Designing Augmented Reality Technologies for Service Systems

Dissertation with the aim of achieving a doctoral degree
at the Faculty of Mathematics, Informatics, and Natural Sciences

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Universität Hamburg

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2024
Hamburg

Date of disputation: 16.09.2024

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Abstract

Motivation

With the emergence and increasing maturity of augmented reality (AR) technologies since their early development in the 1960s, AR has not only become established in the gaming industry over the last decade but is also becoming increasingly relevant for use in organizations as a driver for innovation. The use of AR in organizations can offer numerous benefits to users. By enabling hands-free and mobile working, increasing situational awareness, reducing cognitive load, and supporting collaboration, AR can lead to higher performance, efficiency, and satisfaction. Despite these benefits, however, the use of AR in organizations remains limited due to numerous challenges and risks that hinder effective adoption. These untapped potentials stem from a lack of knowledge in both research and practice about how AR can be used effectively, and in a user-centric way, in organizational contexts.

This dissertation provides systematic guidance and design knowledge to fully realize the potential of AR in organizations, described as service systems, in which actors integrate resources in complex interactions. This cumulative dissertation comprises nine publications and is structured around three main research questions, each addressing different aspects of the application of AR in service systems. A user-centric perspective is adopted for the investigation of the first research question, and an organizational perspective for the second research question. The third research question is examined on a conceptual level.

Research Design

The research design is rooted in the design science research (DSR) approach, which focuses on building and evaluating IT artifacts to solve real-world problems while developing theoretical contributions. A mixed-methods approach is employed, incorporating a variety of qualitative and quantitative methods. Two case studies are conducted to gain in-depth insights into the application of AR in service systems. The first case study examines the complex and demanding case of water depth management in a maritime logistics hub, while the second case study focuses on the use of AR in warehouse inventory at a maintenance, repair, and overhaul service provider in the aviation sector as a typical example of AR use cases. These case studies serve as the basis for developing and refining the design knowledge presented in the dissertation.

Results

The findings of this dissertation provide design knowledge with a view to supporting the effective use of AR technologies in organizations. This includes understanding the barriers, challenges, and state of the art in the use of AR, and the development of artifacts that facilitate its systematic application.

The results answering the first research question present the user-centered requirements for the use of AR in complex and demanding service systems. The case study on water depth management demonstrates the feasibility of AR applications in safety-critical services by identifying specific requirements for the application of AR to measure water depths in a harbor environment with a vessel and autonomous drone.

Systematic approaches for using AR in organizations to realize its potential are presented in form of the findings to investigating the second research question. These include the “dividing complexity framework”, which breaks down the layers of complexity in implementing AR technologies, and the “process augmentability canvas” that serves as a tool to help organizations identify suitable processes for AR implementation. In addition, the suitability of current business process modeling approaches for AR applications is explored, and two taxonomies are presented to systematically classify AR interaction techniques. Furthermore, design principles for no-code AR authoring tools are provided to enable the development of AR applications without programming skills.

The results of the third research question provide insights into conceptual AR research. Through the use of a graph database approach, the leading concepts and constructs in the field are analyzed.

Contribution

This dissertation makes several theoretical and practical contributions to the systematic design of augmented reality technologies for application in service systems.

The user-centered requirements for the use of AR in the context of water depth management contribute to the application of AR in complex environments under challenging conditions and provide design knowledge for AR solutions for such safety-critical services.

The presented artifacts designed to realize the potential of AR contribute to the systematic research and application of AR in service systems. They provide design knowledge and serve as tools and methods for the development of complex service systems and interactions between service systems. This helps organizations to identify potential areas for AR and make informed decisions about its use. The "dividing complexity framework" and the "process augmentability canvas" address both theoretical and practical challenges. The artifacts contribute to the understanding of benefits and requirements, institutional constraints, and key resources, which form the basis of prototypical implementations. Both artifacts enable the systematic exploration of AR potential. The analysis of current business process modeling approaches in terms of their suitability for modeling AR processes contributes to the understanding and application of such approaches and guides further research in this area. Moreover, the investigation and systematic classification of AR interaction techniques, in the form of providing two taxonomies, contribute to the understanding and selection of AR interactions, and to guiding the design and development of AR applications. The design principles for no-code AR authoring tools contribute to the understanding of such tools, and provide design knowledge on how to design and develop them. This facilitates the accessibility of AR development and enables a broader range of users to create and implement AR applications. The combination of artifacts offers practitioners a comprehensive set of tools with which to exploit the full potential of AR and to reduce the barriers to AR adoption.

The overview of conceptual AR research contributes to the understanding of concepts and constructs used, points out theoretical perspectives in conceptual AR research, identifies research gaps and outlines future research directions.

In addition, this dissertation makes two further contributions by expanding methods applied in Information Systems research. First, the think-aloud approach is extended by integrating video recordings from the first- and third-person perspectives and by enriching the think-aloud transcripts with screen recordings of AR application

use. Second, a graph database approach for synthesizing and analyzing literature is adapted, and a new metamodel for representing AR publications in a graph database is presented.

Limitations and Implications for Further Research

While the dissertation provides valuable insights and contributions, it also acknowledges some limitations and opportunities for future research.

The first limitation is methodological, due to its focus on specific cases, which may not fully capture the diversity of AR applications in a wide range of organizational contexts. Future research could continue evaluations with the actual target audience, such as practitioners who have limited AR experience, as well as re-evaluate refined versions of the artifacts in various real-world organizational settings. Second, this dissertation focuses exclusively on AR; however, some aspects might also be applicable to virtual reality and other forms of mixed reality, which could be included in future extensions of the developed artifacts. The third limitation is technological, inherent in the immaturity of the AR hardware considered in this dissertation, and that was available on the market at the time. Inevitably the artifacts developed here reflect the shortcomings of these AR devices. The rapidly evolving AR hardware landscape opens up opportunities for more sophisticated AR hardware that might overcome the existing limitations and potentially reduce the shortcomings. Ultimately, the impact of new technological advances opens up a wide range of research opportunities to be explored in the future.

Kurzfassung

Motivation

Mit dem Aufkommen und der zunehmenden Verbreitung von Augmented-Reality-Technologien seit ihrer frühen Entwicklung in den 1960er Jahren hat sich Augmented Reality (AR) im letzten Jahrzehnt nicht nur in der Spieleindustrie etabliert, sondern wird auch zunehmend als Treiber für Innovationen in Organisationen relevant. Der Einsatz von AR in Organisationen kann für die Nutzenden zahlreiche Vorteile mit sich bringen. AR ermöglicht freihändiges und mobiles Arbeiten, kann das Situationsbewusstsein schärfen, die kognitive Belastung reduzieren und die Zusammenarbeit unterstützen. Dies kann zu einer verbesserten Leistung, Effizienz und Zufriedenheit führen. Trotz dieser Vorteile ist der Einsatz von AR in Organisationen aufgrund zahlreicher Herausforderungen und Risiken, die einer effektiven Einführung im Wege stehen, limitiert. Die ungenutzten Potenziale können auf einen Mangel an Wissen in der Forschung und Praxis zurückgeführt werden, wie AR effektiv und nutzungszentriert in organisatorischen Kontexten eingesetzt werden kann.

Die vorliegende Dissertation bietet systematische Unterstützung und Gestaltungswissen, um das Potenzial von AR in Organisationen voll auszuschöpfen. Organisationen werden dabei als Dienstleistungssysteme bezeichnet, in denen Akteure Ressourcen in komplexen Interaktionen integrieren. Diese kumulative Dissertation umfasst neun Publikationen und ist entlang von drei zentralen Forschungsfragen strukturiert, die jeweils unterschiedliche Aspekte der Anwendung von AR in Dienstleistungssystemen beleuchten. Für die Untersuchung der ersten Forschungsfrage wird eine nutzerzentrierte Perspektive eingenommen. Die zweite Forschungsfrage wird aus organisatorischer Perspektive untersucht und die dritte Forschungsfrage auf konzeptioneller Ebene.

Forschungsdesign

Das Forschungsdesign dieser Dissertation basiert auf dem Design Science Research (DSR) Ansatz, der sich auf die Entwicklung und Evaluierung von IT-Artefakten konzentriert, um praktische Probleme zu lösen und gleichzeitig theoretische Beiträge zu entwickeln. Es wird ein Mixed-Methods-Ansatz verfolgt, der eine Vielzahl qualitativer und quantitativer Methoden umfasst. Um tiefere Einblicke in die Anwendung von AR in Dienstleistungssystemen zu gewinnen, werden zwei Fallstudien durchgeführt. Die erste Fallstudie untersucht den komplexen und anspruchsvollen Fall des Wassertiefenmanagements in einem maritimen Logistikzentrum. Die zweite Fallstudie konzentriert sich auf den Einsatz von AR in der Lagerhaltung eines MRO-Dienstleisters (Maintenance, Repair and Overhaul – Wartung, Reparatur und Überholung) im Luftfahrtsektor als typisches Beispiel für AR-Anwendungsfälle. Die Fallstudien dienen als Grundlage für die Entwicklung und Verfeinerung des in der Dissertation vorgestellten Gestaltungswissens.

Forschungsergebnisse

Die Ergebnisse dieser Dissertation vermitteln Gestaltungswissen, um den effektiven Einsatz von AR-Technologien in Organisationen zu unterstützen. Dies umfasst das Verständnis der Barrieren und Herausforderungen und des Stands der Technik bei der Verwendung von AR sowie die Entwicklung von Artefakten, die den systematischen AR-Einsatz erleichtern.

Zur Beantwortung der ersten Forschungsfrage werden nutzungszentrierte Anforderungen für den Einsatz von AR in komplexen und anspruchsvollen Dienstleistungssystemen vorgestellt. Im Rahmen der Fallstudie des Wassertiefenmanagements wird die Eignung von AR-Anwendungen zum Einsatz in sicherheitskritischen Dienstleistungen demonstriert, indem spezifische Anforderungen für die Messung von Wassertiefen in einer Hafenumgebung mit einem Schiff und einer autonomen Drohne identifiziert werden.

Zur Untersuchung der zweiten Forschungsfrage werden systematische Ansätze zum Einsatz von AR in Organisationen vorgestellt, um dessen Potenzial zu realisieren. Dazu zählen das „Dividing Complexity Framework“, das die Komplexität der Implementierung von AR-Technologien aufschlüsselt, sowie das „Process Augmentability Canvas“, das Organisationen bei der Identifizierung geeigneter Prozesse für die AR-Implementierung unterstützt. Zudem werden aktuelle Geschäftsprozessmodellierungsansätze für AR-Anwendungen untersucht und zwei Taxonomien zur systematischen Klassifizierung von AR-Interaktionstechniken vorgestellt. Weiterhin werden Gestaltungsprinzipien für No-Code-AR-Authoring-Tools präsentiert, um die Entwicklung von AR-Anwendungen ohne Programmiererfahrung zu ermöglichen.

Die Ergebnisse der dritten Forschungsfrage geben Einblicke in die konzeptionelle AR-Forschung. Die Analyse der führenden Konzepte und Konstrukte auf diesem Gebiet erfolgt unter Verwendung eines Graphdatenbankansatzes.

Forschungsbeitrag

Die vorliegende Dissertation leistet theoretische und praktische Beiträge zur systematischen Gestaltung von Augmented-Reality-Technologien für den Einsatz in Dienstleistungssystemen.

Die nutzungszentrierten Anforderungen für den Einsatz von AR im Kontext des Wassertiefenmanagements tragen zur Anwendung von AR in komplexen Umgebungen unter herausfordernden Bedingungen bei und liefern Gestaltungswissen für AR-Lösungen für sicherheitskritische Dienstleistungen.

Die vorgestellten Artefakte unterstützen die systematische Exploration und Anwendung von AR in Dienstleistungssystemen. Sie liefern Gestaltungswissen und dienen als Werkzeuge und Methoden für die Entwicklung komplexer Dienstleistungssysteme und Dienstleistungssysteminteraktionen. Durch die Identifizierung potenzieller Bereiche für AR können Organisationen fundierte Entscheidungen über dessen Einsatz treffen. Das „Dividing Complexity Framework“ und das „Process Augmentability Canvas“ adressieren sowohl theoretische als auch praktische Herausforderungen. Die Artefakte tragen zum Verständnis von Nutzen und Anforderungen bei sowie von institutionellen Einschränkungen und Schlüsselressourcen, die die Grundlage für prototypische Implementierungen bilden. Beide Artefakte ermöglichen eine systematische Erkundung des AR-Potenzials. Die Analyse aktueller Geschäftsprozessmodellierungsansätze im Hinblick auf ihre Eignung zur Modellierung von AR-Prozessen trägt zum Verständnis und zur Anwendung solcher Ansätze bei und liefert Anhaltspunkte für die weitere Forschung in diesem Bereich. Darüber hinaus trägt die systematische Klassifizierung von AR-Interaktionstechniken in Form von zwei Taxonomien zum Verständnis und zur Auswahl von AR-Interaktionen sowie zur Gestaltung und Entwicklung von AR-Anwendungen bei. Die Designprinzipien für No-Code-AR-Authoring-Tools tragen zum Verständnis solcher Anwendungen bei und liefern Gestaltungswissen darüber, wie sie zu entwerfen und zu entwickeln sind. Dies erleichtert die Zugänglichkeit der AR-Entwicklung und ermöglicht es einem breiteren Nutzendenkreis, AR-Anwendungen zu erstellen und zu implementieren. Durch die Kombination der Artefakte kann das volle Potenzial von AR ausgeschöpft und den Barrieren für die Einführung von AR entgegnet werden.

Der Überblick über konzeptionelle AR-Forschung trägt zum Verständnis der verwendeten Konzepte und Konstrukte in diesem Bereich bei, zeigt theoretische Perspektiven in der konzeptionellen AR-Forschung auf, identifiziert Forschungslücken und skizziert zukünftige Forschungsrichtungen.

Darüber hinaus leistet diese Dissertation zwei weitere methodische Beiträge, indem angewandte Methoden der Wirtschaftsinformatik erweitert werden. Zum einen wird der Think-Aloud-Ansatz durch die Integration von Videoaufnahmen aus der First- und Third-Person-Perspektive sowie durch Bildschirmaufzeichnungen der Anwendungsnutzung erweitert. Zum anderen wird ein Graphdatenbankansatz zur Synthese und Analyse von Literatur angepasst und ein neues Metamodell zur Darstellung von AR-Publikationen in einer Graphdatenbank vorgestellt.

Limitationen und Ausblick

Die vorliegende Dissertation liefert wertvolle Einblicke und Beiträge, weist jedoch auch einige Limitationen auf, aus denen Möglichkeiten für zukünftige Forschung resultieren.

Die erste Limitation ist methodischer Natur, da der Schwerpunkt dieser Arbeit auf spezifischen Anwendungsfällen liegt. Dadurch kann die Vielfalt von AR-Anwendungen in einem breiten Spektrum organisatorischer Kontexte möglicherweise nicht vollständig erfasst werden. Zukünftige Forschung könnte weitere Evaluationen mit der angestrebten Zielgruppe vornehmen, z. B. mit Nutzenden aus der Praxis, die über begrenzte AR-Erfahrung verfügen. Zudem könnten weiterentwickelte Versionen der Artefakte in verschiedenen realen organisatorischen Kontexten erneut evaluiert werden. Zweitens konzentriert sich diese Dissertation ausschließlich auf AR. Einige Aspekte könnten jedoch auch auf Virtual Reality und andere Formen von Mixed Reality anwendbar sein, die in zukünftige Erweiterungen der Artefakte einbezogen werden könnten. Die dritte Limitation ist technologischer Natur und ist in den Einschränkungen der zu diesem Zeitpunkt auf dem Markt erhältlichen

AR-Hardware begründet. Die im Rahmen dieser Dissertation entwickelten Artefakte spiegeln daher die Schwächen der berücksichtigten AR-Hardware zwangsläufig wider. Die sich schnell entwickelnde AR-Hardware-Landschaft eröffnet Möglichkeiten für anspruchsvollere und ausgereiftere AR-Hardware, die die bestehenden Defizite überwinden könnte. Letztlich eröffnen die Auswirkungen neuer technologischer Fortschritte ein breites Spektrum an zukünftigen Forschungsmöglichkeiten.

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List of Abbreviations

AI Artificial Intelligence

AIS Automatic Identification System

AR Augmented Reality

ARML Augmented Reality Markup Language

AV Augmented Virtuality

BCI Brain-Computer Interface

BORM Business Object Relation Modeling

BPI Business Process Innovation

BPM Business Process Management / Business Process Modeling

BPMN Business Process Model and Notation

BPR Business Process Reengineering

CAD Computer-Aided Design

DART Designer's Augmented Reality Toolkit

DOF Degrees of Freedom

DOI Digital Object Identifier

DP Design Principle

DSR Design Science Research

EPC Event-driven Process Chains

HCI Human-Computer Interaction

HMD Head-Mounted Display

HUD Head-up Display

IoT Internet of Things

IS Information Systems

IT Information Technology

KPI Key Performance Indicator

MR Mixed Reality

MRO Maintenance, Repair, and Overhaul

MRTK Mixed Reality Toolkit

NASA-TLX NASA Task Load Index

NLP Natural Language Processing

OST Optical See-Through

POI Point of Interest

PPI Process Performance Indicators

PVT Process Virtualization Theory

S-O-R Stimulus-Organism-Response

SDL Service-Dominant Logic

SEM Structural Equation Modeling / Structural Equation Model

SME Small and Medium-Sized Enterprises

SSE Service Systems Engineering

SUS System Usability Scale

TAM Technology Acceptance Model

TTF Task-Technology Fit

UEQ User Experience Questionnaire

UGT Uses and Gratifications Theory

UI User Interface

UML Unified Modeling Language

UTAUT Unified Theory of Acceptance and Use of Technology

UUID Universally Unique Identifier

UX User Experience

VE Virtual Environment

VR Virtual Reality

VST Video See-Through

WIMP Windows, Icons, Menus, Pointer

WMS Warehouse Management System

WYSIWYG What-you-see-is-what-you-get

XR Extended Reality

1 Introduction

1.1 Motivation and Problem Statement

Augmented reality (AR) is a technology that enables users to experience the seamless merging of the virtual and the real world. AR has become increasingly prevalent since its beginnings in the late 1960s (Sutherland, 1968) and is now widely used in a variety of consumer environments (Snap Inc. & Deloitte Digital, 2021). Half a century after its early beginnings, the year 2016—sometimes referred to as "the year of AR" (Boyajian, 2016)—marked an important milestone: namely, the release of the Microsoft Hololens, the first commercially available AR head-mounted display (HMD). In the same year, the mobile AR game Pokémon Go became immensely popular and served as a catalyst for AR's visibility (Chapple, 2022; Lynch & Bank of America, 2016). Today, with the ubiquity of smartphones, every user carries an AR-ready device in their pocket. Another significant milestone for a new generation of mixed reality (MR) hardware was reached in 2024, with the release of the Apple Vision Pro: this mixed-reality headset offers even more computing power and the ability to seamlessly transition between AR and fully immersive virtual reality (VR) (Gans & Nagaraj, 2023; Hackl, 2023).

