use case of unscheduled maintenance activities is that an MR-based HMD that enables remote support is economically viable. The validation through the case study verifies that the DSF-RTM provides support in the identification, selection and implementation of ASs based on RT in maintenance. Furthermore, the DSF-RTM fulfils the two LR and four CR defined in chapter 4.

# Chapter 6
# Summary, Conclusions and Recommendations




The objective of this chapter is to provide an overview of the research undertaken in this thesis. First, a summary of the individual chapters in terms of the research approach and content is provided. Subsequently, conclusions are drawn by answering the research questions. The chapter concludes with the limitations of this research and recommendations for future research.

## 6.1 Research Summary

This thesis is divided into six chapters: (1) Introduction; (2) Literature Review; (3) Empirical Analysis of Assistance Systems Based on Reality Technology in Maintenance; (4) Development of the Decision Support Framework for Reality Technologies in Maintenance; (5) Validation of the Decision Support Framework for Reality Technologies in Maintenance; (6) Summary, Conclusions and Recommendations. In the following sections, a summary of each chapter is presented to provide an overview of this research study.

Chapter 1 introduces this research study. First, background information is provided on ASs based on RT and maintenance. The problem statement is derived and the research questions as well as the research objectives are defined. The research approach of this thesis is presented through the research design and methodology. Subsequently, the delimitations and limitations are stated. The chapter ends with the online of this thesis.

Chapter 2 provides a review of the literature relevant to this research. A background literature review on ASs based on RT is conducted to identify definitions and examine specific characteristics. In addition, a background literature review on maintenance is carried out to investigate definitions and analyse generic types of maintenance activities. Finally, a systematic literature review on ASs based on RT in maintenance is conducted to examine application characteristics and implementation requirements.

In chapter 3, semi-structured interviews are conducted for empirical analysis. The participants in the interviews are maintenance experts from various industries and countries. Empirical information about application characteristics, implementation requirements as well as benefits and challenges of ASs based on RT in maintenance are gathered and investigated.

Chapter 4 covers the development of the DSF-RTM. First, requirements concerning the layout and content of the framework are derived from the acquired theoretical and empirical information on ASs based on RT in maintenance. Subsequently, the four steps of the DSF-RTM are presented: context analysis, implementation requirement analysis, cost-benefit analysis and implementation guideline.

In chapter 5, the DSF-RTM is validated through a case study. The DSF-RTM is applied in the scope of the case study to investigate an RT-based solution for the scheduled as well as unscheduled maintenance activities of the milling machine at Werk150. The chapter ends with the conclusions drawn from the case study and their implications for the layout and the content of the DSF-RTM.

Chapter 6 provides an overview of the research conducted. The key findings are summarised and conclusions are drawn. The chapter ends with recommendations for future research.

## 6.2 Research Conclusions and Contributions

The conclusions drawn and the contributions made as a result of this research are structured in the following sections according to the research questions defined in chapter 1. First, the answers are presented for the SRQs and then for the PRQ.

***SRQ1*** *What technologies and forms of ASs based on RT are currently available?*

The four components of ASs based on RT are the output device, input device, tracking device and development platform. The main component is the output device, which presents the virtual content and creates the illusion of a virtual world. The currently available output devices can generate AR, MR or VR. Output devices based on AR present the real world and superimpose virtual content on top of it. Output devices based on MR blend the real and the virtual world. Output devices based on VR present the virtual world with the total absence of the real world. Furthermore, output devices can be classified

according to the way virtual content or the virtual world is presented in visual, auditive and tactile devices. In addition, visual output devices can be subdivided according to the type of display into HMDs, HHDs, screen-based displays and projector-based displays. In summary, the currently available output devices shown in Table 6.1 are distinguished according to the type of RT provided and the way virtual content or the virtual world is presented.

Table 6.1: Currently available output devices

| | AR | MR | VR |
|---|---|---|---|
| **Visual** | – HMD<br>– HHD:<br>Smartphone and tablet<br>– Screen-based display:<br>Laptop and desktop PC<br>– Projector-based display:<br>SAR display | – HMD | – HMD<br>– HHD:<br>Smartphone and tablet<br>– Screen-based display:<br>Laptop and desktop PC<br>– Projector-based display:<br>Stereoscopic projection system and CAVE |
| **Auditive** | – Loudspeaker<br>– Headphones | | |
| **Tactile** | – Vibrotactile bracelet | | |

The selection of input device, tracking device and development platform of an AS based on RT depends on the type of output device identified. Input devices convey information from the user as well as the environment to the output device and enable interaction with virtual content or the virtual world. Depending on the type of interaction, input devices can be divided into visual, auditive and tactile devices. Furthermore, a distinction can be made whether the information is transmitted in an active or passive way. In summary, the currently available input devices shown in Table 6.2 are distinguished according to the type of interaction and way information is transmitted.