AR technologies can serve as a strategic driver for innovation in an organizational context. According to the hype cycle for emerging technologies (Gartner, Inc., n.d.), AR was last classified as an emerging technology trend in 2018. At that time, AR was in the Trough of Disillusionment phase and expected to reach the plateau of productivity within five to ten years, indicating a transition towards productive use in organizations (Panetta, 2019). Nevertheless, the term spatial computing has recently emerged in Gartner's trend radar as a high-impact technology for organizations (Perri, 2024). Spatial computing encompasses AR technology and is also used by Apple to describe its Vision Pro headset. The emergence of spatial computing reflects AR's enduring importance in the exploration and facilitation of AR utilization in organizational contexts.

Research in consumer environments, such as gaming, has examined various aspects of the mobile AR game Pokémon Go, including user health implications (Laato et al., 2020), user motivation (Ernst & Ernst, 2015), and value co-creation and co-destruction seen through a service lens (Elo et al., 2021; Lintula et al., 2017). Another example of research on AR is the evaluation of technology adoption models and theories for AR smart glasses in consumer settings (Rauschnabel & Ro, 2016).

In service research and practice, novel technologies are catalysts for innovation, due to their potential to fundamentally change the way services are delivered and experienced. Technological advances open up new perspectives for supporting the workforce, which can be particularly beneficial to frontline workers (Ostrom et al., 2021; Ostrom et al., 2015). Previous research has explored the use of AR in organizational contexts. For instance, an attempt was made to provide guidance for exploring potential use cases of AR in service processes (Klinker et al., 2018). Additionally, engineering approaches in Information Systems (IS) were employed to generate design knowledge for the use of smart glasses in intralogistics service (Berkemeier et al., 2019) and technical customer service (Metzger, Niemöller, & Thomas, 2017). Initial proof-of-concepts for individual scenarios have been implemented and have demonstrated the potential of AR to support and enrich services. AR prototypes have been developed and evaluated to address challenges in technical customer service (Niemöller et al., 2019; Niemöller, Metzger, & Thomas, 2017), healthcare (Klinker et al., 2017; Klinker et al., 2019, 2020a, 2020b), intralogistics service (Berkemeier et al., 2019), remote support (Obermair et al., 2020), manufacturing (Kohn & Harborth, 2018), and industrial training scenarios (Büttner et al., 2020). Research has also been conducted in the hospitality industry (Jingen Liang & Elliot, 2021) and in the consumer goods and retail sectors (Hilken et al., 2017; Scholz & Duffy, 2018; Wedel et al., 2020; Zimmermann et al., 2023).

The potential benefits of AR technology for organizations are manifold. These include hands-free working, made possible by displaying information directly into the user's field of view, and by the provision of hands-free interaction mechanisms, such as voice commands or head gestures. AR also enables mobile working, allowing users to work without being tied to a fixed workstation (Klinker et al., 2020a; Niemöller, Metzger, & Thomas, 2017; Prilla et al., 2019). AR can, among others, enhance situational awareness and reduce cognitive load (Coleman & Thirtyacre, 2021; Fang & An, 2020), increase customer engagement and satisfaction (Jessen et al., 2020; Jung et al., 2015), facilitate remote collaboration (Etzold et al., 2014; Johnson et al., 2015; Lukosch, Lukosch, et al., 2015; C. Reuter et al., 2019), and improve learning experiences by providing contextual information (Miyashita et al., 2008; Sparacino, 2002; tom Dieck, Jung, & tom Dieck, 2018). These benefits show the enormous potential for the use of AR in the digital workplace, for example to enhance productivity and reduce error rates (Porter & Heppelmann, 2017, 2020). Such increases in performance and efficiency are also acknowledged in the literature (Egger & Masood, 2020; Fiorentino et al., 2014; Kohn & Harborth, 2018). In a study by Fiorentino et al. (2014), the use of AR to support maintenance tasks was found to result in a significant reduction of completion time, with a time improvement of up to 79.5%, and a reduction in errors by 92.4%.

Although the potential for using AR in organizations is promising, its practical application remain scarce (Steffen et al., 2019). Organizations are facing challenges in exploiting the potential of AR (Masood & Egger, 2019) and realizing new approaches that can keep in step with the increasing pace of innovation cycles (Wehking et al., 2021). These difficulties may originate from a lack of understanding of key challenges and success factors (Masood & Egger, 2019). Previous research has also identified a lack of technological competencies, organizational support, and user readiness as barriers (Chandra & Kumar, 2018). These challenges can result in the failure of innovation projects, abandoned proof-of-concepts, and increased employee resistance. Due to the "missing experience, the implementation of [AR] systems is associated with high risks" (Berkemeier et al., 2019, p. 68). A study by Hobert and Schumann (2017) identified key factors influencing the adoption of AR in industry: technological, environmental, and organizational. Technological factors include hardware maturity and infrastructure. Environmental factors encompass privacy, data security and safety. Organizational factors include expert knowledge, user concerns, culture, and age, among other aspects. However, as the data in this study was collected in 2015, prior to the release of the Microsoft Hololens, only hardware classified as "data glasses", "smart glasses" or "wearable computers" was considered.

In the field of IS research, the terms "AR HMDs", "AR glasses", "data glasses", "smart glasses" and "wearable computers" are sometimes used interchangeably, and the distinction between them is not always clear. The last three often do not enable spatial registration in 3D space; rather, they provide 2D information in the user's field of view. Furthermore, the focus on glasses in previous research excludes mobile AR. In this dissertation, I consider hardware to be AR if it meets the three characteristics of Azuma's definition: "1) Combining real and virtual, 2) Interactive in real time, 3) [Virtual objects are] [r]egistered in 3-D [space]" (Azuma, 1997, p. 2). Consequently, hardware such as Google Glass, which previous research has considered AR, is not classified as an AR HMD, because it lacks the spatial registration characteristic. However, HMDs such as the Hololens or mobile AR, with devices like smartphones and tablets, do align with this definition.

The current state of research indicates a focus on the use of AR for individual scenarios and for rather simple and isolated tasks. In particular, the use of AR in more complex socio-technical systems has not yet been sufficiently studied. We lack of knowledge and design theories on how AR can be used effectively and in a user-centric manner (Berkemeier et al., 2019; Kohn & Harborth, 2018; Metzger, Niemöller, & Thomas, 2017). Accordingly, the use of AR is still associated with high risks regarding "acceptance, usability and user experience, ergonomic design, safety, as well as [...] privacy and data protection" (Berkemeier et al., 2019, p. 78).

These risks could be mitigated, but this would require systematic guidance and evidence-based design knowledge on the utilization of AR in organizational settings, which is currently lacking. Moreover, to understand how value is created through AR technologies, we have to examine how technologies, actors, and knowledges are configured. To do so, service-dominant logic (SDL) offers an appropriate lens with which to examine value co-creation in a specific context, taking into account multiple actors and the integration of resources (Lusch & Vargo, 2006; Vargo & Lusch, 2004, 2008). The concept of service systems examines the complex interactions among actors employing technologies in organizations. Service systems are defined as "a dynamic value-cocreation configuration of resources, including people, organizations, shared information (language, laws, measures, methods), and technology, all connected internally and externally to other service systems by value propositions" (Maglio et al., 2009, p. 399).

Service systems engineering (SSE) (Böhmann et al., 2014) is a systematic approach for designing, developing, and piloting service systems. SSE considers not only individual users as actors and their interactions with technology, but also takes a more holistic view of all the actors and resources in service systems and their interactions in value co-creation. One research challenge for SSE, as highlighted by Böhmann et al. (2014), is the engineering of interactions with and in service systems. New forms of interactions offer new possibilities for contextualization and collaboration. Contextualization is a fundamental aspect of AR technology, whereby information is contextualized in terms of spatial context and location within the 3D environment (Kalkofen et al., 2007). In alignment with the third aspect of Azuma's definition of AR (Azuma, 1997), which posits that information is registered in 3D space, the contextualization of information in AR is inherent, as the context is an inevitable and essential component. To avoid visual clutter, it is crucial for the use of AR to display only the contextual information needed at that time (Julier et al., 2000; Zhao et al., 2019). Furthermore, AR has the potential to support both face-to-face and remote collaboration, thus facilitating immersive collaboration across distances. This can be achieved by, for instance, having shared objects that can be interacted with, or by being able to remotely see what another person sees, thereby creating the feeling of being virtually co-located (Lukosch, Billinghurst, et al., 2015). Böhmann et al. call for “a much deeper understanding of the underlying principles of service systems interaction”, alongside “design research [...] on the impact of specific interactions on the perceptions of service systems” (Böhmann et al., 2014, p. 75).

Three major research gaps are identified, all of which are addressed in this dissertation. First, systematic guidance for the use of AR should prioritize application areas and processes, interactions, and how to engineer AR solutions with low technological entry barriers. In order to fully leverage the potential of AR in organizations, a shift in focus is necessary: instead of asking, “Can we use AR somewhere?” we should ask “How can we leverage the potential of AR in an effective, efficient, and user-centric manner?”. Second, the development of AR solutions is still a major challenge for organizations, due to the specialized technical expertise required for their implementation and testing (Ashtari et al., 2020). A promising major development are low-code and no-code platforms that offer effective and innovative tools for designing and developing workplace applications without the need for programming skills (Atkins, 2020; Bock & Frank, 2021; Elshan et al., 2023). However, initial efforts to create AR applications using low-code and no-code AR authoring tools have not yet reached maturity, and are often complex to learn (Hönemann et al., 2022; Nebeling & Speicher, 2018). Third, the conceptual research on AR in IS research is rather fragmented and diverse, resulting in a lack of synthesized knowledge on the most predominantly studied constructs in the main research gaps. To manually synthesize the existing knowledge describing causal relationships and using structural equation modeling would be a major challenge. The adoption of an approach that sheds light on the current state of research and synthesizes existing knowledge, therefore, offers great potential for facilitating knowledge synthesis.

1.2 Research Goal and Research Questions

The overall research goal (RG) of this dissertation is to gain an understanding of the requirements for the systematic application of AR technologies in service systems.

Understanding these requirements would allow to generate design knowledge that can be used to systematically identify and realize the potential of AR in organizations. The research goal is therefore defined as follows:

> **Research Goal:**
>
> To enable the effective use of augmented reality (AR) technologies in organizations, by understanding the barriers, challenges, and state of the art of using AR, and generating design knowledge that supports the systematic application of AR in organizations.

This dissertation builds upon prior research regarding the application of AR technologies, specifically in service systems. While the field of Human-Computer Interaction (HCI) has extensively studied AR technologies and their interactions, it often neglects the organizational and socio-technical context in which AR is used. In contrast, IS research, also considers the socio-technical context (P. Zhang et al., 2002). Service systems are an instance of complex socio-technical systems that “enable value co-creation through a configuration of actors and resources” (Böhmann et al., 2014, p. 78). Specifically “[s]ervice systems engineering (SSE) focuses on the systematic design and development of service systems” (Böhmann et al., 2014, p. 74). For SSE one key area of research is to design interactions within and with service systems, regarding which Böhmann et al. (2014) suggest that collaboration with HCI research is beneficial. This dissertation explores the use of AR technologies in service systems, drawing on knowledge from both research fields. However, the main contribution of this dissertation is to the field of IS research.

The design science research (DSR) approach is employed to achieve the research goal, as it allows to build and evaluate information technology (IT) artifacts for real-world application scenarios (Gregor & Hevner, 2013; Hevner, 2007; Hevner et al., 2004). To ensure the relevance of the generated design knowledge, the DSR approach was initiated with a specific, problem-centered motivation (Peffers et al., 2007). To thoroughly understand the real-world scenario, a mixed-methods approach (Venkatesh et al., 2016; Venkatesh et al., 2013) is applied, and two case studies are conducted for data collection (Yin, 2018).

This dissertation examines three research questions. The first research question, RQ-1, focuses on the user perspective, with the individual as the unit of analysis. The second research question, RQ-2, takes a broader perspective by placing the organization at the center of the analysis, and includes four sub-questions. The third question, RQ-3, aims to examine closely the theoretical concepts used in AR research using a graph database approach to synthesize and analyze publication information.

RQ-1 investigates the use of AR in complex and demanding service systems. Previous work has primarily explored AR in straightforward, isolated tasks. The objective of the first research question is to assess whether AR can be used successfully in more critical service systems and, if so, what requirements are associated with it. Hence, the first research question:

> **Research Question 1:**
>
> What are the user-centered requirements for applying AR in complex and demanding service systems?

To answer RQ-1, the management of water depth in a harbor area is considered an exemplary case for a complex and demanding service system. Publication P1 (Osterbrink et al., 2021) aims to investigate the feasibility of using AR in water depth management to support depth measurement, also referred to as hydrographic surveying. The publication aims to derive the requirements for using AR in this case. Building on the findings of publication P1, publication P2 (Bräker, Osterbrink, et al., 2023) examines the use of AR as a cognitive assistant to support hydrographic surveying, and extends user-centered requirements for AR application.

The second research question RQ-2 takes a broader and more general perspective by considering the organization as the unit of analysis. It addresses the need for more guidance called for in previous research on how to systematically assess AR in organizations and aims to provide thorough design knowledge. Hence, the second research question:

> **Research Question 2:**
>
> How can organizations systematically assess and realize the potential of AR?

To answer the second research question incrementally, it is further broken down into four sub-questions. Sub-research question RQ-2a focuses on the facet of requirements and potentials for using AR in organizations:

> **Research Question 2a:**
>
> What are the requirements and potentials for AR in service systems?

To investigate research question RQ-2a, a second case study is conducted to assess and understand the specific needs, potentials, and requirements for the use of AR in organizations. Research question RQ-2a is addressed in publications P3 (Bräker & Semmann, 2022) and P4 (Bräker & Semmann, 2023b). Publication P3 (Bräker & Semmann, 2022) provides initial guidance on how to systematically assess and realize the potential of AR in organizations, with a view to supporting services and improving productivity. In order to reduce the barriers to AR adoption, a framework is developed that breaks down the complexity of approaching AR, thus making AR technologies more accessible for organizations. Publication P4 (Bräker & Semmann, 2023b) delves deeper into environmental conditions outlined in publication P3's framework. The objective of publication P4 is to identify the "sweet spot" for the implementation of AR technologies. Criteria for the suitability of AR for services are identified, and the process augmentability canvas is presented as a design artifact and a tool that organizations can use to identify processes that could benefit from AR.

The second sub-research question RQ-2b results from the need to represent AR process models if AR is to be used in organizations:

> **Research Question 2b:**
>
> To what extent are the current approaches and methods for business process modeling applicable to the modeling of AR?

Publication P5 (Bräker & Semmann, 2021) explores the process modeling level of the framework developed in publication P3 (Bräker & Semmann, 2022) and provides an overview of approaches for AR process modeling. Current business process modeling methods and techniques are analyzed for their suitability for modeling AR-based processes, and to ascertain which facets of AR that are represented in these existing modeling approaches. The resulting overview and research agenda of publication P5 addresses RQ-2b.

The third sub-research question RQ-2c focuses on interaction techniques in AR and aims to classify them systematically in order to obtain an overview of possible AR interactions for the design of AR solutions:

> **Research Question 2c:**
>
> Which interaction techniques are used in AR applications, and how can they be systematically classified?

RQ-2c is addressed in publications P6 (Bräker, Hertel, & Semmann, 2022) and P7 (Hertel et al., 2021), which aim to extend the AR scene level of the framework presented in publication P3 (Bräker & Semmann, 2022), which did not focus on interactions. In order to provide a systematic classification of AR interactions and to offer an overview of interactions for the design and development of AR applications, publications P6 and P7 aim to classify atomic interactions as taxonomies. The taxonomies adopt two distinct perspectives. Publication P6 approaches AR interactions from an IS perspective, with the objective of supporting the service design and development of AR applications. Publication P7 approaches the topic from an HCI perspective, with a focus on immersive AR interaction techniques. The resulting taxonomies from publications P6 and P7 contribute to the investigation of research question RQ-2c.

The fourth and final sub-research question RQ-2d deals with the implementation of AR solutions using no-code approaches, and aims to generate design knowledge in the form of design principles for no-code AR authoring tools:

> **Research Question 2d:**
>
> What are the design principles for no-code AR authoring tools?

The RQ-2d is addressed in publication P8 (Bräker, Hertel, & Semmann, 2023b), which focuses on the challenge of developing AR applications without experience in AR programming. The framework presented in publication P3 (Bräker & Semmann, 2022) includes a description of the process, the AR scene, and the technical specifications of the scene, but does not cover software development. Therefore, publication P8 aims to derive design principles for no-code AR authoring tools with the objective of enhancing the accessibility of AR development for users.

The third research question (RQ-3) addresses conceptual AR research from a more abstract perspective and aims to analyze the current state of conceptual AR research using a graph database approach to represent causalities.

> **Research Question 3:**
>
> How can conceptual research on AR be investigated using a graph database approach to represent causal models?

Publication P9 (Bräker & Semmann, 2023a) addresses the lack of synthesized knowledge about conceptual AR research by using a graph database approach to analyze and synthesize previous knowledge on causal models. The objective is to gain a deeper understanding of leading concepts and constructs in AR research. Research question RQ-3 is deliberately less comprehensive than RQ-1 and RQ-2, and serves to supplement them by adopting a more theoretical and conceptual perspective.

Figure 1 illustrates the publications included in this cumulative dissertation and the research question each of these addresses. In the remainder of this dissertation, reference will be made to the three overarching research questions, also referred to as the three different strands of this research. The publications included in this dissertation are described in Chapter 4.

RQ-1

Publication P1 (Osterbrink et al., 2021)
Requirements for Augmented Reality Solutions for Safety-Critical Services –
The Case of Water Depth Management in a Maritime Logistics Hub

Publication P2 (Bräker, Osterbrink, et al., 2023)
User-Centered Requirements for Augmented Reality as a Cognitive Assistant for Safety-Critical Services

RQ-2

RQ-2a

Publication P3 (Bräker & Semmann, 2022)
Dividing Complexity to Conquer New Dimensions –
Towards a Framework for Designing Augmented Reality Solutions

Publication P4 (Bräker & Semmann, 2023b)
The Process Augmentability Canvas –
How to Find the Sweet Spot for Augmented Reality

RQ-2b

Publication P5 (Bräker & Semmann, 2021)
How Does Business Process Modeling Reflect Augmented Reality-Based Processes?