Tracking devices determine the pose and orientation of the user to render the virtual content coherently to the real-world view or to render the perspective on the virtual world according to the perspective of the user. The currently available tracking devices are based either on sensors or cameras. For sensor-based tracking, a distinction can be made as to whether electromagnetic, acoustic, inertial, optical or mechanical sensors are utilised.

Camera-based tracking can be subdivided by whether markers are applied into marker-based tracking or vision-based tracking.

Table 6.2: Currently available input devices

| Visual | Auditive | Tactile | |
|---|---|---|---|
| **Passive Input** | **Active Input** | **Active Input** | **Passive Input** |
| – Camera | – Microphone | – PC mouse/ space mouse<br>– Keyboard<br>– Buttons<br>– Touch surface/ screen<br>– Joystick<br>– Controller | – Data glove<br>– Vibrotactile bracelets |

Development platforms process information acquired from input devices and tracking devices in order to create virtual content or the virtual world. The currently available development platforms can be divided into four types. If the development platform is to be created from the ground up, specific programming languages can be applied. Otherwise, games engine, software platforms or SDKs can be employed.

***SRQ2*** *What generic types of activities are used to perform maintenance?*

Maintenance activities can generally be classified into either execution, planning or training.

The activities in the line of execution represent the four basic measures of maintenance: service, inspection, repair and improvement. Service measures aim to delay the reduction of the wear margin of an item to increase its service life and cover things such as cleaning or lubrication. Inspection measures include the performance of error analyses and aim to examine the current state of an item compared to its initial state. Repair measures describe the physical activities necessary to re-establish the required function of a faulty item by processing or restoring it. Improvement measures refer to the combination of all technical, administrative and managerial activities that aim to improve the intrinsic reliability, maintainability and safety of an item without changing its original function.

The planning activities depend on the maintenance strategy applied, which defines which maintenance task is to be performed for which item, at what time and with what frequency. Maintenance strategies have evolved in four phases up to now and the relevance of planning

has increased. In the first phase, maintenance measures are either not planned in the scope of a reactive strategy or planned in periodic intervals in the scope of a preventive strategy. In the next phase, maintenance measures are planned as part of a condition-based strategy according to the wear margin of the item. As a further development, the condition of the object is forecasted in the scope of a predictive strategy and the maintenances measures are planned accordingly. The final development includes the strategy of smart maintenance in which self-regulation of maintenance is added to predictive planning.

The activities in the scope of training serve to qualify the maintenance personnel for the execution and planning of the maintenance measures. The relevance of qualified personnel has increased with the era of smart maintenance. The number of maintenance objects, the complexity of systems as well as the technical and organisational interlinking of systems is growing. Thus, the execution and planning of maintenance measures are more complex and time-consuming as well as having shifted from labour-intensive to being knowledge-intensive tasks. The consequence is that training is more complex and maintenance personnel have to acquire knowledge in ICTs in addition to technical knowledge through training.

***SRQ3*** *Which application characteristics and implementation requirements are necessary for successfully establishing ASs based on RT in maintenance?*

The determination as to which application characteristics are necessary can be derived from the type of maintenance activities, the nature and the environment of the application as well as the characteristics of the output device. From the type of maintenance activities of the application, the type of RT can be derived, since certain types of RT are in most cases utilised for certain types of maintenance activities. ASs based on AR are primarily applied in the line of execution and training, ASs based on MR are primarily employed in the line of execution and ASs based on VR are primarily utilised in the line of planning and training. In terms of the nature of the application, types of ASs based on RT can be derived from the following requirements of the application: the requirement for transportation, the required way of transportation, the required type of RT or the required size of the display. In addition, the lighting conditions, noise level and working space of the environment of the application are further factors to determine types of ASs based on RT. Furthermore, the characteristics of output devices in terms of, for example, visualisation, battery life and size of FOV are other factors to identify types of ASs based on RT.

Regarding the implementation requirements, the following six requirements are crucial for successfully establishing ASs based on RT in maintenance:

- Acceptance of employees
- Skills of employees

- Maturity of technologies and machines
- Degree of digitalisation
- Data security
- Safety

The employees of the maintenance department, have, on the one hand, to accept the new technology and be open to integrate it into their daily work, and on the other hand, be familiar with the hardware and software as well as its maintenance to ensure a successful implementation as well as long-term and sustainable usage. In addition, three requirements concern the technical infrastructure of the maintenance application. These are the maturity of technologies and machines, the degree of digitalisation and the level of data security, which have to be sufficient for the requirements of the application. The last requirement relates to safety. The safety standard has to be sufficient to ensure that no danger is posed to the user or the environment at any time by the AS based on RT. Furthermore, the importance of the requirements depends on the general circumstances of the application. Therefore, no general conclusion can be drawn about the order of relevance of the implementation requirements for successfully establishing ASs based on RT in maintenance.