RQ-2c

Publication P6 (Bräker, Hertel, & Semmann, 2022)
Conceptualizing Interactions of Augmented Reality Solutions

Publication P7 (Hertel et al. 2021)
A Taxonomy of Interaction Techniques for Immersive Augmented Reality Based on an Iterative Literature Review

RQ-2d

Publication P8 (Bräker, Hertel, & Semmann, 2023b)
Empowering Users to Create Augmented Reality-Based Solutions –
Deriving Design Principles for No-Code AR Authoring Tools

RQ-3

Publication P9 (Bräker & Semmann, 2023a)
Is There More Than Pokémon Go? –
Exploring the State of Research on Causal Modeling in the Field of Augmented Reality

Figure 1. Research questions and the publications that address them

1.3 Structure of the Dissertation

Table 1 shows the structure of this dissertation, which consists of 17 chapters. Chapter 1 introduces the motivation for this dissertation and presents the problem statement, the research goal, and the research questions. Chapter 2 covers the theoretical foundations of augmented reality, process virtualizability and augmentability, and the use of AR in service systems. Chapter 3 describes the research design, including the research strategy, the research context, and the methods used. Chapter 4 presents the publications that directly and indirectly contribute to this dissertation, and summarizes each included publication. Chapter 5 presents the research contributions, comprising the theoretical and methodological contributions, and Chapter 6 describes the practical contributions. Chapter 7 discusses the limitations of this dissertation, followed by implications for further research in Chapter 8. Chapters 9 to 17 contain the publications included in this dissertation, which constitute its main contribution.

Table 1. Dissertation structure

Wrapper	**1. Introduction**	**2. Theoretical Foundations**	**3. Research Design**	**4. Publications**
	5. Research Contribution	**6. Practical Contribution**	**7. Limitations**	**8. Implications for Further Research**
Publications	**9. Publication P1**	Osterbrink, A., Bräker, J., Semmann, M., & Wiesche, M. (2021). Requirements for Augmented Reality Solutions for Safety-Critical Services – The Case of Water Depth Management in a Maritime Logistics Hub. *Proceedings of the International Conference on Wirtschaftsinformatik*		
	10. Publication P2	Bräker, J., Osterbrink, A., Semmann, M., & Wiesche, M. (2023). User-Centered Requirements for Augmented Reality as a Cognitive Assistant for Safety-Critical Services. *Business & Information Systems Engineering*, *65*, 161–178. https://doi.org/10.1007/s12599-022-00779-3		
	11. Publication P3	Bräker, J., & Semmann, M. (2022). Dividing Complexity to Conquer New Dimensions – Towards a Framework for Designing Augmented Reality Solutions. *Proceedings of the Americas Conference on Information Systems*		
	12. Publication P4	Bräker, J., & Semmann, M. (2023b). The Process Augmentability Canvas – How to Find the Sweet Spot for Augmented Reality. *Proceedings of the European Conference on Information Systems*		
	13. Publication P5	Bräker, J., & Semmann, M. (2021). How Does Business Process Modeling Reflect Augmented Reality-Based Processes? *Proceedings of the Pacific Asia Conference on Information Systems*		
	14. Publication P6	Bräker, J., Hertel, J., & Semmann, M. (2022). Conceptualizing Interactions of Augmented Reality Solutions. *Proceedings of the Hawaii International Conference on System Sciences*, 712–721		
	15. Publication P7	Hertel, J., Karaosmanoglu, S., Schmidt, S., Bräker, J., Semmann, M., & Steinicke, F. (2021). A Taxonomy of Interaction Techniques for Immersive Augmented Reality based on an Iterative Literature Review. *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality*, 431–440. https://doi.org/10.1109/ISMAR52148.2021.00060		
	16. Publication P8	Bräker, J., Hertel, J., & Semmann, M. (2023b). Empowering Users to Create Augmented Reality-Based Solutions – Deriving Design Principles for No-Code AR Authoring Tools. *Proceedings of the International Conference on Information Systems*		
	17. Publication P9	Bräker, J., & Semmann, M. (2023a). Is There More Than Pokémon Go? – Exploring the State of Research on Causal Modeling in the Field of Augmented Reality. *Proceedings of the Hawaii International Conference on System Sciences*		

2 Theoretical Foundations

The theoretical foundations of this dissertation stem from several research areas. First, I draw on Human-Computer Interaction (HCI) research for the fundamentals of augmented reality (AR), which are essential to this dissertation. Second, I draw on service science research to examine AR technologies in the context of service systems. As the use of AR in service systems research typically focuses on tasks or processes, this chapter provides additional background on processes and on their augmentability.

This chapter begins with the theoretical foundations of AR to provide a comprehensive understanding of the technology, including hardware functionalities, visualization techniques, interactions, tracking, and AR application development. Next, the fundamentals of service systems as a theoretical lens and application areas of AR in service systems are laid out. The chapter concludes with foundations of the virtualizability and augmentability of processes. When considering the use of AR in an organizational context, it is crucial to understand business processes and the importance of aligning tasks and technology to support them, followed by two theoretical approaches for analyzing processes regarding virtualizability and augmentability.

2.1 Foundations of Augmented Reality

Research on virtual reality (VR) and augmented reality (AR) dates back decades to the 1960s. Ivan Sutherland imagined the vision of an "ultimate display" thus:

> The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and

> a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked. (Sutherland, 1965, p. 508)

Three years later, Sutherland presented a prototype of an AR head-mounted display (HMD) implementing 3D perspective image overlays (Sutherland, 1968). After multiple attempts, AR became more commercialized in the 1980s and 1990s, and sample applications were to be found in organizational settings. Over two decades later, the advanced maturity of AR hardware has enabled it to be increasingly used in a wide range of scenarios. One milestone was the release of the Microsoft HoloLens in 2015, which has made AR HMDs accessible to a broad range of users (Cipresso et al., 2018).

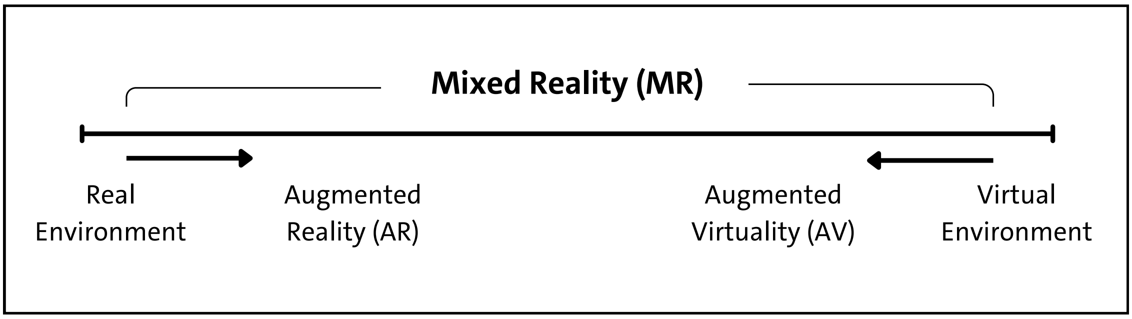

Figure 2. Reality-virtuality continuum (adapted from Milgram and Kishino, 1994)

Milgram and Kishino (1994) conceptualized a virtuality continuum (see Figure 2), which describes the blending of virtual and real environments. At one end of the spectrum is a completely virtual environment, known as VR. VR environments are fully immersive virtual worlds, in which the user cannot see the real-world environment at all and where the law of physics do not necessarily apply. If, however, aspects of reality are visible in a predominantly virtual environment, one speaks of augmented virtuality (AV). Where the real environment prevails, but is enriched with virtual computer-generated objects, one speaks of AR. Both AR and AV are implementations of mixed reality (MR). More recently, the term extended reality (XR) has been coined to encompass MR and VR technologies (Mann et al., 2018).

Augmented reality allows users to perceive the real world while blending virtual objects into reality, i.e., by enriching or extending reality, or by overlaying real-world objects with virtual content. Thus, AR aims to create the illusion that virtual objects exist in the real-world environment and behave like real-world objects. Three main characteristics define AR (Azuma, 1997; Azuma et al., 2001):

1. AR blends real and virtual objects in a real-world environment.
2. AR is interactive in real-time.
3. Virtual objects have a registered location in 3D space in the real-world environment.

AR can be implemented with a range of display technologies and hardware options. They can be head-attached, hand-held, or spatially aligned (Bimber & Raskar, 2006) (see Figure 3). A traditional technology mainly associated with AR is HMDs. These are known as smart glasses or AR glasses, and are worn like goggles. Unlike VR glasses, they do not fully isolate the user from the outside world but leave the user present in the real world. Video see-through (VST) HMDs capture a video stream of the real-world environment, blend in the virtual objects, and display an enriched video image to the user. Optical see-through (OST) HMDs use a transparent display through which the real world is directly perceivable. Virtual objects are then rendered and visualized on the display and, in this way, blend into reality. Microsoft's HoloLens is an example of an OST HMD. Hand-held AR devices include smartphones and tablets. They function in a video-see-through manner. Spatial displays are detached from the user's body and use projectors (also known as projection-based AR), for example, to directly overlay real-world objects. Another example of projection-based AR is the use of transparent projection screens.

These different display technologies are not without some challenges. For HMDs, these include limitations due to resolution, brightness, contrast, field of view, and refresh rates, leading to delays. Other challenges are limitations due to the safety, ergonomics or comfort of wearable devices. Perception and focusing issues include objects appearing unsharp or occlusion issues between real and virtual contents. Challenges for hand-held AR include a limited screen size, processor- and memory-intensive rendering, and limited freedom of movement if one hand is needed to hold the device. However, mobile AR is more accessible to users who are familiar with smartphones and tablets. Finally, HMDs are still quite expensive. Challenges in spatial AR occur regarding the fixed projection area, and applications are primarily single-user. However, they may have improved ergonomics or a larger field of view (Azuma, 1997; Bimber & Raskar, 2006). Feelings like nausea or anxiety—termed cybersickness—during AR use can result from sensory conflicts (McCauley & Sharkey, 1992). Although VR is more likely to cause cybersickness, AR is not free from it (Hughes et al., 2020).

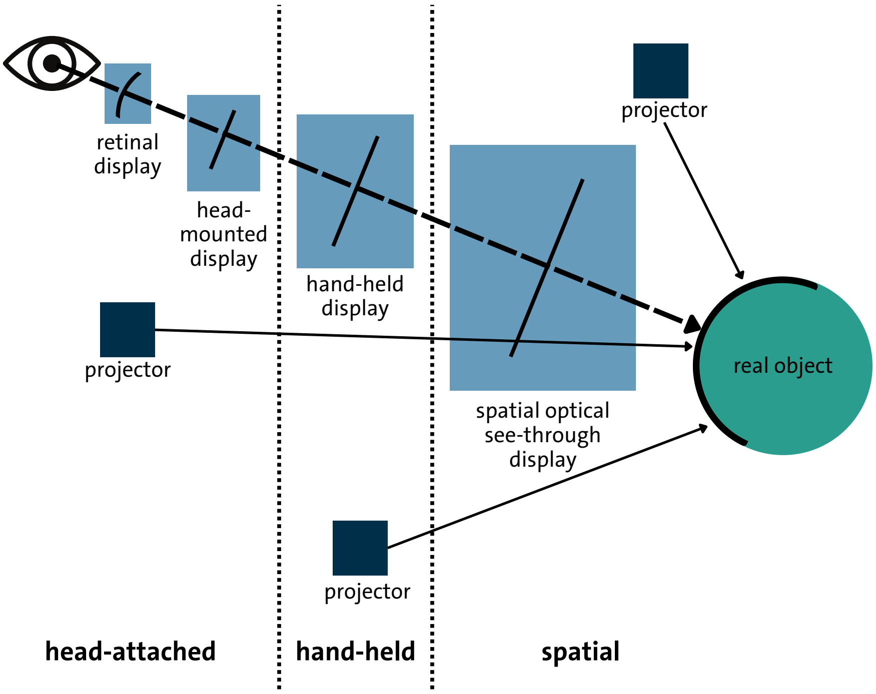

Figure 3. Image generation for AR displays (adapted from Bimber and Raskar, 2006)

Visualization in AR follows a pipeline of different steps (Kalkofen et al., 2009; Zollmann et al., 2021). For correct AR visualization, it is necessary to map spatial relationships. Mapping requires visual content to be carefully integrated into the real-world environment, to ensure realistic fit, alignment, and depth perception of virtual objects. Depth cues and perspective cues have to be created, e.g., through recording the size and details of real objects, and their shadows. Occlusion occurs when nearer objects cover objects that are far away or behind them. Nearer objects also appear larger and have more detail. Objects further away appear blurrier. Shadow casting and linear perspective also give distance estimation hints. When rendering AR objects to obtain realistic blending, it is essential to synchronize the camera parameters so that the depth information of the 3D objects matches that of the real environment. One of the main challenges for correct visualization is correct occlusion (occlusion handling), for which it is important that no essential real-world objects, or information, are accidentally occluded by virtual objects (Kalkofen et al., 2009). Components for AR visualization include the camera image (to capture the real-world environment), registration data (spatial relationships between real and virtual), geometric data (the virtual objects or overlays), and often additional masking data. Zollmann et al. (2021) describe different visualization pipelines. Correct visualization follows the first characteristic in the definition of AR by Azuma (1997), which refers to the blending of real and virtual elements to create a realistic experience: “AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world” (Azuma, 1997, p. 2).

The effectiveness and efficiency of interactions with AR interfaces has a direct bearing on the usefulness of AR applications (see the second characteristic in Azuma’s definition of AR, “interactive in real time”, Azuma, 1997, p. 2). AR interfaces offer more interaction techniques than classical WIMP desktop interfaces (windows, icons, menus, pointer) using a keyboard and a mouse. Tangible user interfaces enable the interaction with the AR application via the interaction with physical objects. Intangible user interfaces utilize, e.g., mid-air interaction, which means that hand gestures in the air are tracked and used as input (Jacob et al., 2008; Kim et al., 2018). Bowman and Hodges (1999), in their early attempts to classify interaction techniques in immersive virtual environments, identified three main interaction tasks. The first is traveling/motion control, describing how the user can navigate and move in a virtual environment. The second and third are, respectively, the selection and the manipulation of virtual objects. Several interaction techniques can fulfill each of the interaction tasks. Interaction techniques can also be multimodal, involving more than one input modality, e.g., gesture and speech (Muhammad Nizam et al., 2018).

Reliable tracking mechanisms are essential to achieve the spatially correct visualization and registration of virtual objects in AR. Tracking the position and orientation of the user in the environment is required to make virtual objects appear in the correct location, size, and orientation in real-time. The rotation around six axes can describe the orientation of an object, also called six degrees of freedom (DOF). According to the third part of the definition by Azuma (1997), virtual objects need to be registered in 3D space. Among the different mechanisms available for tracking are, for example, sensor-based tracking, which uses inertial, optical, and acoustic sensors, and vision-based tracking, which uses image processing methods to calculate camera position. Further options are model-based or feature-based tracking, including marker tracking or hybrid variations (F. Zhou et al., 2008). Tracking with low latency and high accuracy is still challenging to achieve, and research, especially in the field of HCI, continues to develop new tracking mechanisms (Kim et al., 2018).

Game engines like Unity (Unity Technologies, n.d.-a) or Unreal Engine (Epic Games, Inc., n.d.) have become standard for the development of AR applications. Game engines enable the creation of 3D scenes following the what-you-see-is-what-you-get (WYSIWYG) principle. However, functionalities and events in the scenes need to be programmed manually (e.g., in C# or C++). Game engines already come with the functionality to support AR and VR hardware, like HMDs. Further, several toolkits, libraries, and frameworks are available to support the AR development process. The most popular ones are Apple's ARKit (Apple Inc., n.d.), Google's ARCore (Google LLC, n.d.), and Microsoft's Mixed Reality Toolkit (MRTK) (Microsoft, 2023). With ARKit and ARCore, for example, already integrating tracking functionalities for mobile AR, developers no longer have to develop tracking from scratch. Skills in 3D modeling are often required to generate customized assets for 3D scenes. The complexity of the AR development process shows that an entire toolchain is needed to create AR applications. However, there currently is no out-of-the-box, single tool solution available to create AR applications. Besides, domain knowledge is often an important requirement. For example, to develop a medical surgery assistance application, sufficient knowledge about surgery is essential. Hence, to bring the diverse sets of skills required to develop an AR application normally involves more than one person (Broll et al., 2022).

One of the approaches to creating AR applications without advanced software development skills is offered by AR authoring tools. Their aim is to enable AR application development in a low-code or even a no-code way. This might be especially useful for designers, authors, and creators with limited programming experience. AR authoring tools enable a quick and easy way to create prototypes and proof of concepts, and aim to offer prefabs for 3D models, interactions, and animations to choose from (Krauß et al., 2022; Nebeling & Speicher, 2018). One of the first AR authoring tools is the Designer's Augmented Reality Toolkit (DART) (MacIntyre et al., 2004). However, an evaluation conducted ten years later found that the tool still did not meet the AR authors' actual needs (Gandy & MacIntyre, 2014).

Further, a 2018 study found that most AR authoring tools still need to be more accessible. Although there is a variety of AR authoring tools on the market, they usually require intense training and costly licenses, and many are either restricted in their functionality or represent barriers to non-technical designers. Workarounds to avoid using game engines are not necessarily less complex because different tools, not always aligned with each other, may be needed for the toolchain. AR authoring tools that do not require extensive programming knowledge lack the functionalities of 3D modeling and interaction (Nebeling & Speicher, 2018). A thorough analysis of 26 AR authoring tools has confirmed this issue (Dengel et al., 2022). As AR is increasingly found in a broad range of consumer environments, and AR-enabling hardware like smartphones and tablets have become more readily accessible, even end-users can become AR content creators (Ashtari et al., 2020). Ashtari et al. (2020) mention eight key barriers for users of AR authoring tools, including difficulties in understanding the tool landscape, deciding where to start, finding up-to-date training materials to self-study, and the need for design guidelines on how to create good user interfaces (UI) and user experiences (UX) with the tools. Further problems arise in the design and prototyping stage of AR, as well as with testing, debugging, and evaluation.

2.2 Augmented Reality in Service Systems

This dissertation researches the use of AR in service systems. The next sections provide a concise introduction to service science and service systems, with a focus on service system engineering. Then, the areas of application of AR in service systems are discussed, and essential preliminary work on using AR in service systems is presented.

2.2.1 Service Science and Service Systems

In order to understand the effective application of AR, a perspective is needed that helps to understand how actors and resources such as technologies, knowledge, and information interact to create value. This dissertation is thus informed by the service-dominant logic (SDL) perspective that shifts the focus from a traditional goods-centered view to a service-centered view and considers service provision as fundamental to economic exchange (Lusch & Vargo, 2006; Vargo & Lusch, 2004, 2008). While goods-oriented approaches focus on tangibles, SDL shifts this view to intangibles such as skills, information, and knowledge. However, tangible goods can also be resources (e.g., appliances in service provision). Here, the collaboration between, and the shift from the producer (of goods) to the consumer (of the service) are at the center of attention (Vargo & Lusch, 2004). Vargo and Lusch thereby define services [as] “the application of specialized competences (knowledge and skills) through deeds, processes, and performances for the benefit of another entity or the entity itself” (Vargo & Lusch, 2004, p. 2). According to this view, service is no longer seen as an output or exchange of goods but as a process of value co-creation that takes place through the collaboration of the actors. Value co-creation happens through the interaction of multiple actors who integrate resources. In a goods-dominant perspective, value is created by buying something (value-in-exchange). In a service perspective, the value is created by using the service (value-in-use) and applying it in a certain context (value-in-context) (Vargo & Lusch, 2004, 2008).