***PRQ*** *How can a framework be designed to assist companies with the identification, selection and implementation of ASs based on RT to improve maintenance?*

In the scope of this thesis, the decision support framework for reality technologies in maintenance (DSF-RTM) is established. The DSF-RTM is user-friendly and requires no prior knowledge about RT to be applied. This generic and practical framework is structured in four steps. The first two steps support in the identification, the third step in the selection and the fourth step in the implementation of ASs based on RT in maintenance.

The first step of the DSF-RTM covers the context analysis, in which the hardware and software as well as the associated costs are identified. Through the environmental conditions and the requirements of the maintenance application, the suitable output device and its costs are determined. Then, the compatible input device, tracking device and development platform as well as their costs are identified. The second step of the DSF-RTM includes the implementation requirements analysis. The requirements concerning the acceptance of employees, skills of employees, maturity of technologies and machines, degree of digitalisation, data security as well as safety are evaluated and weighted according to their relevance for the maintenance application. Subsequently, the adjustments necessary to fulfil the implementation requirements are determined. The result of the second step is the identification of the implementation costs. The third step of the DSF-RTM consists of the cost-benefits analysis. The one-off costs for hardware and implementation as well as the running costs for software and maintenance are compared to the benefits of using an

AS based on RT for maintenance in terms of risk, performance and costs. In the situation where the costs outweigh the benefits, an alternative solution can be investigated through repeating the first, second or third step, or the framework can be terminated. In the case that the benefits outweigh the costs, the identified AS based on RT is selected and the framework proceeds with the fourth step. The final step of the DSF-RTM provides a guideline for the implementation of an AS based on RT in maintenance. The guideline includes recommendations for the five phases of the implementation and application: initial phase, definition phase, development phase, realisation phase and the conclusion phase.

## 6.3 Limitations and Recommendations for Further Research

Based on the limitations of this research, recommendations for future research are made in the following section.

The purpose of this thesis is to propose a decision support framework that organisations can apply, irrespective of the industry. The development of a practical and generic framework is limited in this research due to the empirical analysis and the validation. The empirical analysis is conducted through interviews with nine participants representing six different industries and two different countries. The validation is carried out through a case study in a learning factory. To acquire substantiated empirical information, further interviews and forms of validation have to be performed. The recommendation for further interviews is to increase the number of participants and include participants from other industries and countries. The recommendation for further validation is to carry out additional case studies in companies representing different industries and countries. Furthermore, the case study is conducted with a research associate of the learning factory who has knowledge about RT. In the validation phase of this research no final conclusion could be drawn as to whether the DSF-RTM fulfils the second LR, which states that no prior knowledge about RT is necessary for the application of the framework. For further case studies, the proposal is therefore made to include participants who have no prior knowledge about RT.

A further limitation resulting from the purpose of designing a practical and generic framework is that the level of in-depth support is restricted. The DSF-RTM provides rather generic information and guidance in order to be applicable and useful irrespective of the industry. In this context, the recommendation for further research is to focus on one industry or several similar industries and provide targeted support for the industry specific conditions and requirements. Moreover, three further aspects regarding the content or structure of the proposed framework can be enhanced. First, in the context analysis of the DSF-RTM, a flow chart is provided for the technical identification of the output device. The reason is that the output device is the decisive element of an AS based on RT and the other main components are identified accordingly. However, flow charts for the technical

identification of input device, tracking device and development platform can be established as additional guidance. Second, the final step of the DSF-RTM can be extended and the level of detail increased. The implementation guideline provides an overview and general information to be considered for the implementation. As a recommendation, the implementation process of ASs based on RT can be examined through for example a case study to provide detailed and specific information and support in the framework. Third, a distinct reference between maintenance strategies and the application of ASs based on RT can be established. By analysing the requirements, circumstances as well as challenges associated with each maintenance strategy, a proposal can be made as to which type of AS based on RT is most beneficial in which area of maintenance.

Another limitation of this research is the determination of the costs for hardware and software of ASs based on RT as well as for the adjustments to fulfil the implementation requirements. The identification of the hardware and software costs is based on a price analysis. However, the price analysis is rather limited as many companies do not quote their prices for industrial equipment online but only on request. The costs for the adjustments necessary to fulfil the implementation requirements are estimated. Therefore, the recommendation is made that a survey regarding the prices of hardware and software as well as a survey regarding the adjustments are conducted with companies from different industries and countries for an accurate cost assessment.

## 6.4 Concluding Summary

This chapter provides an overview of the research conducted. Initially, the chapters of this thesis are summarised. Subsequently, the contributions of this research are presented by answering the research questions. Finally, the limitations of this research are outlined and recommendations for future research are given on this basis.

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# Appendices

# Appendix A
# Interviews

## A.1 Research Ethics Committee Approval

UNIVERSITEIT
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**NOTICE OF APPROVAL**

REC: Social, Behavioural and Education Research (SBER) - Initial Application Form

19 November 2019

Project number: 11814

Project Title: Framework to establish an assistance system by using reality technology in maintenance.

Dear Ms Magdalena Bertele

Your REC: Social, Behavioural and Education Research (SBER) - Initial Application Form submitted on 21 October 2019 was reviewed and approved by the REC: Humanities.

Please note the following for your approved submission:

**Ethics approval period:**

| Protocol approval date (Humanities) | Protocol expiration date (Humanities) |
|---|---|
| 19 November 2019 | 18 November 2022 |

**GENERAL COMMENTS:**

**The researcher is reminded to submit an amendment for approval of the case studies as soon as the case studies have been identified. The researcher is therefore requested to contact the REC office for advice on how to submit an amendment prior to the collection of data. [ACTION REQUIRED]**

Please take note of the General Investigator Responsibilities attached to this letter. You may commence with your research after complying fully with these guidelines.

**If the researcher deviates in any way from the proposal approved by the REC: Humanities, the researcher must notify the REC of these changes.**

Please use your SU project number (11814) on any documents or correspondence with the REC concerning your project.

Please note that the REC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

**FOR CONTINUATION OF PROJECTS AFTER REC APPROVAL PERIOD**

Please note that a progress report should be submitted to the Research Ethics Committee: Humanities before the approval period has expired if a continuation of ethics approval is required. The Committee will then consider the continuation of the project for a further year (if necessary)

**Included Documents:**

| Document Type | File Name | Date | Version |
|---|---|---|---|
| Research Protocol/Proposal | Magdalena Bertele - Research Proposal | 21/10/2019 | 2 |
| Informed Consent Form | Magdalena Bertele - Written Consent | 21/10/2019 | 2 |
| Data collection tool | Magdalena Bertele - Data Collection | 21/10/2019 | 2 |

If you have any questions or need further help, please contact the REC office at cgraham@sun.ac.za.

Sincerely,

Clarissa Graham

REC Coordinator: Research Ethics Committee: Human Research (Humanities)

## Investigator Responsibilities

### Protection of Human Research Participants

Some of the general responsibilities investigators have when conducting research involving human participants are listed below:

**1.Conducting the Research**. You are responsible for making sure that the research is conducted according to the REC approved research protocol. You are also responsible for the actions of all your co-investigators and research staff involved with this research. You must also ensure that the research is conducted within the standards of your field of research.

**2.Participant Enrollment.** You may not recruit or enroll participants prior to the REC approval date or after the expiration date of REC approval. All recruitment materials for any form of media must be approved by the REC prior to their use.

**3.Informed Consent.** You are responsible for obtaining and documenting effective informed consent using **only** the REC-approved consent documents/process, and for ensuring that no human participants are involved in research prior to obtaining their informed consent. Please give all participants copies of the signed informed consent documents. Keep the originals in your secured research files for at least five (5) years.

**4.Continuing Review.**The REC must review and approve all REC-approved research proposals at intervals appropriate to the degree of risk but not less than once per year. There is **no grace period.** Prior to the date on which the REC approval of the research expires, **it is your responsibility to submit the progress report in a timely fashion to ensure a lapse in REC approval does not occur.** If REC approval of your research lapses, you must stop new participant enrollment, and contact the REC office immediately.

**5.Amendments and Changes.**If you wish to amend or change any aspect of your research (such as research design, interventions or procedures, participant population, informed consent document, instruments, surveys or recruiting material), you must submit the amendment to the REC for review using the current Amendment Form. You **may not initiate** any amendments or changes to your research without first obtaining written REC review and approval. The **only exception** is when it is necessary to eliminate apparent immediate hazards to participants and the REC should be immediately informed of this necessity.

**6.Adverse or Unanticipated Events.**Any serious adverse events, participant complaints, and all unanticipated problems that involve risks to participants or others, as well as any research related injuries, occurring at this institution or at other performance sites must be reported to Malene Fouche within **five (5) days** of discovery of the incident. You must also report any instances of serious or continuing problems, or non-compliance with the RECs requirements for protecting human research participants. The only exception to this policy is that the death of a research participant must be reported in accordance with the Stellenbosch University Research Ethics Committee Standard Operating Procedures. All reportable events should be submitted to the REC using the Serious Adverse Event Report Form.

**7.Research Record Keeping.** You must keep the following research related records, at a minimum, in a secure location for a minimum of five years: the REC approved research proposal and all amendments; all informed consent documents; recruiting materials; continuing review reports; adverse or unanticipated events; and all correspondence from the REC

**8.Provision of Counselling or emergency support.** When a dedicated counsellor or psychologist provides support to a participant without prior REC review and approval, to the extent permitted by law, such activities will not be recognised as research nor the data used in support of research. Such cases should be indicated in the progress report or final report.