In the Information Systems (IS) literature, this has been summarized by characterizing service as contextual and collaborative (Böhmann et al., 2014). In the context of value propositions, a service system can thus be defined as a socio-technical system (Böhmann et al., 2014). How such service systems can be systematically designed, developed, and piloted is the objective of service systems engineering (SSE). SEE "emphasizes the importance of design knowledge on service systems" (Böhmann et al., 2014, p. 76). One purpose is to create (evidence-based) design knowledge for (real-world) service systems. The design knowledge can relate to the design, implementation, and evaluation stages.

According to Böhmann et al. (2014) new possibilities for contextualization and collaboration are enabled by new forms of service systems interactions. Understanding these interactions, generating design knowledge for them, and thoroughly evaluating interaction principles, ideally embedded in real-world contexts, is critical for SSE. The emergence of new technologies opens up tremendous opportunities for novel interactions in service systems. For engineering service systems interactions, technologies and methods from HCI research can be beneficial, so close exchange with HCI research is recommended (Böhmann et al., 2014).

According to Spohrer and Maglio (2008, p. 244), "[s]ervice innovations have the potential to impact service productivity, service quality, and rates of growth and return for service systems". Thus, continually emerging innovations do shape services and the way they are provided. In service innovation, IT plays a central role, and many of the current innovations are of a digital nature or are digitally enabled (Lusch & Nambisan, 2015). In other words, new or changed technologies (technological resources) are a driver for service innovation in service systems (Spohrer & Maglio, 2008).

The piloting of innovations in socio-technical systems—the implementation and successful use of the innovation in its natural environment to prove its value (Schwabe & Krcmar, 2000)—enables new forms of service innovation and, therefore, can support and accelerate their diffusion (Böhmann et al., 2014).

2.2.2 Application Areas of AR in Services Systems

Augmented reality is an innovative technology that can function as a driver for service innovation. Previous research shows that AR has been used and integrated into service and service systems for years, and been applied in various domains and contexts to support service provision.

Typical application areas, where AR has the potential to lead to performance and efficiency improvements, have so far included maintenance, repair, overhaul, and assembly service (Egger & Masood, 2020; Fernández del Amo et al., 2018; Gattullo et al., 2020; Kohn & Harborth, 2018; Masood & Egger, 2019; Zubizarreta et al., 2019). Following the first attempts of AR use in manufacturing in the early 1990s (Caudell & Mizell, 1992), the support of AR was evaluated, some years later, as applied to the handling of welding guns in vehicle construction (Sandor & Klinker, 2005). Aimed at facilitating the correct positioning of studs in automotive assembly, the AR welding gun helped workers to work faster by augmenting the exact position of studs using AR overlays. Platonov et al. (2006) developed a markerless AR tracking system for a lightweight mobile device to support maintenance and repair tasks in industrial automotive settings. The system was used with a monocular HMD and proved to be robust and stable. Another example of automotive maintenance and repair are AR-supported localization tasks. Virtual arrows, text instructions, labels, and animations assisted workers with their task. The AR prototype enabled quicker task execution and reduced head movements. The users perceived the AR solution to be more intuitive and satisfying to use (Henderson & Feiner, 2011). Maintenance training also holds support potential due to the complexity of maintenance tasks. With trained personnel being essential for performing maintenance tasks, AR training aims to improve the efficiency of such training. Unlike theoretical training, AR provides the opportunity to teach the underlying skills and the practical performance of maintenance tasks (i.e., procedural skills). For example, a prototype HMD-based AR application was used in the context of maintenance of a photocopier. The goal was to replace 2D instructions with 3D instructions and anchor them in the real world (Webel et al., 2011). Preliminary work has provided guidance on the selection of an AR system for maintenance tasks in terms of hardware selection, development software, and visualization method (Palmarini et al., 2017). In a study that used two prototypes designed to support assembly tasks, Kammler et al. (2019) investigated whether AR can support technical service tasks in mechanical engineering using HMDs. The results of the study have shown that AR is useful for supporting this task, but there are some limitations regarding hardware maturity. Illing et al. (2021)

conducted a study on multitasking assembly tasks under time pressure. When two or more tasks had to be completed in parallel, the authors observed an increase in mental stress and a decrease in attention. In this study, mobile AR (using a tablet with a mount) was able to support multitasking, resulting in lower error rates and reduced cognitive load while increasing the quality and motivation of participants. In addition, tasks were completed faster, notably because AR enabled hands-free working. Besides supporting the execution of services, AR can also support the runtime modeling of services, such as documenting processes on-site, e.g., by a technician during process execution (Metzger et al., 2018).

In the construction industry, AR can also be used for digital planning and designing activities, for example, through an AR-CAD (computer-aided design) prototype (Dunston & Wang, 2005). When investigating the support of service technicians using AR, one study found that user-centered system design is essential (Matijacic et al., 2013). Etzold et al. (2014) developed a prototype for communication support for using AR in CAD planning scenarios. The AR application helps support locally distributed workers in construction processes who need to collaborate with other experts and decision-makers. The AR application includes photo snapshots of the construction site and combines them with the traditional CAD data. The IKEA Place app is another example of planning and construction processes (Jessen et al., 2020). Applying more creative methods to the process, such as visualizations with AR, increases customer engagement.

AR has been applied to a wide range of services in the logistics industry. For example, HMDs were used in intralogistics services to support monitoring, information provision, process guidance, documentation, training, navigation, and the localization of objects (Berkemeier et al., 2019). Another example is the application of AR for manual order picking in a warehouse using an HMD. The AR application supported navigation in the warehouse and the identification of materials, which resulted in improved efficiency and a lower mental load (Fang & An, 2020).

Healthcare and medical services presents a vast application area for AR that has been studied for decades, becoming popular in the 1990s, which is reflected in an increasing number of publications about AR in healthcare (Eckert et al., 2019; Fuchs et al., 1998; Sielhorst et al., 2008). AR has been used to augment ultrasound images in medical education (visualizing anatomic details on body structures), surgery support, and clinical care. AR windows, augmented monitors, augmented microscopes, and augmented endoscopes have been piloted as hardware alternatives. HMDs in medical use cases are critical for hygienic reasons and, thus, alternatives were needed (Munzer et al., 2019; Sielhorst et al., 2008). Enabling hands-free working through AR was seen to have great potential for the healthcare sector (Prilla et al., 2019). For example, in previous work, an AR application was developed to support the documentation of wound treatment with an HMD (Klinker et al., 2020a). An important aspect to consider in healthcare settings is patient trust, which is also the subject of recent research (Klinker et al., 2020b).

Besides the training scenarios in the domain context described above, AR can also be used in education (Akçayır & Akçayır, 2017; Garzón et al., 2019; Mohammadhossein et al., 2022, 2024). One of the first examples of this is a geometric construction tool in the context of mathematics and geometry teaching. AR, in this context, was able to improve spatial skills and maximize learning transfer due to 3D visualization (Kaufmann & Schmalstieg, 2002). Previous research has shown that the use of AR in educational settings can enhance the learning experience, e.g., through positive effects on student motivation, interest, and engagement (Mohammadhossein et al., 2022, 2024).

For entertainment, AR has been used in the gaming industry for years to create immersive experiences (Das et al., 2017). One of the first AR games developed in 2000 was ARQuake, an outdoor game that used a portable device to locate the user's real-world position (Piekarski & Thomas, 2002). Other examples range from tabletop games, such as AR checkers, to HMD-based, more immersive AR games (Thomas, 2012). With the ubiquitous use of smartphones and the release of the mobile AR game Pokémon Go in 2016, AR has become accessible to almost everyone (Elo et al., 2021; Lintula et al., 2017).

In edutainment, museum tours, for example, have been enriched with audiovisual augmentations in several studies. AR museum guides function like traditional museum audio guides, and can be used asynchronously to convey contextual information in an (audio-)visual manner (Miyashita et al., 2008; Sparacino, 2002). Further examples are wearable AR guides in art galleries, to improve the users' learning experience by providing contextual information (tom Dieck, Jung, & tom Dieck, 2018), or an AR application in a theme park, which has been shown to increase user satisfaction (Jung et al., 2015). In cultural services and tourism, AR has been proven to be useful by serving as digital tourist guides. This can either focus on simply providing information, or engage users more actively by providing information in a more game-based way, with users solving mysteries and pursuing adventurous tasks to explore a city. Another possibility is the overlaying of historical data of a city, which enables travel into the past (Kounavis et al., 2012).

AR shopping services in retail enable new forms of interaction, new customer touchpoints, and improved customer experiences. AR can offer customers the opportunity to view products virtually and spatially before purchasing (Henningsson et al., 2020). This can lead to a higher purchase intention for the product. AR can be used both for online shopping and for the in-store shopping experience. In terms of hardware, AR is mainly used in a mobile format as it is easily accessible to customers (Riar et al., 2021). An example of AR shopping is the IKEA Place app, which visualizes products from the IKEA product range in the user's environment, e.g., in their home. It promotes creative thinking, customer engagement, and satisfaction (Jessen et al., 2020). In marketing, AR has been used to augment traditional print ads. The enhancement of AR ads was preferred over additional information on ads using QR codes. However, traditional ads were still preferred over digitally augmented ones (Yaoyuneyong et al., 2016).

In safety-critical service, AR is used in manifold ways. Safety-critical is defined as a situation where "failure might endanger human life, lead to substantial economic loss, or cause extensive environmental damage" (Knight, 2002, p. 547). In such a service, AR can act as a cognitive assistant that aims to support the service by enhancing human capabilities (Engelbart, 1962; C. Peters et al., 2016). By using AR training in safety-critical environments, such as an oil refinery, AR can replace expensive on-site training (Träskbäack & Haller, 2004). Further, AR can, for example, assist cyclists in their training by augmenting speed and route details into the field of view. In this way, AR applications are intended to promote greater road safety and reduce risks in road traffic (Berkemeier et al., 2018). Head-up displays (HUDs) in cars are expected to provide similar assistance and support driver safety training with simulations of dangerous situations in traffic (Regenbrecht et al., 2005). In a maritime context, AR can be used on sailboats to augment navigation information, reducing cognitive load and the risk of errors (Wisernig et al., 2015). Airport control tower personnel require situational awareness for their work. AR has been used to support traffic control operators with head-up information. The AR system successfully supported situational awareness and reduced cognitive load (Bagassi et al., 2020). The situational awareness of drone pilots can also be increased by AR, as the head-down time is shortened and overall cognitive load is reduced (Coleman & Thirtyacre, 2021). This also applies to security. Security personnel need to be highly aware of their surroundings. The use of AR for information exchange enables security teams to collaborate better (e.g., with the police) and react faster in critical situations (Lukosch, Lukosch, et al., 2015). AR can lead to improved safety in search tasks with rescue dogs in emergency service teams. An AR prototype was able to support the search task, which is characterized by time pressure and uncertain circumstances while requiring collaboration and situational awareness. HMDs were successfully used to support this task, with one of the main benefits being hands-free interaction (C. Reuter et al., 2019).

2.3 Process Virtualizability and Augmentability

In order to utilize augmented reality in service systems, it is essential to identify and analyze the processes that are intended to be augmented. Not all processes in an organization are suitable for the application of AR, however, as the suitability for augmentation depends on specific process characteristics. Understanding business processes (i.e., the tasks performed) and aligning them with technology is therefore crucial when considering AR. Based on this understanding, the theoretical approach of process virtualizability is introduced. Yeo's (2017) theory of process augmentability, which describes the suitability of processes for AR, serves as a significant foundation for this dissertation.

2.3.1 Business Processes

Hammer's principle, that „all work is process work" (Hammer, 2015, p. 11), underlines the relevance of considering business processes when applying AR in organizations. A traditional view sees processes as defining chains of activities (i.e., tasks performed by actors), events, and decisions taking place in an organization (Dumas et al., 2018). Dumas et al. (2018) provide a systematic approach to describing the steps an organization takes to deliver a service or product. However, the focus is usually on how the work is performed rather than on what is performed (Davenport, 1993). Processes lead to outcomes that ideally aim to create value for the customer. Actors, whether individuals or organizations, play a key role in executing processes, while objects, both physical and informational, provide the necessary resources (Dumas et al., 2018).

A more recent conceptualization by vom Brocke et al. (2021) defines processes as "a coherent series of changes that unfold over time and occur at multiple levels" (vom Brocke et al., 2021, p. 3). By extending the understanding of processes, this perspective allows the description of a wider range of phenomena. Thus, "processes become central to understanding the dynamics of socio-technical networks" (vom

Brocke et al., 2021, p. 3) by discovering, explaining, and intervening in the dynamics of change.

Processes are crucial to understanding and improving the efficiency and quality of service in organizations. Through business process management (BPM), organizations can identify opportunities for cost reduction, reduce execution times and error rates, increase productivity, and gain a competitive advantage through innovation (Dumas et al., 2018; van Der Aalst, 2012). Business process innovation (BPI) can pave the way for new ways of working and performing processes (Davenport, 1993). New information technologies can serve as both an enabler and a catalyst for BPI (Anand et al., 2013).

BPM involves the systematic identification, modeling, analysis, implementation, and continuous monitoring and improvement of processes. Dumas et al. (2018) describe a lifecycle for the management of business processes, beginning with the process identification phase as the first step. Process metrics such as cost, time, quality, error rates, and flexibility are needed to measure process performance. Next is the process discovery phase, in which the business processes should be understood in detail so that the documentation of an as-is process model is possible to create a shared understanding. The process analysis phase examines the process regarding issues and improvement opportunities, e.g., in terms of quality and efficiency. These improvement ideas are then incorporated into the process model and documented as a to-be process in the process redesign phase. The to-be process is then implemented and put into execution, which is called the process implementation phase. Any subsequent changes should be monitored in the process monitoring phase to determine if adjustments are necessary and the lifecycle begins again with the process discovery phase.

Business process modeling languages enable the visualization, description, standardization, and formalization of processes (Dumas et al., 2018). Modeling languages used in service research include flowcharts, the Unified Modeling Language (UML), Event-driven Process Chains (EPCs), Petri nets, or the Business Process Model and Notation (BPMN), and support organizations to represent their processes in a structured manner. Flowcharts offer a simple way to visualize process flows, while UML offers a more technical approach. EPCs are a form of flowchart with a control-flow structure, whereas Petri nets provide a mathematical representation of processes. BPMN is a common and widely used modeling language that enables detailed representations of processes (Dumas et al., 2018; van Der Aalst, 2012). Another approach is service blueprinting, which has a more customer-centric focus.

In addition to visualizing the process within the organization, service blueprinting takes into account the customer journey, customer interaction, and lines of visibility (Bitner et al., 2008).

2.3.2 Aligning Task and AR Technology Characteristics

When intending to use technological innovations such as AR in service systems it is important to look at the task, or in other words, the activities a user performs, to investigate whether AR as a technology could fit the task. If the task and the technology are well aligned, this will have a positive impact on performance, user acceptance, usage behavior, and adoption. In research, several models aim to determine the fit of a technology to a task. Previous work explored approaches to investigate the usefulness and acceptance of AR applications.

The task-technology fit (TTF) model, which attempts to predict performance (Goodhue & Thompson, 1995), has been applied in previous research to determine the feasibility of AR in use cases such as architecture, engineering, and construction (Shin & Dunston, 2008). Shin and Dunston (2008) identified different task and AR characteristics based on process steps and mapped them onto AR system functionality to evaluate the task-technology fit.

The technology acceptance model (TAM) is an extension of the TTF model (Davis, 1985; Davis et al., 1989) and aims to explain technology usage. Regarding AR applications, TAM has been used in previous research to evaluate, for example, the technology acceptance of an AR museum application. The results of the study indicate that the quality of AR impacts various dimensions of immersion, which, in turn, influences technology acceptance (Cheng et al., 2023).

A further extension and development of the TAM is the unified theory of acceptance and use of technology (UTAUT) (Venkatesh et al., 2003), which takes into account specific factors and moderators to explain technology use, especially in organizational contexts. As a further development, the UTAUT2, aims to measure acceptance in a consumer context (Venkatesh et al., 2012). Previous research on AR even combined the UTAUT2 and the TTF models. For example, in education, AR adoption behavior has been studied for home-based AR learning applications (Faqih & Jaradat, 2021), and in retail, the adoption of an AR smart shopping application has been evaluated (Khashan et al., 2023). Hence, it can be said that the rationale of aligning task and technology is supported by AR research. The usefulness of the technology in relation to the task is thereby the dominant explanatory model of AR use in previous studies.

2.3.3 Virtualizability of Processes

Not every manually executed (or physical) process can be virtualized, because as a consequence of virtualization, physical interaction is removed (Overby, 2008). Certain criteria determine the virtualizability of a process, i.e., how amenable it is to being executed virtually. Overby's (2008) process virtualization theory (PVT) aims to explain and predict the virtualizability of processes. Virtual processes include e-commerce, online distance learning, and online banking.

Figure 4 shows the theoretical model of the PVT. Process virtualizability is the dependent variable. As it is a continuous, rather than a binary variable, it indicates the degree to which a process is virtualizable, rather than answering it with a yes or no. Four key constructs have a negative impact on process virtualizability (Overby, 2008):

1. Sensory requirements: Virtualizing a process reduces human sensory experiences such as sight, smell, hearing, touch, and taste. If human sensory experiences are required, the process is less amenable to virtualization.
2. Relationship requirements: Virtualizing a process reduces face-to-face interactions between people. Personal interactions facilitate knowledge acquisition, trust, and personal connections. If personal and physical interaction between people is required, the process is less amenable to virtualization.
3. Synchronism requirements: Virtualizing a process reduces its synchronicity. If a process cannot handle delays and asynchronism, it is less amenable to virtualization.
4. Identification and control requirements: Virtualizing a process reduces the feasibility of secure user identification. If the process requires the unique identification of users and the ability to control their behavior, it is less amenable to virtualization.

Information technology functions as a moderator between process virtualizability and the four main constructs. Three IT characteristics positively moderate the relations between them, as follows (Overby, 2008):

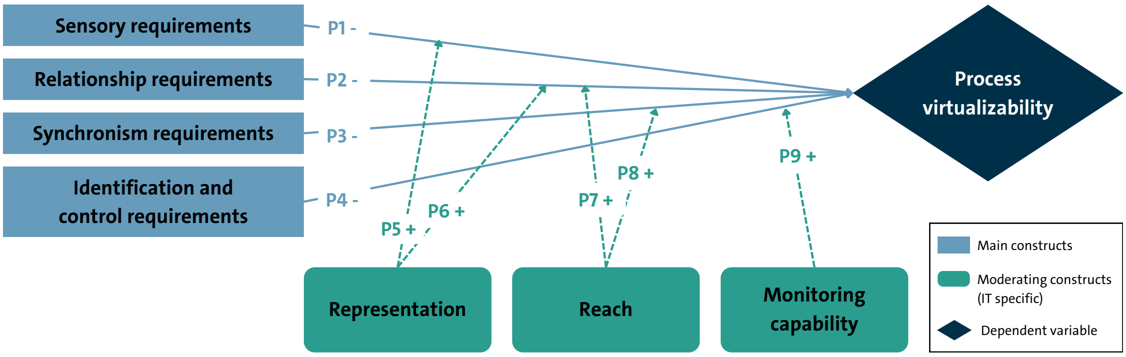

Figure 4. Theoretical model of the process virtualization theory (adapted from Overby, 2008)

- IT's representation capability simulates sensory elements of physical processes, such as visual, auditory, or haptic perceptions (i.e. through touch) of actors and objects and their interactions with them. The representation capability positively moderates the relation between sensory requirements and process virtualizability. Because of IT's potential to match and bring people together (e.g., through social networks), it also moderates the relation between relationship requirements and process virtualizability.

- Reach capability refers to the ability of IT to facilitate process participation across time and space. Therefore, it moderates the relationship between relationship requirements and process virtualizability by enabling long-distance collaboration and matching with people. In addition, reach moderates the relation between the synchronism requirement and process virtualizability by enabling synchronous work from multiple locations.

- The monitoring capability of IT allows the authentication and activity control of process participants. IT can provide login or authentication mechanisms and monitor activities automatically. The monitoring capability moderates the relation between identification and control requirements and process virtualizability.

The PVT has been applied in research in several contexts. Examples include the analysis of the virtualizability of an airport check-in process (Balci & Rosenkranz, 2014), the digitalization of retail banking (Graupner & Maedche, 2015), and the support of green IT initiatives (Bose & Luo, 2011).

2.3.4 Augmentability of Processes

Augmenting a process has different requirements than simply virtualizing it. The process augmentability theory by Yeo (2017) adapts the PVT and provides characteristics that allow to analyze a process in terms of its augmentability.

The virtualization of processes removes physical interaction. Augmentation, in this sense, enriches rather than replaces the physical interaction. Consequently, the requirements of the PVT cannot be applied to AR without further adjustments.

Figure 5 shows the theoretical model of process augmentability theory. The main construct, authenticity requirement, positively influences the dependent variable process augmentability, which refers to "how amenable a process is to being conducted in AR environments" (Yeo, 2017, p. 5). Process augmentability, like virtualizability in PVT, measures a degree of augmentability rather than a binary variable. Authenticity means that the process is experienced as expected. Sensory genuineness creates an authentic experience. Because AR can simulate sensory experiences in virtuality, it can enhance processes that require an authentic sensation.

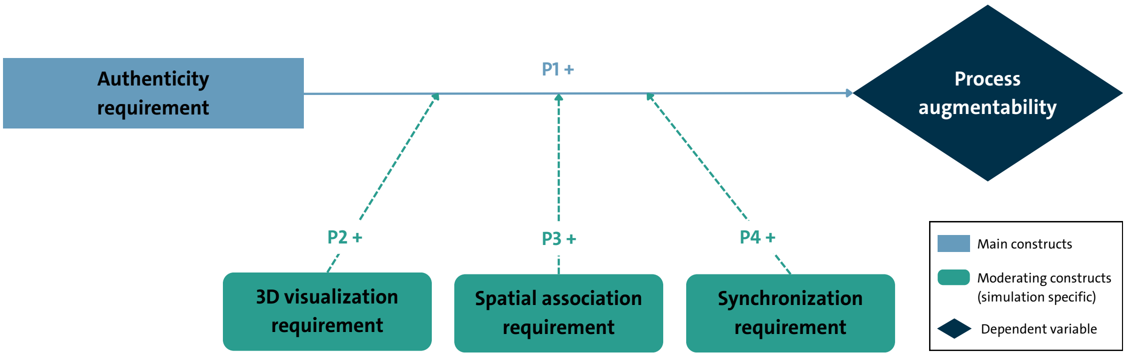

Figure 5. Theoretical model of the process augmentability theory (adapted from Yeo, 2017)

Building on Azuma's (1997) definition of AR, three moderators positively influence the relation between authenticity requirement and process augmentability (Yeo, 2017):

- The 3D visualization requirement indicates the extent to which the process requires 3D objects or overlays for a more authentic experience. Because AR can visualize 3D objects, it can provide an authentic experience. This requirement is informed by cognitive load theory (W. Huang et al., 2009). 3D visualizations can reduce the cognitive load of processes. If processes require visualizations of complex content to achieve an authentic experience, the process is more amenable to augmentation.

- The spatial association requirement is based on the concept that geospatial environments enrich process experiences (Henderson & Feiner, 2011; Sandor & Klinker, 2005; Sielhorst et al., 2008). For AR to provide an authentic experience, virtual objects must be geospatially registered in the real world, and geospatial interaction (between the user and their surroundings) is required.
- The synchronization requirement, according to PVT, assumes that physical processes are often synchronous. Because augmented processes may involve physical and virtual interactions, they must be synchronous to sustain a sense of immersion. AR can simulate synchronization, resulting in a more authentic experience.

Process augmentability theory has been applied to the mobile AR game Pokémon GO to demonstrate its applicability (Yeo, 2017). The theory aims to provide a conceptual foundation for the further investigation of processes in terms of their augmentability.

3 Research Design

This chapter describes the research strategy, context, and methods applied to answer the research questions in this dissertation.

The goal of this research is to generate design knowledge for the application of AR in service systems. Design science is a commonly used approach for service systems engineering (Böhmann et al., 2014). Hence, this dissertation follows a design science research strategy, employing a mixed-methods approach, utilizing both qualitative and quantitative methodologies. The design science research (DSR) approach fosters rigorous insights from real-world scenarios, providing solutions for real-world problems. Two case studies frame the research context.

In the following, the overall research strategy is described, including design science and mixed methods and how they are applied in this dissertation. This is followed by presenting the research context, including a description of both case studies. Finally, the various research methods used are described.

3.1 Research Strategy

Design science is a widely applied and accepted paradigm in Information Systems (IS) research, which seeks to answer questions about "what is effective" (Hevner et al., 2004, p. 98).

DSR advances research "through the building and evaluation of artifacts designed to meet the identified business need" (Hevner et al., 2004, pp. 79–80). The focus is on understanding a problem domain and then developing a solution to that problem through the iterative construction and evaluation of a socio-technical artifact. In other words, design science is a problem-solving approach that aims to create new artifacts (Gregor & Hevner, 2013; Hevner et al., 2004). Artifacts can be instantiations such as prototypes, constructs, models, and methods (March & Smith, 1995), as well as design theories (Gregor & Hevner, 2013; Gregor & Jones, 2007).

Hevner et al. (2004) propose seven guidelines for design science in IS research (see Table 2). The first emphasizes that design science research should aim to create an artifact that is both innovative and purposeful. The artifact should be developed for a clearly defined problem domain (guideline 2) and evaluated within its environment (guideline 3). Design science research should provide new and interesting contributions in the form of a design artifact, design foundations for the knowledge base, or design methods (guideline 4). This requires a rigorous methodology for the design and evaluation of the artifact (guideline 5). DSR is an iterative search process of finding a problem space and then finding a solution (guideline 6). Finally, it is essential to communicate the results to a technical and managerial audience (guideline 7).

Table 2. Design-science research guidelines (adapted from Hevner et al., 2004)

Guideline	**Description**
1. Design as an artifact	Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.
2. Problem relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
3. Design evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
4. Research contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.
5. Research rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
6. Design as a search process	The search for an effective artifact requires utilizing available Process means to reach desired ends while satisfying laws in the problem environment.
7. Communication of research	Design-science research must be presented effectively both Research to technology-oriented as well as management-oriented audiences.

According to Hevner (2007), DSR is composed of three interrelated cycles: the relevance cycle, the rigor cycle, and the design cycle (see Figure 6).

At the center is the design cycle, which entails two research activities: the development and the evaluation of design artifacts and processes. Typically, several iterations of creation and evaluation are needed before the contributions flow into the relevance and rigor cycle. For the relevance cycle, the environment provides the requirements for the research. The research artifacts developed in the design cycle are brought back into the environment for evaluation. The environment describes the area of application, which includes people, organizational systems, and technical systems. It also defines the problem space, i.e., the problem to be solved.

For the rigor cycle, the knowledge base, which consists of scientific foundations in the form of theories and methods, experience and expertise, and existing artifacts and processes, provides input for the design cycle. New knowledge is, in turn, generated from the design cycle and added to the knowledge base in the form of design artifacts, processes, and experience. The knowledge base contains the knowledge from (previous) research.

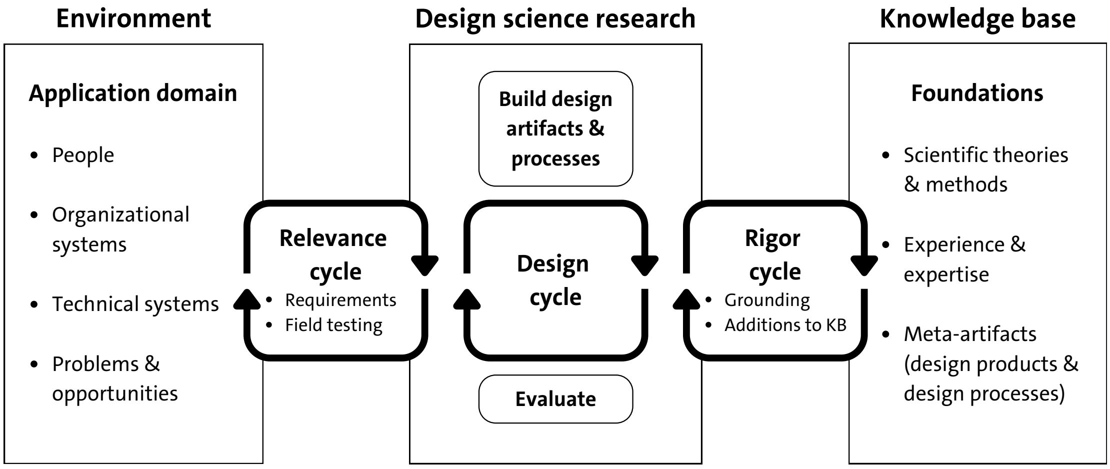

Figure 6. Design science research cycles (adapted from Hevner, 2007)

Design science research methods can be combined or complemented with qualitative methods, quantitative methods, or both, for data collection and analysis, and for evaluation. In qualitative research, the focus is on qualitative data, i.e., words instead of numbers. Therefore, qualitative methods aim to understand something in its context, and draws on, for example, case studies, observations, or interviews. Quantitative research focuses on quantitative data, which is measurable in numbers. This data can stem from experiments or surveys. Structural equation modeling

(SEM) also counts as a quantitative method that provides data for explaining causalities with calculations. Quantitative data is often analyzed with statistical methods (Recker, 2021).

Combining more than one qualitative and/or quantitative methods is called multimethod research, and combining qualitative and quantitative methods in one research study is called mixed-methods research. By combining qualitative and quantitative methods either concurrently or sequentially, allows to gain a more thorough understanding and integrative view of findings than can be obtained with only one approach. In this way, complementary strengths are used advantageously, while the weaknesses of single methods are minimized (Venkatesh et al., 2016; Venkatesh et al., 2013).

This dissertation aims primarily to generate novel design knowledge to answer the research questions. By taking a problem-centered DSR approach, design knowledge is generated to address real-world problems and find effective solutions (Hevner, 2007; Hevner et al., 2004; Peffers et al., 2007).

Figure 7 illustrates where each of the publications included in this dissertation is situated in the design science cycle. For the environment, two case studies have been conducted. The first is the case of water depth management in a harbor environment at a maritime logistics hub, which provides the environmental context for publication P1 (Osterbrink et al., 2021) and publication P2 (Bräker, Osterbrink, et al., 2023). The second case is a warehouse inventory, which serves as the environmental context in publication P3 (Bräker & Semmann, 2022) and publication P4 (Bräker & Semmann, 2023b). The cases are described in more detail in Chapter 3.2.

Publications P5 (Bräker & Semmann, 2021) develops a research agenda drawing from existing literature. Publications P6 (Bräker, Hertel, & Semmann, 2022) and P7 (Hertel et al., 2021) are building and evaluating taxonomies. In publication P8 (Bräker, Hertel, & Semmann, 2023b) an AR authoring prototype was evaluated in a laboratory user study, to derive design principles for such AR authoring tools. Publication P9 (Bräker & Semmann, 2023a) analyzes previous work on conceptual AR research.

This dissertation follows a mixed-methods research strategy, combining qualitative and quantitative methods. The mixed-methods approach is followed in several publications and across the entire dissertation research project. Figure 8 illustrates how the methods employed in each of the publications are distributed and combined.

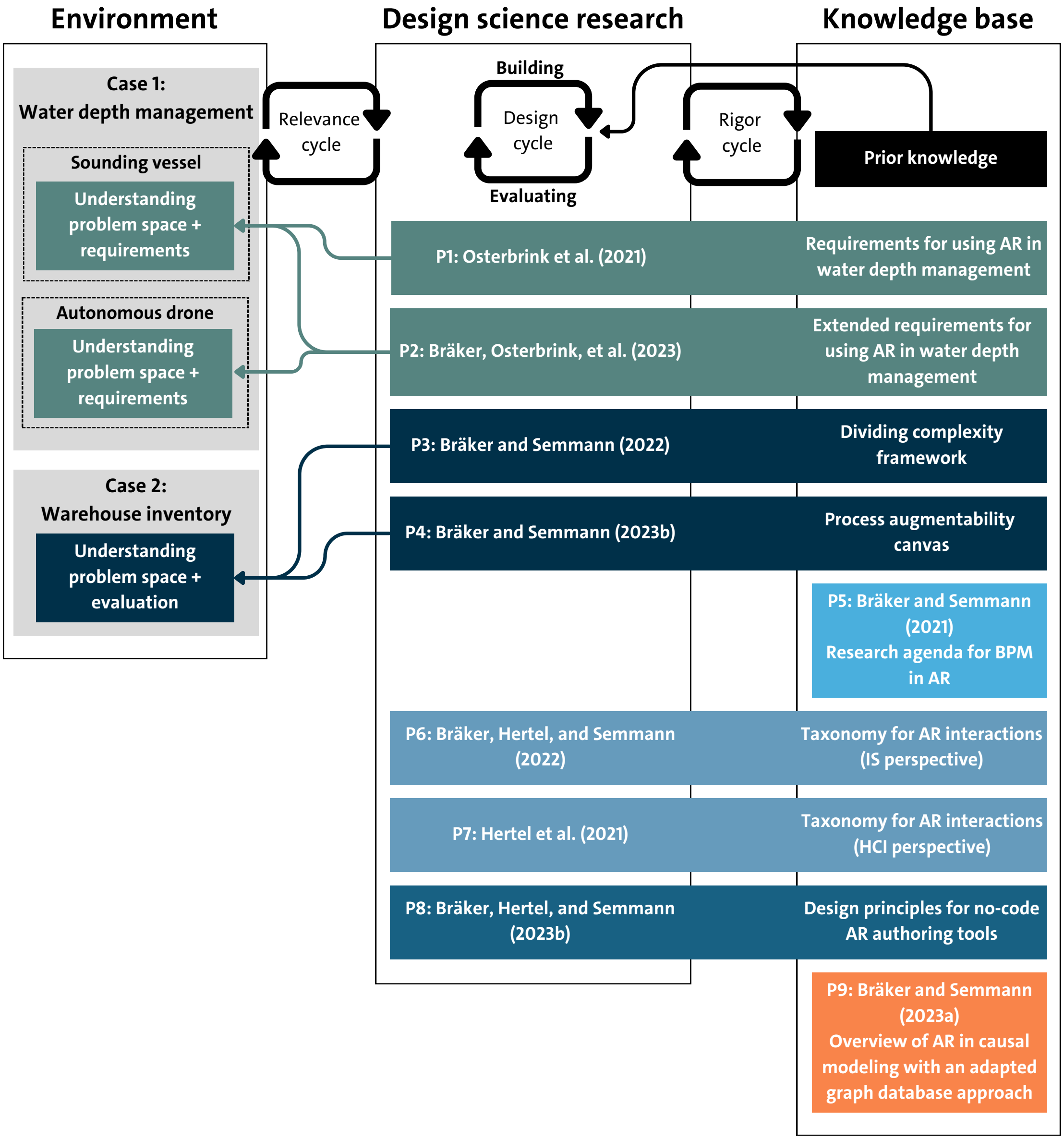

Figure 7. Classification of the publications included in this dissertation in the design science cycles according to Hevner (2007)

Qualitative methods are used for the exploration of a phenomenon or problem space. Following design science, an artifact is then built and evaluated. The evaluation involves both qualitative and quantitative methods, undertaken concurrently, drawing on two different perspectives with the aim of strengthening the validity of the results.

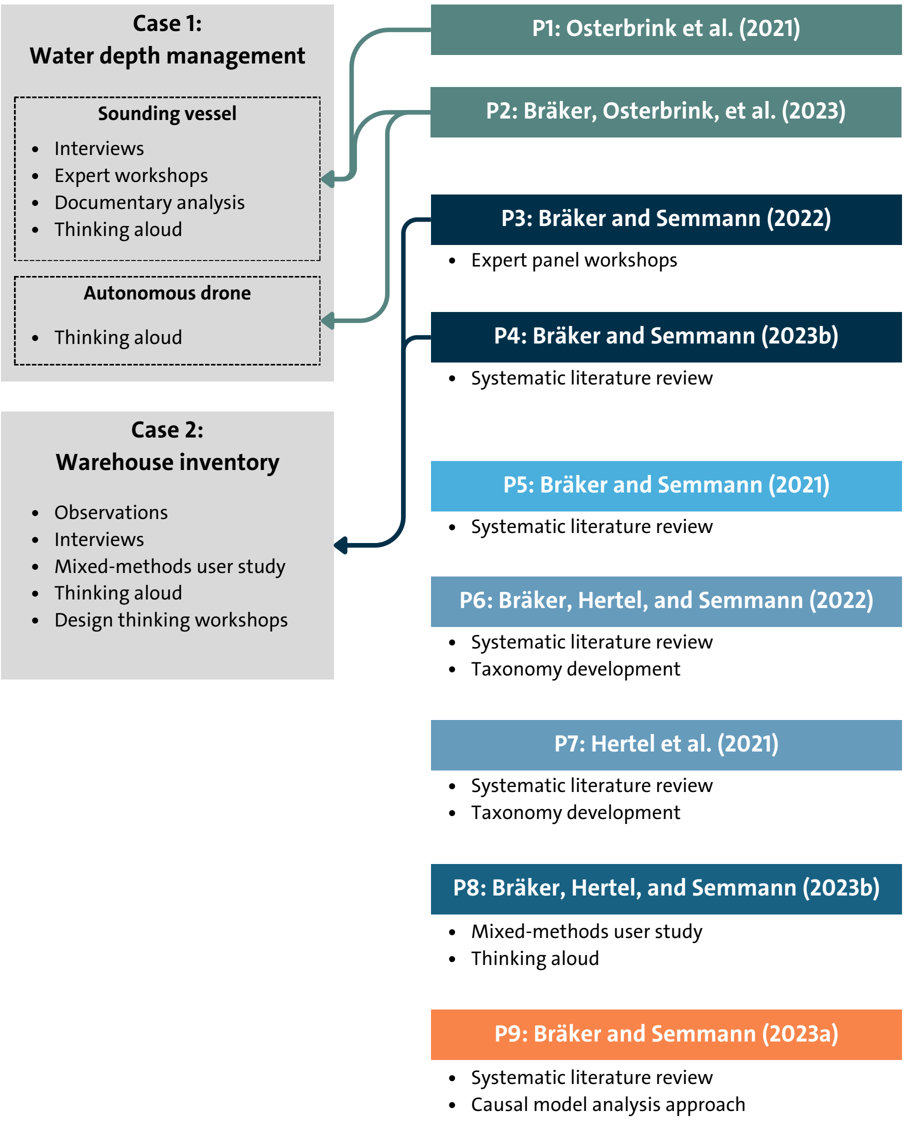

Figure 8. Methods used within each included publication

3.2 Research Context

The research context of this dissertation is given by two case studies, which are described in more detail in the following.