**9.Final reports.** When you have completed (no further participant enrollment, interactions or interventions) or stopped work on your research, you must submit a Final Report to the REC.

**10.On-Site Evaluations, Inspections, or Audits.** If you are notified that your research will be reviewed or audited by the sponsor or any other external agency or any internal group, you must inform the REC immediately of the impending audit/evaluation.

## A.2 Consent Form

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

STELLENBOSCH UNIVERSITY
WRITTEN CONSENT TO PARTICIPATE IN RESEARCH

| | |
|---|---|
| TITLE OF RESEARCH PROJECT: | A framework to establish an assistance system by using reality technology in maintenance. |
| REFERENCE NUMBER: | ING-2019-11814 |
| PRINCIPAL INVESTIGATOR: | Magdalena Bertele |
| ADDRESS: | Engineering Building, Industrial Engineering Department, Joubert Rd, Stellenbosch |
| CONTACT NUMBER: | +27840869236 |
| E-MAIL: | 23989807@sun.ac.za |

Dear Participant,

Kindly note that I am a MEng student at the Department of Industrial Engineering at Stellenbosch University, and I would like to invite you to participate in a research project entitled "Framework to establish an assistance system by using reality technology in maintenance".

Please take some time to read the information presented here, which will explain the details of this project and contact me if you require further explanation or clarification of any aspect of the study. This study has been approved by the Research Ethics Committee (REC) at Stellenbosch University and will be conducted according to accepted and applicable national and international ethical guidelines and principles.

1. INTRODUCTION: Based on the research I have done, the maintenance environment faces challenges regarding rapid technological developments and a lack of qualified specialists, leading to a difficulty in coping with increasing complexity of machines and their maintenance. However, assistance systems associated with reality technology have become viable and affordable to the general industry. Those kinds of assistance systems

can support maintenance, but the problem at hand is the absence of a framework that assists companies with their selection and implementation.

2. **PURPOSE:** The aim of the study is designing a framework to assist industry with the identification, selection, development and implementation of assistance systems associated with reality technology to improve maintenance efficiency.
3. **PROCEDURES:** The procedure is to conduct a semi-structured interview with participants to collect a range of valuable information about the selection and implementation of assistance systems including reality technology in maintenance from their experience. Prospective participants will only be required to engage in one semi-structured interview.
4. **TIME:** Each semi-structured interview will be managed to have a duration of 30 minutes. Preparation for the meeting will speed up the process. The duration of the total study depends on the number of participants. The intention is to conduct interviews with about ten participants.
5. **RISKS:** The only risk for any of the prospective participants is the inconvenience of taking time to participate in the interview and respond to the interview questions.
6. **BENEFITS:** The benefit with regards to participation is the contribution that participants would be able to help to develop a framework that assists companies with the selection and implementation of assistance systems including reality technology by engaging in the interview and sharing their valuable experience. The participant can use and apply the framework in his maintenance environment.
7. **PARTICIPATION & WITHDRAWAL:** The prospective participants will be interviewed and recorded via skype. If the need arises for them to withdraw from participating, they can leave the interview at any time. The collected data and information will be destroyed and the recording will be deleted.
8. **CONFIDENTIALITY:** The name of the potential participants will be replaced by ID codes in my research report, and my research report will not contain any direct quotes or links to personal identifiers. The collected data will only be used for research purpose regarding this specific thesis.
9. **RECORDINGS:** Voice recordings will be made during interviews to be able to play back what was discussed in order to ensure that the information gathered from the interview is accurate. The recordings will not be shared to any person apart from the principal investigator and her supervisor.
10. **DATA STORAGE:** The collected data from the interview will be accessible only to the principal investigator and her supervisor. The information will be stored on the principal investigator's computer and One Drive, both password protected. The collected data will be anonymised by replacing the name of the potential participants with ID codes. Sharing the collected data is not envisaged.

If you have any questions or concerns about this research project, please feel free to contact:

Magdalena Bertele (Principal Investigator) Dr. J.L. Jooste (Supervisor)

**RIGHTS OF RESEARCH PARTICIPANTS:** You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché (mfouche@sun.ac.za / 021 808 4622) at the Division for Research Development. You have the right to receive a copy of this Consent Form.

**If you are willing to participate in this research project, please sign the Declaration of Consent below and hand it to the investigator.**

DECLARATION BY THE PARTICIPANT

As the **participant** I hereby declare that:
I have read the above information and it is written in a language with which I am fluent and comfortable.
I have had a chance to ask questions and all my questions have been adequately answered.
I understand that taking part in this study is voluntary and I have not been pressurised to take part.
I may choose to leave the study at any time and will not be penalised or prejudiced in any way.
If the principal investigator feels that it is in my best interest, or if I do not follow the study plan as agreed to, then I may be asked to leave the study before it has finished.
All issues related to privacy, and the confidentiality and use of the information I provide, have been explained to my satisfaction.