3.2.1 Case Studies

Case study research is a qualitative method that is widely used in many research fields, including the IS domain. It focuses on a phenomenon in its natural or real-life setting, typically an organization, to gain new insights on a topic by thoroughly understanding the context and actions. To do this, however, the researcher needs to have good access to the organization and its data (Recker, 2021).

Yin (2018) offers comprehensive methodological guidelines for conducting case studies. Yin defines case study research as “an empirical method that investigates a contemporary phenomenon (the ‘case’) in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident” (Yin, 2018, p. 45). Furthermore, case study research addresses situations with multiple variables and sources of evidence.

The process of conducting case studies is typically iterative. Case studies are used to research how and why questions are appropriate when an in-depth understanding of a phenomenon is needed. They are particularly useful when there is little or no control over behavioral events, and the focus of the study is a contemporary rather than a historical phenomenon. Case studies can also be part of a mixed-methods study that uses both quantitative and qualitative methods (Yin, 2018).

Yin (2018) outlines five structured phases. The first phase involves identifying and formulating research questions during the planning stage. The subsequent phase involves designing the case study, which includes defining the unit of analysis and the cases to be studied. The case study design can be either single-case or multiple-case. If only one unit is analyzed, the design is holistic; if multiple units of analysis exist, the design is embedded (see Figure 9). Once the design is decided, the case study can be prepared, and data can be collected and documented. This is followed by the data analysis and interpretation, and by the communication and dissemination of the research results.

This dissertation includes two case studies, with each study being reported in separate publications. The first case, researched in publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023), is a single-case study with an embedded design. The context is a maritime logistics hub, the case is water depth management, and the embedded units of analysis are the sounding vessel and the autonomous drone. The second case, considered in publication P3 (Bräker & Semmann, 2022) and P4 (Bräker & Semmann, 2023b), is a single-case holistic design. The context is a maintenance, repair, and overhaul service logistics provider in the aviation sector and the case is warehouse inventory.

According to Yin (2018), different rationales can underpin the choice of case selection. The first case deals with a critical activity and represents an unusual scenario with

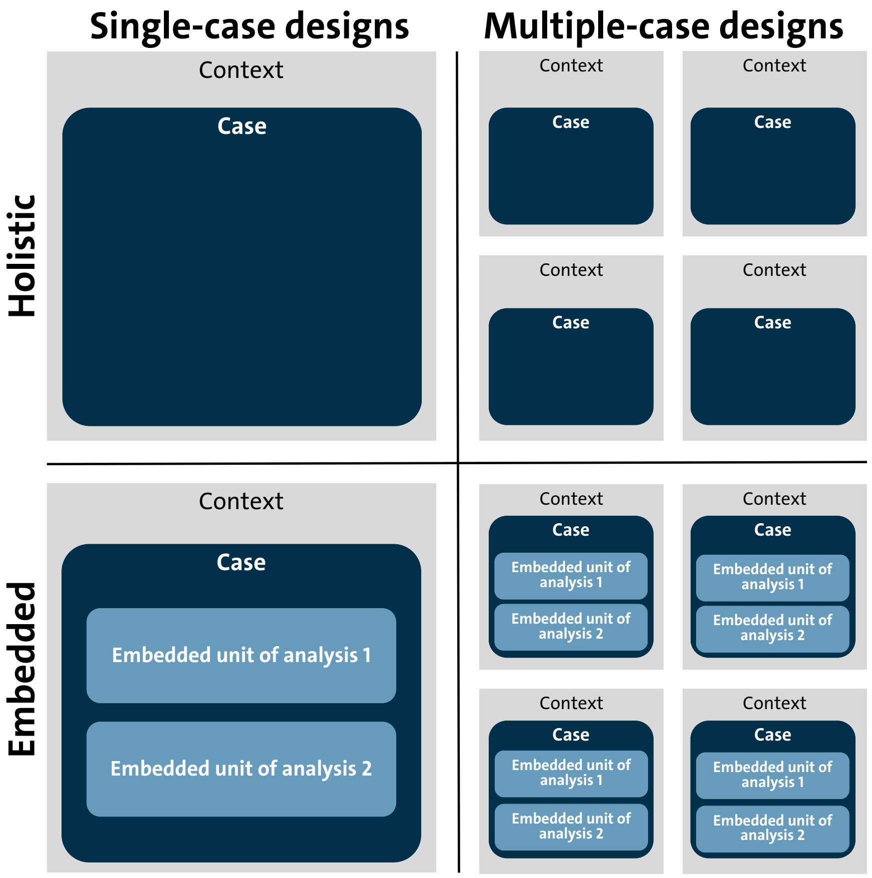

Figure 9. Case study designs (adapted from Yin, 2018)

extreme requirements. The second case is more common and, therefore, more representative for the application of AR. The following sections provide a detailed description of the two cases and their respective research context.

3.2.2 Case 1: Water Depth Management in a Harbor Environment at a Maritime Logistics Hub

The maintenance of the water infrastructure in harbor areas is critical to ensuring navigation safety for all water traffic participants. Water depths have to be continuously measured and controlled because they can change over time due to erosion and sedimentation. Besides, obstacles in the water can pose a risk to navigational safety. Continuous monitoring of water depths and identification of obstacles is necessary to prevent accidents and ensure a safe harbor infrastructure. Figure 10 describes the cyclic task of water depth management. The daily measurements create knowledge about current water depths in the harbor area. This knowledge can trigger action to be taken, for example, when a harbor area has to be deepened or obstacles in the water removed. To deepen an area involves dredging. When the action, for example, the dredging of an area, has been done, the changes have to be measured once again, resulting in new measurement data. A central hydrographic office coordinates water depth management and, for example, issues schedules for harbor areas that need to be measured.

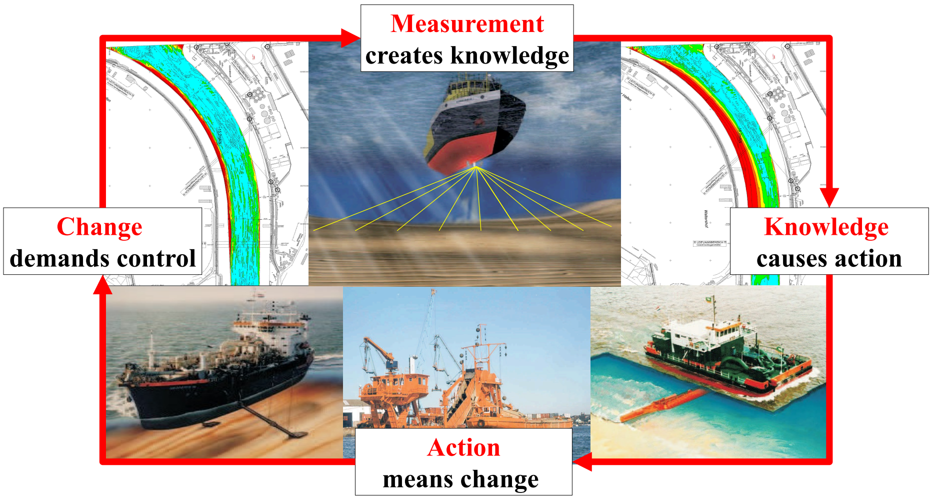

Figure 10. Water depth management cycle (Bräker, Osterbrink, et al., 2023; Osterbrink et al., 2021)

Water depth management can be seen as a service system that integrates different actors and resources. For this dissertation, the focus lies on the measurement part, also called hydrographic surveying or sounding process, of water depth management. Dedicated sounding vessels equipped with an onboard echo-sounder system measure water depth in real-time. Autonomous water drones can support the sounding vessels in shallow or difficult areas or act as escort vessels in large areas. The hydrographic-surveying service involves two actors on board the vessel: the skipper, who steers the vessel and is responsible for safe navigation, and a measurement engineer, who is responsible for the quality of the measured data.

The hydrographic-surveying service is characterized by its safety-criticality, multitasking, collaboration, and dynamic environment. The service is safety-critical from two perspectives. On the one hand, the maintenance of the infrastructure is safety-critical for all traffic participants in the harbor area. On the other hand, the service provision itself is safety-critical because the skipper has to pay attention to the traffic, the water depths (especially at the shore to avoid running aground), weather and tide conditions, the details of the measurement task, with real-time water depths being displayed on a screen. The skipper also has to collaborate with other actors, constantly monitor and adjust the vessel's position, steering the vessel to ensure the precise measurement of the areas. This requires constantly shifting the view between the monitoring screen and the windows to pay attention to the vessel's surroundings.

Multitasking is required because the skipper must (1) navigate the vessel safely, (2) navigate the vessel either by following a route on the monitor (given by the measurement engineer) or by determining the route themselves within a marked measurement area, (3) keep track of the measurement data and water depths, and (4) collaborate, not only with other harbor traffic vessels but especially with the measurement engineer to ensure that the entire area designated for the task is measured accurately, to a high standard.

The environment is dynamic because the service takes place on the water on a vessel that can move and rotate in six degrees of freedom. Inside the vessel, the actors can also move, adding to a rather dynamic and unstable environment.

Previous research addressed some aspects of these characteristics. For example, AR has been used in dynamic mobile environments while cycling or driving (Berkemeier et al., 2018; Heymann & Degani, 2016) or on sailboats (Wisernig et al., 2015). There are also examples of AR in safety-critical service, such as in an airport control tower (Bagassi et al., 2020), to support aerial drone pilots (Coleman & Thirtyacre, 2021) or security tasks (Lukosch, Lukosch, et al., 2015; C. Reuter et al., 2019). Other studies explore the use of AR to support multitasking (Illing et al., 2021) and collaboration (Johnson et al., 2015). However, none of these cases combine these characteristics in such a complex and demanding example (see Table 3). Thus, the hydrographic-surveying service is an example that differs from previous research in its complexity. It is a suitable and intriguing case to analyze user-centered requirements for the use of AR in such a context.

3.2.3 Case 2: Warehouse Inventory at a Maintenance, Repair, and Overhaul Service Provider in the Aviation Sector

The second case study is located in the context of a major European maintenance, repair, and overhaul (MRO) service provider in the aviation sector. The MRO service provider has an in-house logistics service provider responsible for conducting

Table 3. Characteristics of the water depth management case compared to previous research

Case	**Safety-criticality**	**Multitasking**	**Collaboration**	**Dynamic environment**
Airport control tower (Bagassi et al., 2020)	✓	✓	(✓)	-
Drone pilots (Coleman & Thirtyacre, 2021)	✓	-	-	-
Security (Lukosch, Lukosch, et al., 2015)	✓	-	✓	-
Rescue dog search (C. Reuter et al., 2019)	✓	-	✓	-
Cycling (Berkemeier et al., 2018)	✓	-	-	✓
Driving (Heymann & Degani, 2016)	✓	-	-	✓
Sail boats (Wisernig et al., 2015)	✓	-	-	✓
Multitasking assembly (Illing et al., 2021)	-	✓	-	-
Collaboration in construction industry (Etzold et al., 2014; Johnson et al., 2015)	-	-	✓	-
Water depth management	✓	✓	✓	✓

inventories in their warehouses, which follows a typical logistics process. In this case, a daily inventory is performed to continuously monitor current stock levels.

The material barcodes are scanned, and the available inventory stock recorded, by using either a paper-based inventory or mobile hand-held devices with scanning functions. The data is then transferred to the warehouse management system, where all materials and stock levels are listed. In the warehouse, workers have to cover long distances on foot to record larger materials on high racks. For smaller materials, they can order them automatically to their workstation. The inventory coordination office manages and coordinates the process and the inventory assignments.

This case provides an example of a typical process where AR can be applied. In previous research, AR has been used in various logistics processes, such as order picking (Berkemeier et al., 2019; Fang & An, 2020). This use case is sufficient as it represents a common example. Unlike the first case, which is more demanding and complex, the second case involves a more straightforward process. It is a typical example of how AR process support can be used and is transferable to other cases. It is also more accessible and relatable for organizations aiming to implement AR.

3.3 Research Methods

This dissertation employs several research methods for data collection and analysis, which are described as follows.

3.3.1 Literature Review

As part of this dissertation's publications, several literature reviews were conducted to serve as the foundation for the research. According to vom Brocke et al. (2015), researchers use literature reviews to gain an understanding of a domain, identify gaps in research, develop a research agenda, justify research problems, learn about the evolution of ideas, identify common research methods and strategies, recognize active authors in a field, synthesize existing research, and resolve conflicts in the literature. In design-oriented studies, literature reviews can be conducted to demonstrate the novelty of design ideas or to identify knowledge that informs the design process.

For this dissertation, literature reviews were conducted systematically and in a structured manner (vom Brocke et al., 2009; Webster & Watson, 2002). Vom Brocke et al. (2009) suggest a transparent and rigorous approach. Transparency is essential for replicating, extending, and updating reviews, as literature reviews only synthesize knowledge up to a certain point in time and quickly become outdated.

The following five-step framework for reviewing and documenting the relevant literature is proposed by vom Brocke et al. (2009):

1. Define the scope of the review.

2. Conceptualize the topic.
3. Conduct the literature search in carefully selected journals, conferences, and databases, using specific keywords and search parameters. Evaluate the articles found by scanning their titles, abstracts, or full texts. Perform additional forward and backward searches to identify further relevant articles.
4. Analyze and synthesize the literature using a concept-centric approach.
5. Utilize the synthesized knowledge to establish a research agenda and identify potential avenues for further research.

IS is an interdisciplinary field. Therefore, it is important to consider literature from other research fields (Webster & Watson, 2002). In the literature reviews of this dissertation's publications, a comprehensive selection of high-quality outlets from both IS and Human-Computer Interaction (HCI) was utilized. The reason for this is that AR is a topic that has been extensively researched within the HCI community, and therefore, relying solely on the IS literature is not sufficient for this interdisciplinary field. Each publication contains a description of the outlets and databases included in the literature search, and a thorough description of the literature review process.

3.3.2 Interviews

Interviews are a prominent and essential method for gathering qualitative data (Myers, 2013; Recker, 2021). Qualitative interviewing is a research method in which open-ended questions are asked of individuals selected on the basis of their knowledge or experience of a particular problem. To gain a comprehensive understanding of the topic it is recommended to interview a diverse group of people from different backgrounds. Through interviews, detailed information about the experiences, motivations, and opinions of others can be uncovered to gain a thorough understanding of a topic (Myers, 2013; Rubin & Rubin, 2011).

Semi-structured interviews are a type of interview that uses some pre-formulated questions while also allowing for flexibility in the order in which they are put to the interviewee. This format is particularly suitable to gain additional insights by allowing the research to ask additional questions that may arise naturally during the conversation. By contrast, unstructured interviews involve preparing only a few pre-formulated questions and improvising the rest depending on the interviewee's talkativeness (Myers, 2013; Myers & Newman, 2007; Recker, 2021). In IS research, semi-structured and unstructured interviews are the most commonly used types for gaining in-depth qualitative insights (Myers & Newman, 2007; Rubin & Rubin, 2011).

Several interviews were conducted to acquire data for this dissertation. The purpose was to gain contextual knowledge about the case study settings. For the first case study (see Chapter 3.2.2), semi-structured interviews were conducted and documented via video recordings and hand-written notes (Bräker, Osterbrink, et al., 2023; Osterbrink et al., 2021). In the second case study (see Chapter 3.2.3), qualitative, unstructured interviews based on a few guiding questions were conducted to gain additional insight into service provision, identify challenges in service delivery, and gather requirements and criteria for the use of AR. The interviewees' responses were documented with handwritten notes during the interview and included in the analysis (Bräker & Semmann, 2022, 2023b). The interviewees were stakeholders from various areas, with either domain expertise or technical expertise.

3.3.3 Observations

Observing people in their natural environment is another form of qualitative data collection that provides in-depth understanding and an additional dimension of insight into people's actions.

The objective of publications P3 (Bräker & Semmann, 2022) and P4 (Bräker & Semmann, 2023b) was to understand the inventory process in a warehouse and to document how the actual process was carried out. To this end, a qualitative approach using direct observations to gather insights was employed. Observations offer a method that is less formal than interviews and where the researcher strives to be a passive and neutral spectator, watching from the outside with little or no interaction with the research subjects. This allowed to identify challenges in process delivery and potential areas for process improvement. Ethnographic field notes were used for documentation (Emerson et al., 2001, 2011).

3.3.4 Documentary Analysis

Documentary analysis is a valuable source of information that can provide a more complete understanding of the past. Documents can take many forms, including text, image, video, or audio, such as meeting transcripts or letters. They should be analyzed similarly to interview transcripts and are most valuable when combined with other data, such as interviews (Myers, 2013; Recker, 2021; Rubin & Rubin, 2011).

For publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023), various documents were analyzed to get a thorough understanding of the context. This included a video of the harbor operator, documentation of the depth measurement management cycle, and information and pictures of the sounding vessel.

3.3.5 Design Thinking and Expert Panel Workshops

In order to collect additional data for this dissertation, several workshops were conducted. The design thinking approach (Brown, 2008) was adapted for workshops in publications P3 (Bräker & Semmann, 2022) and P4 (Bräker & Semmann, 2023b). The participants were domain experts and IT experts. The goal was to assess the suitability of different services for the application of AR and to derive practical criteria. The workshop was structured around two main guiding questions. The principle of diverging and converging phases of design thinking was adapted from Brown (2008). The workshop started with a diverging brainstorming phase to collect relevant processes, with the following converging phase aimed at clustering the ideas. In a further diverging phase, criteria for these core ideas were derived. In the final convergence phase, the results were systematically documented and refined in the form of a process profile.