By signing below, I _____ agree to take part in this research study, as conducted by Magdalena Bertele.

_____ _____

**Signed at** ***(place)*** **Date**

_____

**Signature of Participant**

## DECLARATION BY THE PRINCIPAL INVESTIGATOR

As the **principal investigator** I hereby declare that the information contained in this document has been thoroughly explained to the participant. I also declare that the participant has been encouraged (and has been given ample time) to ask any questions. In addition I would like to select the following option:

| | |
|---|---|
| | The conversation with the participant was conducted in a language in which the participant is fluent. |
| | The conversation with the participant was conducted with the assistance of a translator, and this "Consent Form" is available to the participant in a language in which the participant is fluent. |

Signed at *(place)* _____ Date _____

Signature of Principal Investigator _____

## A.3 Interview Guideline

### Question 1

Explain your experience and involvement as a maintenance practitioner.

a. What is your role/ position?
b. What is your area of expertise (i.e. equipment that you maintain)?
c. Do you currently follow a structured maintenance process?
d. What technologies are typically used in the area of your expertise?
e. How do you document your maintenance (process)?
f. Are status, fault/ malfunction or failure information collected?
   - This information is not collected
   - This information is collected and documented manually
   - This information is automatically collected and stored within the plant
   - This information is automatically recorded and transmitted to a central system (e.g. ERP)
g. On which data basis are maintenance measures initiated?
   - No data
   - History data
   - Real-time data
h. In general, what are the typical weak points of maintenance processes? Where do you see optimisation potential?

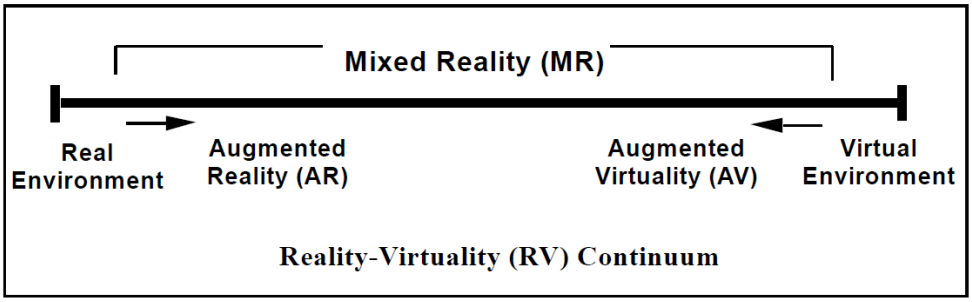
### Question 2

Are you familiar with reality technology? What do you know about reality technology?

***Augmented Reality:*** *"Type of mixed reality in which virtual world data are embedded and/ or registered with the representation of physical world data." (ISO/ IEC 18039:2019) – Overlays virtual objects on the real world (Head-Up Display).*

***Virtual Reality:*** *"Virtual Reality is a computer-simulated reality or artificial world into which people are transferred and interactively integrated with the help of technical equipment and extensive software." (Brockhaus 1997) – Immersed in virtual reality.*

***Mixed Reality:*** *"Mixed Reality refers to environments or systems which mix the natural perception of the user with an artificial perception." or "System that uses a mixture of representations of physical world data and virtual world data as its presentation medium." (ISO/ IEC 18039:2019) – AR plus the ability to interact (Holograms).*




(Milgram *et al.* 1994, p. 283)

**Question 3**

a. In general, where could reality technology be integrated into maintenance processes?
b. Which problems in maintenance processes could be solved or simplified with reality technology?
c. Are there any problems that could only be solved or simplified with reality technology?

**Question 4**

How can reality technology be integrated into each of these areas?

**Question 5**

Which type of reality technology – augmented reality (AR), mixed reality (MR) virtual reality (VR) – is helpful in your maintenance environment?

**Question 6**

What kind of hardware or technology of reality technology would you use?

*What do you think about Tablets, Smartphones, Data Glasses, Smart Glasses, Google Glasses, VR-Glasses, Microsoft HoloLens?*

**Question 7**

How can reality technology support or enhance your maintenance?

- Providing targeted information
- Enabling communication with technical experts via remote support
- Carrying out documentation

**Question 8**

Which conditions and requirements have to be considered to implement reality technology into the maintenance environment? Please rank your answer!

- Acceptance of employees
- Skills of employees (e.g. lack of know-how)
- Financial resources (e.g. lack of cost-benefit ratio)
- Maturity of technologies and machines
- Degree of digitalisation (e.g. no internet connection)
- Data security

**Question 9**

Where do you see the greatest benefit of augmented reality?

- Optimisation of maintenance training ("Making mistakes at no cost")
- Optimisation of maintenance planning (e.g. model development)
- Optimisation of maintenance processes
- Optimisation of occupational health and safety
- Optimisation of process reliability
- Optimisation of availability of machines and systems
- Support in case of shortage of skilled employees
- Other benefit
- No Benefit

**Question 10**

Where do you see the greatest benefit of mixed reality?