For publication P3 (Bräker & Semmann, 2022), expert panel workshops were conducted with participants from academia and practice. The goal of the first workshop was to understand the general AR development process independent of a specific use case. The result is a user journey for the service design of AR applications. The expert panel evaluated the results of the first workshop in a second round.

For publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023), workshops were conducted to understand the use case and the process steps and to generate and evaluate first ideas for the requirements of an AR solution in the use case of water depth management.

3.3.6 Thinking Aloud

Thinking aloud is a verbal protocol analysis method used to trace decision-making processes in human cognition and behavior. Its purpose is to understand thought processes and to provide design knowledge for the development of design guidelines (Todd & Benbasat, 1987). Ericsson and Simon (1980) provide the theoretical basis for thinking aloud in cognitive psychology. Verbalizations can be done concurrently with a task, or retrospectively after the task. For this dissertation, concurrent verbalization is employed.

Thinking-aloud protocols (Boren & Ramey, 2000) are used in usability testing, where they contribute to identifying usability problems and designing a usable knowledge-based system. Participants are asked to verbalize their thoughts and decisions while interacting with the system. The researcher provides instructions on how the methodology works and frequently reminds the participants to keep talking. While researcher interactions with participants did not feature in Ericsson and Simons' (1980) approach, in practice, the researcher is often not entirely invisible and could be viewed more as an interested learner and listener who provides reassurance to and acknowledges the participant. Thinking-aloud sessions are recorded on audio or video tape for later transcription and analysis (Boren & Ramey, 2000; van Someren et al., 1994). Verbal protocols can be analyzed using the scanning method, a straightforward protocol analysis technique, or with more detailed coding (Bouwman, 1983, 1985; Todd & Benbasat, 1987).

The thinking-aloud method was used in several publications of this dissertation. In the water depth management case study, the skippers performed think-aloud during hydrographic surveying, reported in publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023). This allowed a more detailed insight into the process, on the basis of which user-centered requirements were derived. The think-aloud sessions were recorded using two cameras, one from a first-person perspective and the other from a third-person perspective. This allowed for additional analysis of the user's behavior. A protocol analysis was conducted using the scanning method.

The thinking-aloud method was also employed in user studies to evaluate the interaction with a prototype in publications P3 (Bräker & Semmann, 2022), P4 (Bräker & Semmann, 2023b), and P8 (Bräker, Hertel, & Semmann, 2023b). This enabled an understanding of usage behavior and revealed the occurrence of problems. For publications P3 (Bräker & Semmann, 2022) and P4 (Bräker & Semmann, 2023b), the participants' thoughts were paraphrased using handwritten notes. For publication P8 (Bräker, Hertel, & Semmann, 2023b), the thinking-aloud sessions were documented with screen capturing. The interactions with the prototype were documented and aligned with the verbalized thoughts. The resulting transcripts were analyzed using the open coding method (Strauss & Corbin, 1994).

3.3.7 User Studies

The evaluation of the prototypes in this dissertation has been the subject of several user studies. The mixed-method studies were designed with both qualitative and quantitative measures.

Experimental research, both laboratory and non-laboratory, is commonly used in HCI research to evaluate prototypes. Usability studies are one of the most frequently used methods in this field. The objective of usability testing is to assess user interfaces and identify areas for improvement.

User studies were conducted to evaluate the AR prototype for Microsoft Hololens in publications P3 (Bräker & Semmann, 2022) and P4 (Bräker & Semmann, 2023b) and the AR authoring prototype for a tablet computer in publication P8 (Bräker, Hertel, & Semmann, 2023b). The objective was to gain insight into usability, user experience, usefulness, intuitiveness, and expectations. Improvement potentials were identified, from which requirements and design principles were derived as a form of design knowledge. The studies gathered demographic data and utilized established questionnaires to collect quantitative data, along with open-ended questions. The questionnaires had a predetermined set of questions and instructions for analyzing and interpreting the results.

The dissertation publications utilized the NASA task load index (NASA-TLX) questionnaire to evaluate subjective workload and stress levels when using AR applications (Hart, 1986; Hart & Staveland, 1988). Additionally, the system usability scale (SUS) was used to measure the usability of AR applications on a 10-item scale. The identified usability score has a range from 0 to 100 and indicates the usability level (Brooke, 1996; Lewis, 2018). The user experience questionnaire (UEQ), in its short version, measures user experience on an 8-item scale. The user experience is divided into pragmatic and hedonic qualities. Pragmatic quality describes how well users can achieve their goals with the prototype. Hedonic quality focuses on the novelty and enjoyment of using an application. The resulting overall quality is a combination of both (Schrepp, 2015; Schrepp et al., 2017). Besides, technology acceptance with questions based on the technology acceptance model (TAM) (Davis, 1989; Davis et al., 1989) and unified theory of acceptance and use of technology (UTAUT) (Venkatesh et al., 2003) was evaluated using questionnaires.

All user studies included additional questions to gather feedback, user preferences, and estimations. These questions were either designed to be answered on Likert scales, or were open-ended questions that allowed comments in text form. In publication P8 (Bräker, Hertel, & Semmann, 2023b), task completion time was additionally measured as a quantitative measure to draw conclusions about learning effects and task complexity.

During the user studies, the thinking-aloud methodology (see Chapter 3.3.6) was applied to collect additional qualitative data. The study design, procedure, and participants for each study are described in the respective publications.

3.3.8 Design Principles

Design principles (DPs) are guidelines that aim to specify design knowledge in a structured and standardized manner. They address specific design challenges and are a common approach to documenting knowledge in design science research. The principles should support the creation of other artifacts and be abstract and transferable (Gregor & Hevner, 2013; Gregor et al., 2020; Purao et al., 2020). Gregor et al. (2020) provide guidance on how to formulate design principles and define them as “prescriptive statements that indicate how to do something to achieve a goal” (Gregor et al., 2020, p. 1622). Design principles can describe user activity, features of the artifact, or both. The principles regarding user activity describe what the user can do with an artifact to achieve a certain goal. The principles regarding features describe what the system should be able to do. The third category encompasses both and specifies the features that an artifact should have to enable the user to achieve a goal.

Design principles can follow a particular structure or syntax. Gregor et al. (2020, p. 1633) provide a standardized syntax for formulating design principles:

> DP Name: For Implementer I to achieve or allow for Aim A for User U in Context C, employ Mechanisms M1, M2, ... Mn involving Enactors E1, E2, ... En because of Rationale R.

Actors can take on the roles of implementers, users, enactors, and theorizers, which can be either human or nonhuman. Mechanisms facilitate the achievement of goals, and the rationale provides the reasoning behind why the mechanism will be effective.

Design principles can be generated in various ways. One approach is through the creation of new artifacts. By evaluating these artifacts, it is possible to determine what works and what does not work as expected with the artifact (Purao et al., 2020). Möller et al. (2020) propose a methodology for developing design principles. First, design requirements are derived, which are then mapped to design principles.

Publication P8 (Bräker, Hertel, & Semmann, 2023b) presents and evaluates a newly designed artifact and derives design principles from insights gained through a user study. Think-aloud protocols and questionnaire results inform the design principles. The data was coded using the grounded theory open coding method (Strauss & Corbin, 1994). The atomic codes were then clustered and merged into concepts from which design requirements were derived. The design requirements were mapped to design principles, resulting in the final formulation of design principles, following Möller et al.'s (2020) approach.

3.3.9 Taxonomy Development

Nickerson et al. (2013) propose a systematic approach to developing taxonomies, which is widely applied and adopted in IS research (Kundisch et al., 2022). A taxonomy aims to conceptualize objects in a domain of interest to achieve a better understanding, which is especially useful for conceptualizing knowledge in design science research (Iivari, 2007).

Taxonomies are defined as "systems of groupings that are derived conceptually or empirically" (Nickerson et al., 2013, p. 338). Taxonomies consist of a set of dimensions, each of which consists of multiple characteristics that are mutually exclusive (meaning that no object can have more than one characteristic in a dimension) and collectively exhaustive (meaning each object must have one characteristic in each dimension).

Nickerson et al.'s (2013) method for developing a taxonomy involves identifying a meta-characteristic as the central question and the basis of the taxonomy. The meta-characteristic is chosen based on the purpose of the taxonomy.

The next step is to define subjective and objective ending conditions that determine when to terminate. The subjective ending conditions for the taxonomy include conciseness (a reasonable range of dimensions), robustness (sufficient differentiation of dimensions and characteristics), comprehensiveness (all objects are classifiable with the taxonomy), extensibility (new dimensions and characteristics can easily be added), and explainability. Objective ending conditions include ensuring that a representative sample of literature is included, nothing new is added, merged, or split in the last iteration, and at least one object is classified for each characteristic, and that dimensions, characteristics, and cells are all unique.

Taxonomy development can begin with either an empirical-to-conceptual or conceptual-to-empirical approach. The empirical-to-conceptual approach involves identifying, including, and grouping characteristics of a subset of objects, such as those resulting from a literature review, into dimensions. This approach is recommended when the researcher has a limited understanding of the domain but sufficient data is available. The conceptual-to-empirical approach involves conceptualizing characteristics and dimensions based on existing work and prior knowledge of the researchers and then examining objects for these dimensions and characteristics. This approach is recommended when there is insufficient data available, but the researcher has some understanding of the domain.

The taxonomy is developed iteratively by adding new dimensions and characteristics. The choice of approach may differ from one iteration to another. Taxonomy development terminates when the ending conditions are met, after which the taxonomy can be evaluated.

The taxonomies in publications P6 (Bräker, Hertel, & Semmann, 2022) and P7 (Hertel et al., 2021) used results from a literature review as input. The process of developing the taxonomies is described in detail in the respective publications.

3.3.10 Causal Model Analysis with a Graph Database Approach

Song, Watson, and Zhao (2021) and Song, Watson, Zhao, and Kelley (2021) propose a causal model analysis approach to improve the literature review process. This approach aims for a more efficient way of synthesizing literature, which is often fragmented and difficult to analyze and synthesize manually. The core knowledge of publications is encoded as a directed graph and imported into a graph database, which can then be queried for analysis in terms of knowledge extraction and synthesis. This approach builds on Watson and Webster's (2020) work, in which the contributions of publications are stored in a graph database.

A graph is composed of nodes (circles) and edges (arrows) that indicate relationships between the nodes. Song, Watson, and Zhao (2021) and Song, Watson, Zhao, and Kelley (2021) focus on publications with structural equation models (SEMs) and causal models, as they are easily representable as graphs. The elements and relationships in an SEM are depicted as nodes and connections between them. Thus, an SEM can be translated into a graph. Adding the publication's metadata to the graph allows for the storage of additional information. For each publication, Cypher code can be generated to describe the graph's nodes and relations.

Song, Watson, Zhao, and Kelley (2021) define six different node types to represent different kinds of information: author, publication, element, definition, model, and theory. Labels and properties can be used in the Cypher language to store additional specifications. To simplify the Cypher coding process, the authors developed a tool called Codasaurus ("T-Rex – Theory Research Exchange," n.d.). This application runs on R and has a graphical user interface. It automatically generates Cypher files from publication information, which can then be imported into a graph database tool like Neo4j.

An overarching graph stored in a graph database can be created by adding several publications, such as those from a literature review. In this graph database, each node is created only once. Therefore, if one person authors multiple publications, the graph database displays the connections between them. This applies not only to authors but also to other metadata or SEM elements. For instance, if an element called "behavioral intention" is used in different publications, the database can show the coherences. The graph database can be queried to extract information about graph nodes and relations. Knowledge extraction, for example, involves finding specific nodes or relations and analyzing their frequencies or similarities. Knowledge synthesis involves connecting findings from different publications, performing calculations, and understanding the relationships between publications.

The comprehensive visualization of connections between different publications enables the exploration of new research fields and the identification of connections, blind spots, research gaps, and focal research areas.

4 Publications

The following section gives an overview of the publications included in this dissertation, and related publications that have indirectly influenced the research.

4.1 Overview

As part of this cumulative dissertation, twelve publications were developed and published in journals and conference proceedings, of which nine contribute directly to the dissertation's topic and, hence, are included here.

A further three publications contribute indirectly to the topic and are intended specifically to disseminate the results to practitioners and other stakeholder communities. Of these, Bräker, Osterbrink, et al. (2022) sharpen the requirements for augmenting hydrographic surveying from publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023) (see Chapters 9 and 10), intended for practitioners and published in the journal "HMD—Praxis der Wirtschaftsinformatik" to make them accessible for the German-speaking community of Information Systems professionals and managers. For dissemination to a wider audience of relevant professionals and researchers in the field, these requirements are also published with a practical focus in the journal "The International Hydrographic Review" (Bräker, Hertel, Briede, et al., 2022). For dissemination to practitioners and other communities outside of Information Systems (IS) and hydrography, a technical analysis of hardware alternatives meeting the requirements for augmented reality (AR) in hydrographic surveying is published as part of the "World Congress on Intelligent Transport Systems (ITS)" (Bräker et al., 2021). This systematic analysis provides valuable insights into different hardware options for the implementation of AR in hydrographic surveying.

All directly and indirectly related publications are listed in Table 4 and Table 5 in reverse chronological order of publication date, divided into journal and conference publications.

Table 4. Overview of journal publications

Included	**Journal publications**
yes	Bräker, J., Osterbrink, A., Semmann, M., & Wiesche, M. (2023). User-Centered Requirements for Augmented Reality as a Cognitive Assistant for Safety-Critical Services. *Business & Information Systems Engineering*, *65*, 161–178. https://doi.org/10.1007/s12599-022-00779-3
no	Bräker, J., Hertel, J., Briede, M., Thies, T., & Semmann, M. (2022). Augmented Reality for Crewed Hydrographic Surveys – How Augmented Reality Can Leverage Water Depth Management in the Port of Hamburg. *International Hydrographic Review*, *28*, 205–211. https://doi.org/10.58440/ihr-28-n10
no	Bräker, J., Osterbrink, A., Wiesche, M., & Semmann, M. (2022). Anforderungen sicherheitskritischer Dienste an Augmented Reality-Lösungen – Wassertiefenmessung in einem Seehafen. *HMD Praxis der Wirtschaftsinformatik*, *59*, 411–423. https://doi.org/10.1365/s40702-021-00829-6

Table 5. Overview of conference publications

Included	**Conference publications**
yes	Bräker, J., Hertel, J., & Semmann, M. (2023b). Empowering Users to Create Augmented Reality-Based Solutions – Deriving Design Principles for No-Code AR Authoring Tools. *Proceedings of the International Conference on Information Systems*
yes	Bräker, J., & Semmann, M. (2023b). The Process Augmentability Canvas – How to Find the Sweet Spot for Augmented Reality. *Proceedings of the European Conference on Information Systems*
yes	Bräker, J., & Semmann, M. (2023a). Is There More Than Pokémon Go? – Exploring the State of Research on Causal Modeling in the Field of Augmented Reality. *Proceedings of the Hawaii International Conference on System Sciences*
yes	Bräker, J., & Semmann, M. (2022). Dividing Complexity to Conquer New Dimensions – Towards a Framework for Designing Augmented Reality Solutions. *Proceedings of the Americas Conference on Information Systems*
yes	Bräker, J., Hertel, J., & Semmann, M. (2022). Conceptualizing Interactions of Augmented Reality Solutions. *Proceedings of the Hawaii International Conference on System Sciences*, 712–721
no	Bräker, J., Hertel, J., Osterbrink, A., Briede, M., Baldauf, U., Wiesche, M., Steinicke, F., & Semmann, M. (2021). Augmenting Safety-Critical Processes – Requirements and Technologies for Soil Sounding in the Port of Hamburg. *Proceedings of the ITS World Congress*
yes	Hertel, J., Karaosmanoglu, S., Schmidt, S., Bräker, J., Semmann, M., & Steinicke, F. (2021). A Taxonomy of Interaction Techniques for Immersive Augmented Reality based on an Iterative Literature Review. *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality*, 431–440. https://doi.org/10.1109/ISMAR52148.2021.00060

yes	Bräker, J., & Semmann, M. (2021). How Does Business Process Modeling Reflect Augmented Reality-Based Processes? *Proceedings of the Pacific Asia Conference on Information Systems*
yes	Osterbrink, A., Bräker, J., Semmann, M., & Wiesche, M. (2021). Requirements for Augmented Reality Solutions for Safety-Critical Services – The Case of Water Depth Management in a Maritime Logistics Hub. *Proceedings of the International Conference on Wirtschaftsinformatik*

4.2 Included Publications

Nine double-blinded, peer-reviewed publications are included in this dissertation as they directly answer the research questions. At the time of submitting the dissertation, all these articles have been published. The publications are presented in Chapters 9-17, and the format has been adapted to ensure a consistent appearance. Each individual publication is briefly presented below in the order in which they are included in the dissertation.

Chapter 9—Publication P1

Table 6. Summary of publication P1 (Osterbrink et al., 2021)

Citation	Osterbrink, A., Bräker, J., Semmann, M., & Wiesche, M. (2021). Requirements for Augmented Reality Solutions for Safety-Critical Services – The Case of Water Depth Management in a Maritime Logistics Hub. *Proceedings of the International Conference on Wirtschaftsinformatik*
Ranking	VHB-Rating 2024[1]: B CORE2018: C
Type	Completed research paper
Track	Digital services and smart product-service systems
Research questions	RQ1: How amenable is the service process of soil sounding[2] to be supported by AR? RQ2: What are the requirements for AR solutions to improve the service process of soil sounding?
Aim	This paper aims to examine the service of water depth measurement, referred to as soil sounding, based on its process characteristics and suitability for AR. It also aims to derive user-centered requirements for AR solutions for such safety-critical and demanding service.
Methodology	Case study, thinking aloud, semi-structured interviews, expert workshops

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[1] This refers to the VHB Rating for the Wirtschaftsinformatik / Information Systems section, which distinguishes between the publication types of scientific journals and proceedings.

[2] In publications P1 and P2, the process of measuring water depth as part of water depth management is also referred to as "soil sounding". In hydrography, however, the term "hydrographic surveying" is commonly used, as this refers specifically to the sounding of depth below the water surface. The term hydrographic surveying is therefore used in the summarizing part of this dissertation, although the individual publications refer to soil sounding.