- Optimisation of maintenance training ("Making mistakes at no cost")
- Optimisation of maintenance planning (e.g. model development)
- Optimisation of maintenance processes
- Optimisation of occupational health and safety
- Optimisation of process reliability
- Optimisation of availability of machines and systems
- Support in case of shortage of skilled employees
- Other benefit
- No Benefit

### Question 11

Where do you see the greatest benefit of virtual reality?

- Optimisation of maintenance training ("Making mistakes at no cost")
- Optimisation of maintenance planning (e.g. model development)
- Optimisation of maintenance processes
- Optimisation of occupational health and safety
- Optimisation of process reliability
- Optimisation of availability of machines and systems
- Support in case of shortage of skilled employees
- Other benefit
- No Benefit

### Question 12

Where do you see the disadvantages of augmented reality, mixed reality and virtual reality or in general reality technologies?

# Appendix B
# Identification of Output Devices

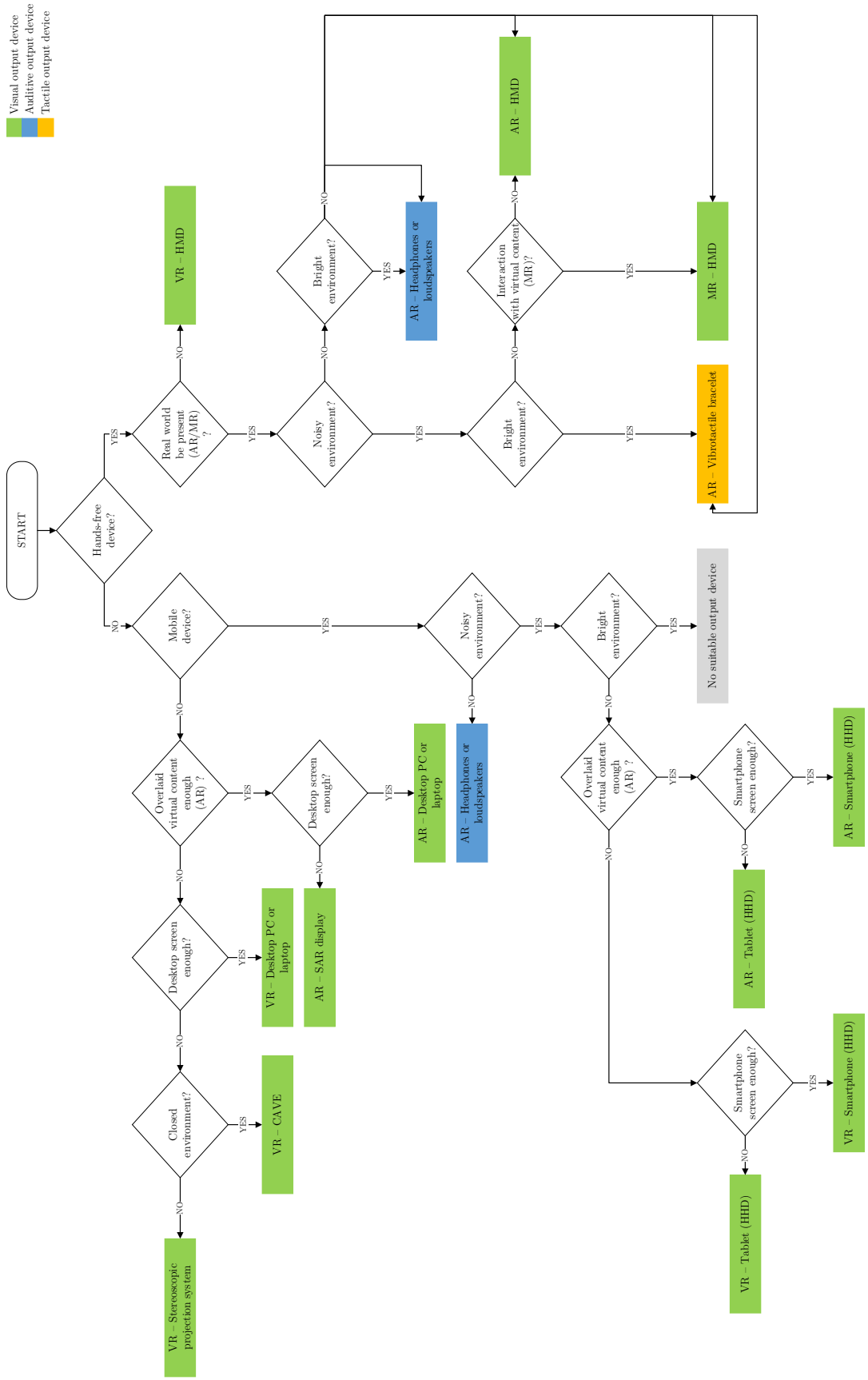



Figure B.1: Flow chart for the identification of output devices

# Appendix C
# Price Analysis

## C.1 Output Devices

Table C.1: References of the price analysis for output devices

| Output Device | Reference |
|---|---|
| AR-HMD | Epson (2020a); Mobile Advance (2020); Vuzix (2020b) |
| MR-HMD | Microsoft (2020c) |
| VR-HMD | Bezmalinovic (2020); HTC (2020a) |
| Smartphone | CW Mobile (2020); Etiden (2020) |
| Tablet | Bechtle (2020b); ICO (2020) |
| Laptop | Bullman (2020); MTX (2020) |
| Desktop PC | BMC Solutions (2020a, 2020b); Dell (2020a) |
| SAR display | Sony (2020) |
| Stereos. proj. syst. | Kreylos (2020) |
| CAVE | Borrego *et al.* (2015); Miller *et al.* (2005) |
| Headphone | Comhead (2020); SKS (2020) |
| Loudspeaker | Sonos (2020); Visaton (2020) |
| Vibrot. bracelet | Price offer from Sensodrive (2020) |

## C.2 Input Devices

Table C.2: References of the price analysis for input devices

| Additional Input Device | Reference |
|---|---|
| Camera | Edmund Optics (2020); GET Cameras (2020) |
| Microphone | Thomann (2020a, 2020b) |
| PC mouse/ space mouse | Bechtle (2020a); Microsoft (2020a) |
| Keyboard | Bechtle (2020c); Dell (2020b) |
| Joystick | Logitech (2020); Thrustmaster (2020) |
| Controller | HTC (2020b); Oculus (2020c) |
| Data glove | IMSYS (2020) |
| Vibrotactile bracelet | Price offer from Sensodrive (2020) |

## C.3 Tracking Devices

Table C.3: References of the price analysis for tracking devices

| Tracking Device | | Reference |
|---|---|---|
| Sensor-based tracking | Electromagnetic sensor | Ong *et al.* (2008, p. 2712) |
| | Acoustic sensor | Ong *et al.* (2008, p. 2711) |
| | Inertial sensor | Mouser Electronics (2020a, 2020b) |
| | Optical sensor | Edmund Optics (2020); GET Cameras (2020) |
| | Mechanical sensor | Aguinis *et al.* (2001, p. 72) |
| Camera-based tracking | Marker-based tracking | Edmund Optics (2020); GET Cameras (2020) |
| | Vision-based tracking | Edmund Optics (2020); GET Cameras (2020) |

## C.4 Development Platforms

Table C.4: References of the price analysis for development platforms

| Development Platform | License | Reference |
|---|---|---|
| Programming languages | Free | None |
| Game Engine | Proprietary | Included in hardware price |
| | Commercial | Unity (2020a); Unreal Engine (2020) |
| | Free | None |
| Software Platforms | Proprietary | Included in hardware price |
| | Commercial | (Present4D 2020) |
| | Free | None |
| SDK | Proprietary | Layar (2020); Vuforia (2020) |
| | Commercial | Included in hardware price |
| | Free | None |

## C.5 Price Offer from Sensodrive for the Vibrotactile Bracelet "VibroTac"

**Angebot Nr. 4001857**

Thank you for your inquiry and your interest in our SENSO-Wheels.
For the first tests and for setup purposes you can use our free of charge software tools.
Code examples enable the software developers a fast and easy integration in the respective simulator environment.
If there are additional question during the setup process our engineers will readily assist you.

I am looking forward to collaborating with your company.

If you have any questions do not hesitate to contact me either by email or phone.

| Pos | Menge | | Nummer | Text | Einzelpreis EUR | Gesamtpreis EUR |
|---|---|---|---|---|---|---|
| 1 | 1,00 | Stck. | 5000436 | Vibrotactile feedback device „VibroTac"<br>Evaluation model composed of:<br>- central module, communication via Bluetooth<br>- six motor modules, that can be individually controlled<br>- five intermediate modules, that increase expansibility<br>- standard snap-in lock<br>The delivery includes:<br>- 1x micro-USB to USB adapter cable<br>- 1x charger<br>- Manual<br>Engineering support:<br>The VibroTacs are evaluation models. SENSODRIVE will assist you to implement the interface and will answer questions regarding VibroTac. In return SENSODRIVE will get a customer feedback related to usability and potential for improvements. | 5.000,00 | 5.000,00 |
| 2 | 1,00 | Stck. | | Packing and Shipping:<br>According to actual costs | | |
| Zwischensumme | | | | | | 5.000,00 |

| | | |
|---|---|---|
| Gesamt Netto | | 5.000,00 |
| zzgl. 16,00 % USt. auf | 5.000,00 | 800,00 |
| **Gesamtbetrag** | | **5.800,00** |