Contribution	The paper presents the first study on the applicability and feasibility of AR in the maritime context for safety-critical and demanding services. It contributes to the understanding of which processes are suitable for AR by analyzing the process augmentability of the water depth management use case. By providing five core requirements for the use of AR in water depth measurement services, the paper contributes to the understanding and development of AR applications in specific domains. The results are transferable to other use cases in the maritime industry and other industrial or logistic contexts. The aspect of multidimensional tracking with multiple degrees of freedom and the need to deal with this complexity contributes to ongoing research in the field of Human-Computer Interaction (HCI). From a practical perspective, the requirements can guide the development of AR solutions for safety-critical and demanding services. In terms of methodological contribution, the paper offers a new way of applying the thinking-aloud method. The recording of video footage from a first and third-person perspective is beneficial for non-standard scientific environments, such as noisy environments.
Co-authors' contribution	Anna Osterbrink, Martin Semmann, and Manuel Wiesche co-authored the paper. Anna Osterbrink and Manuel Wiesche contributed to the initial idea. Anna Osterbrink helped with the writing of the paper; in particular, she made the initial proposal for the introduction, related work, and methodology, which I subsequently extended and revised. She helped with the transcription of the think-aloud material, which I transcribed, in the main. After I had analyzed the think-aloud material and derived requirements, Anna Osterbrink gave feedback on the results and helped me structure them. On this basis, I described, discussed, and summarized the results in the paper. Martin Semmann helped with the revision of the introduction, the discussion, and the conclusion of the paper. Both Martin Semmann and Manuel Wiesche provided valuable feedback for the overall revision of the paper.

Chapter 10—Publication P2

Table 7. Summary of publication P2 (Bräker, Osterbrink, et al., 2023)

Citation	Bräker, J., Osterbrink, A., Semmann, M., & Wiesche, M. (2023). User-Centered Requirements for Augmented Reality as a Cognitive Assistant for Safety-Critical Services. *Business & Information Systems Engineering*, *65*, 161–178. https://doi.org/10.1007/s12599-022-00779-3
Ranking	VHB-Rating 2024: B CORE2020: not listed
Type	Completed research paper
Track	Not applicable
Research questions	RQ1: How amenable is the service process of soil sounding to be supported by AR? RQ2: What are the requirements for an AR cognitive assistant to improve the service process of soil sounding?
Aim	This paper investigates how AR can be used as a cognitive assistant in safety-critical and demanding services, and derives user-centered requirements for that purpose. The publication considers the use case of water depth management at a large European maritime logistics operator, involving either sounding vessels or autonomous drones for measuring water depth. The paper analyzes the augmentability of the water depth measurement service and identifies five key requirements for the use of AR as a supporting cognitive assistant in this service. Thus, the paper aims to extend publication P1 (see Chapter 9) by integrating the use case of the autonomous drone and specializing in using AR as a cognitive assistant.
Methodology	Case study, thinking aloud, semi-structured interviews, expert workshops

Contribution	The paper builds on publication P1 (see Chapter 9) and contributes to research by constituting the first study on the applicability and feasibility of AR in a maritime context. In particular, it identifies requirements for a cognitive AR assistant for safety-critical processes that require multitasking and collaboration in mobile environments. The five identified core requirements contribute to understanding AR usage and guide design decisions for AR cognitive assistants in such challenging environments. The results are transferable to other safety-critical contexts. In particular tasks requiring high concentration and situational awareness can benefit from these requirements. As described in Table 6, the paper contributes to the challenge of multidimensional tracking with multiple degrees of freedom in the field of HCI research. The methodological contribution lies in adapting the thinking-aloud methodology as mentioned above. The enrichment with first- and third-person video material allows the methodology to be applied in environments that do not offer laboratory conditions.
Co-authors' contribution	Anna Osterbrink, Martin Semmann, and Manuel Wiesche co-authored the paper. This paper is an extension of publication P1 (Chapter 9). Anna Osterbrink, Martin Semmann and Manuel Wiesche contributed to the first version of the paper (see Chapter 9) and to the ideas of its further development. I transcribed and analyzed the additional think-aloud material, integrated the new findings with the existing ones, and expanded the results accordingly. I also extensively expanded and revised all sections of the entire paper. Martin Semmann provided valuable feedback for the revision and helped to refine and improve the paper.

Chapter 11—Publication P3

Table 8. Summary of publication P3 (Bräker & Semmann, 2022)

Citation	Bräker, J., & Semmann, M. (2022). Dividing Complexity to Conquer New Dimensions – Towards a Framework for Designing Augmented Reality Solutions. *Proceedings of the Americas Conference on Information Systems*
Ranking	VHB-Rating 2024 : C CORE2018: A
Type	Completed research paper
Track	Adoption and diffusion of IT
Research question	RQ: How can organizations systematically approach AR as a technology to support services and improve productivity while reducing the initial barriers to AR adoption and diffusion?
Aim	The paper aims to divide the complexity of designing and developing AR solutions. Especially inexperienced organizations and small and medium-sized enterprises (SMEs) with limited resources have a need for support for the adoption and diffusion of AR solutions. The paper introduces a framework with four levels of abstraction in a top-down approach that supports the step-by-step design of AR applications.
Methodology	Case study, mixed methods, observations, non-standardized interviews, user study with questionnaires and thinking aloud, design thinking workshops, expert panel workshops

Contribution	The paper contributes to the understanding of how to approach AR development and application structurally. The framework provides a comprehensive perspective for initial AR explorations. It helps to explore, analyze, and define AR use cases, understand requirements, and identify benefits and resources. The framework can be used to specify environmental conditions, model user actions and process steps, design the AR scene and describe the technical specifications of the scenes. The paper contributes to the research in process-oriented IS research and more interaction- and AR-scene-oriented HCI research. Thus, it bridges the gaps between the two disciplines. From a practical perspective, the framework can reduce barriers to AR exploration in organizations. It enables actors with limited AR experience to design, develop, and document ideas for AR applications by providing step-by-step guidance. The framework thus serves as a foundation for prototypical AR implementation.
Co-authors' contribution	Martin Semmann co-authored the paper. I discussed the initial idea with him, collected and analyzed the data, and developed the framework. Martin Semmann shared his expertise with me to discuss the framework. He contributed to the writing of the introduction, the discussion, and the conclusion, and helped me with the revision of the paper.

Chapter 12—Publication P4

Table 9. Summary of publication P4 (Bräker & Semmann, 2023b)

Citation	Bräker, J., & Semmann, M. (2023b). The Process Augmentability Canvas – How to Find the Sweet Spot for Augmented Reality. *Proceedings of the European Conference on Information Systems*
Ranking	VHB-Rating 2024 : A CORE2018: A
Type	Completed research paper
Track	Designing and managing digital services and service systems
Research questions	RQ1: What criteria determine the suitability of AR for services? RQ2: How can processes be identified that benefit from AR?
Aim	The paper aims to provide a framework for assessing and evaluating AR process applicability. For this purpose, criteria are identified that determine the suitability of using AR in service processes. These are then categorized at a process level and integrated into the form of a canvas. The canvas aims to assist in understanding the use and appropriateness of AR in organizational environments.
Methodology	Case study, literature review, mixed methods, observations, non-standardized interviews, user study with questionnaires and thinking aloud, design thinking workshops

Contribution	The paper contributes to understanding the efficient use of AR in organizational environments by providing a framework termed the Process Augmentability Canvas. It provides an overview of relevant criteria for the analysis of processes with regard to the suitability of AR. It bridges the gap between the IS and HCI literature by considering the characteristics of the processes to be augmented. In so doing, it contributes to the ongoing discourse on AR in terms of embedding innovation in organizations. Furthermore, it deepens the understanding of the challenges and opportunities of emerging digital technologies. From a practical perspective, the canvas enables organizations to facilitate structured, criteria-based decisions. Therefore, it encourages organizations to approach AR in a low-risk manner and helps them to either select a promising use case for piloting AR, or analyze their processes for AR suitability. The canvas is designed to support decision-making and encourage communication and collaboration among stakeholders.
Co-authors' contribution	Martin Semmann co-authored the paper. He helped me with screening the literature review articles and contributed his expertise to the discussion of the structure of the canvas that I proposed. He also helped revise the introduction, discussion, and conclusion of the paper.

Chapter 13—Publication P5

Table 10. Summary of publication P5 (Bräker & Semmann, 2021)

Citation	Bräker, J., & Semmann, M. (2021). How Does Business Process Modeling Reflect Augmented Reality-Based Processes? *Proceedings of the Pacific Asia Conference on Information Systems*
Ranking	VHB-Rating 2024 : C CORE2018: A
Type	Completed research paper
Track	General topics
Research question	RQ: To what extent are current business process modeling methods and techniques able to support the modeling of augmented reality-based processes in businesses, and which facets of AR do those existing modeling approaches represent?
Aim	This paper aims to investigate the extent to which state-of-the-art business process modeling can be used to model AR processes. The modeling of processes for AR requires advanced approaches. Hence, current approaches are analyzed for their usefulness, and their respective advantages and shortcomings are highlighted and discussed.
Methodology	Literature review
Contribution	The paper contributes to the understanding of AR by systematically examining process modeling approaches for their applicability to AR processes. It gives an overview of the current state of representations for AR in business process modeling. It provides a research agenda to guide the further development of process modeling for AR processes. The paper thus contributes to the ongoing discourse on the impact of digitalization in organizations.

Co-authors' contribution	Martin Semmann co-authored the paper. Together, we developed the idea for the paper. He helped me screen the papers from the literature review and provided valuable feedback throughout the research process. He helped with writing the discussion of the results and with the revision of the paper.

Chapter 14—Publication P6

Table 11. Summary of publication P6 (Bräker, Hertel, & Semmann, 2022)

Citation	Bräker, J., Hertel, J., & Semmann, M. (2022). Conceptualizing Interactions of Augmented Reality Solutions. *Proceedings of the Hawaii International Conference on System Sciences*, 712–721
Ranking	VHB-Rating 2024 : B CORE2018: A
Type	Completed research paper
Track	General topics
Research question	RQ: How can atomic interactions with AR systems be systematically classified to support service design and AR application development?
Aim	The paper aims to conceptualize interactions with AR solutions as a taxonomy. It focuses on the literature in IS research. It is part of a project that includes two taxonomy papers (see Chapter 15—publication P7). The aim is to guide the design and orchestration of interactions within AR systems from an IS perspective. The taxonomy intends to support the service design and development of AR applications.
Methodology	Literature review, taxonomy development

Contribution	The paper contributes to understanding interactions in AR by providing a taxonomy for the systematic analysis and classification of AR interactions. It focuses on atomic interactions, highlights common patterns, and categorizes them into different dimensions. The taxonomy guides the design of AR solutions by describing the solution space for interactions. From a practical perspective, the taxonomy helps designers and developers by guiding the selection of different interaction patterns, thus supporting the implementation of AR interactions and decision-making for a range of possible interactions.
Co-authors' contribution	Julia Hertel and Martin Semmann co-authored the paper. We decided to examine AR interactions from two different perspectives. This paper explores the topic from an IS perspective, whereas publication P7 (see Chapter 15) approaches it from an HCI research perspective. Martin Semmann helped with shaping the idea of developing the taxonomy. He assisted in screening and coding the results of the literature review. He also provided feedback on the different iterations of the taxonomy. He further helped write and revise the paper's introduction, discussion, and conclusion. Julia Hertel assisted in proofreading and revising the paper.

Chapter 15—Publication P7

Table 12. Summary of publication P7 (Hertel et al., 2021)

Citation	Hertel, J., Karaosmanoglu, S., Schmidt, S., Bräker, J., Semmann, M., & Steinicke, F. (2021). A Taxonomy of Interaction Techniques for Immersive Augmented Reality based on an Iterative Literature Review. *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality*, 431–440. https://doi.org/10.1109/ISMAR52148.2021.00060
Ranking	VHB-Rating 2024 : not listed CORE2023: A*
Type	Completed research paper
Track	Not applicable
Research questions	RQ1: Which immersive AR interaction techniques are investigated in the current literature? RQ2: Which characteristics can be found among these techniques and how can these be systematized?
Aim	The paper aims to conceptualize the interactions of immersive AR solutions in the form of a taxonomy. It is part of a project that includes two taxonomy papers (see Chapter 14—publication P6). The focus of this paper is the literature on HCI research. The goal is to examine the interaction techniques mentioned in the HCI literature, highlight their characteristics, and then systematically classify them.
Methodology	Literature review, taxonomy development

Contribution	The paper contributes to the understanding of immersive interactions in AR by facilitating a systematic analysis and holistic classification of AR interactions. The taxonomy guides the development and selection of AR interaction techniques. It also provides a common ground for discussion. The paper serves as a basis for identifying emerging trends and research gaps and, thus, the potential for future research. From a practical perspective, the taxonomy serves as a basis for developers to determine methods for performing specific tasks in AR.
Co-authors' contribution	Julia Hertel, Sukran Karaosmanoglu, Susanne Schmidt, Martin Semmann, and Frank Steinicke co-authored the paper. This publication is part of a project that examines AR interactions from two different perspectives. This article explores the topic from an HCI perspective, whereas publication P6 (Chapter 14) approaches it from an IS perspective. Martin Semmann and I proposed the idea of developing an HCI-based taxonomy for AR interactions and suggested the taxonomy development method. We motivated the other co-authors to approach the topic from an HCI perspective, complementing Publication 6. Following up on the initial idea, Julia Hertel became the primary author of this paper. Julia Hertel, Sukran Karaosmanoglu, and Susanne Schmidt collected the data, analyzed it, and wrote the paper. I helped with the final revision and provided feedback. Martin Semmann and Frank Steinicke gave feedback throughout the process and helped revise the paper.

Chapter 16—Publication P8

Table 13. Summary of publication P8 (Bräker, Hertel, & Semmann, 2023b)

Citation	Bräker, J., Hertel, J., & Semmann, M. (2023b). Empowering Users to Create Augmented Reality-Based Solutions – Deriving Design Principles for No-Code AR Authoring Tools. *Proceedings of the International Conference on Information Systems*
Ranking	VHB-Rating 2024 : A CORE2018: A* ICIS 2023 Best paper nominee
Type	Completed research paper
Track	General IS topics
Research question	RQ: How to design no-code AR authoring tools to make them accessible to a wide range of users?
Aim	This paper aims to investigate how to design no-code AR authoring tools in order to enable users to create AR applications without the need for programming. A user study is conducted to investigate the extent to which an existing no-code AR authoring tool meets user needs. Based on this analysis, design principles for no-code AR authoring tools are generated.
Methodology	Mixed methods, user study, questionnaires, thinking aloud, design principle generation and formulation

Contribution	The paper contributes to the understanding of no-code AR authoring tools and generates concrete design knowledge for such tools by deriving design principles. These cover a wide range of relevant facets and can serve as a guide for the future design and development of no-code AR authoring tools. From a practical point of view, no-code AR authoring tools can empower users to access AR, as the results of the study show. They can facilitate and broaden the application of AR in practice. Methodologically, the paper is an example of a mixed-methods study using quantitative surveys to validate qualitative findings.
Co-authors' contribution	Julia Hertel and Martin Semmann co-authored the paper. Martin Semmann contributed to the idea of the paper. Together with Julia Hertel, I developed the design of the user study. Both co-authors helped with data collection by assisting with the user study. Martin Semmann helped with the transcription and coding of the study data. He also helped to discuss the granularity of the design principles that I developed. Julia Hertel helped with the statistical analysis of the data and with the description and discussion of the statistical results. Both Julia Hertel and Martin Semmann helped to revise and improve the paper.

Chapter 17—Publication P9

Table 14. Summary of publication P9 (Bräker & Semmann, 2023a)

Citation	Bräker, J., & Semmann, M. (2023a). Is There More Than Pokémon Go? – Exploring the State of Research on Causal Modeling in the Field of Augmented Reality. *Proceedings of the Hawaii International Conference on System Sciences*
Ranking	VHB-Rating 2024 : B CORE2018: A
Type	Completed research paper
Track	Mixed, augmented and virtual reality: services and applications
Research questions	RRQ1: What constructs are applied to model causalities regarding AR? RQ2: Which theoretical perspectives guide research on AR?
Aim	The paper aims to investigate which constructs are used in causal models in AR research. Following this approach, the literature on structural equation models of AR is reviewed and analyzed. The paper examines how conceptual research is conducted in the field of AR and what dominant theoretical perspectives are relevant.
Methodology	Literature review, causal model analysis approach

Contribution	This paper contributes to the understanding of conceptual AR research by applying a causal modeling approach to literature analysis using graph databases. It provides an in-depth analysis of the literature and identifies the major theories, themes, and manifestations associated with AR. The paper provides an overview of the gaps that exist in the research. It also highlights the immaturity and exploratory nature of the field. From a methodological perspective, the paper contributes to the approach of analyzing causal models with graph databases. It validates the usefulness of existing prior work and extends a meta-model according to which articles can be encoded as a graph so that more information can be mapped and extracted in a simple and structured way.
Co-authors' contribution	Martin Semmann co-authored this paper. He had the initial idea of using an existing approach of graph databases to represent causal models. Together, we developed the idea for the paper. He helped with screening and coding the literature review results. I then created the graph database and refined the metamodel for the graph. I created the Cypher files for the database and did the knowledge extraction and synthesis. Martin Semmann gave valuable feedback and helped me with ideas for queries in the database. He helped with the writing of the paper, especially the introduction, discussion, and conclusion, as well as with the general revision of the paper.

5 Research Contribution

The research goal of this dissertation is to understand the application of augmented reality (AR) technologies in service systems and to generate design knowledge aimed at improving systematic approaches to AR in organizations. In order to achieve this goal, this dissertation explores various facets of AR utilization from both the user and organizational perspectives within the boundaries of a service system. The derived design knowledge contributes to the body of design knowledge for the systematic design of service systems—namely service systems engineering (SSE).

A user-centered perspective is adopted to answer the first research question (RQ-1). The unit of analysis is actors, specifically users and their actions, resource integration, and interactions with and in the service system. The context of the water depth management use case is particularly demanding due to its specific characteristics. While traditional AR use cases have typically linear and isolated processes, hydrographic surveying in the context of water depth management in a large European logistics hub is an instance of a safety-critical, complex, and demanding service (see Chapter 3.2.2). The first research strand contributes to the use of AR in complex environments under demanding conditions.

An organizational perspective is adopted to answer the second research question (RQ-2) and its sub-questions (RQ-2a to RQ-2d). The focus here is to investigate the systematic application of AR in organizations, regardless of the specifics of the use case at hand. The publications related to RQ-2 address the embedding of AR in service systems and, more specifically, the identification of potentials and requirements for augmentable processes, the suitability of approaches for modeling AR processes, the understanding of interaction techniques, and the no-code design and development of AR applications for piloting. By answering the second research question, this dissertation contributes to the systematic assessment and realization of the potential of AR in organizations and of the support required in the early phases of service design. The proposed design artifacts serve as tools and methods for the engineering of these complex service systems and service systems interactions.

The third research question (RQ-3) investigates AR research on a conceptual level. RQ-3 explores the potential of using a graph database approach to represent and analyze publications for the purpose of exploring new research fields. By applying this approach to AR research, a theoretical contribution is made by providing an overview, identifying research gaps, and suggesting future research directions.

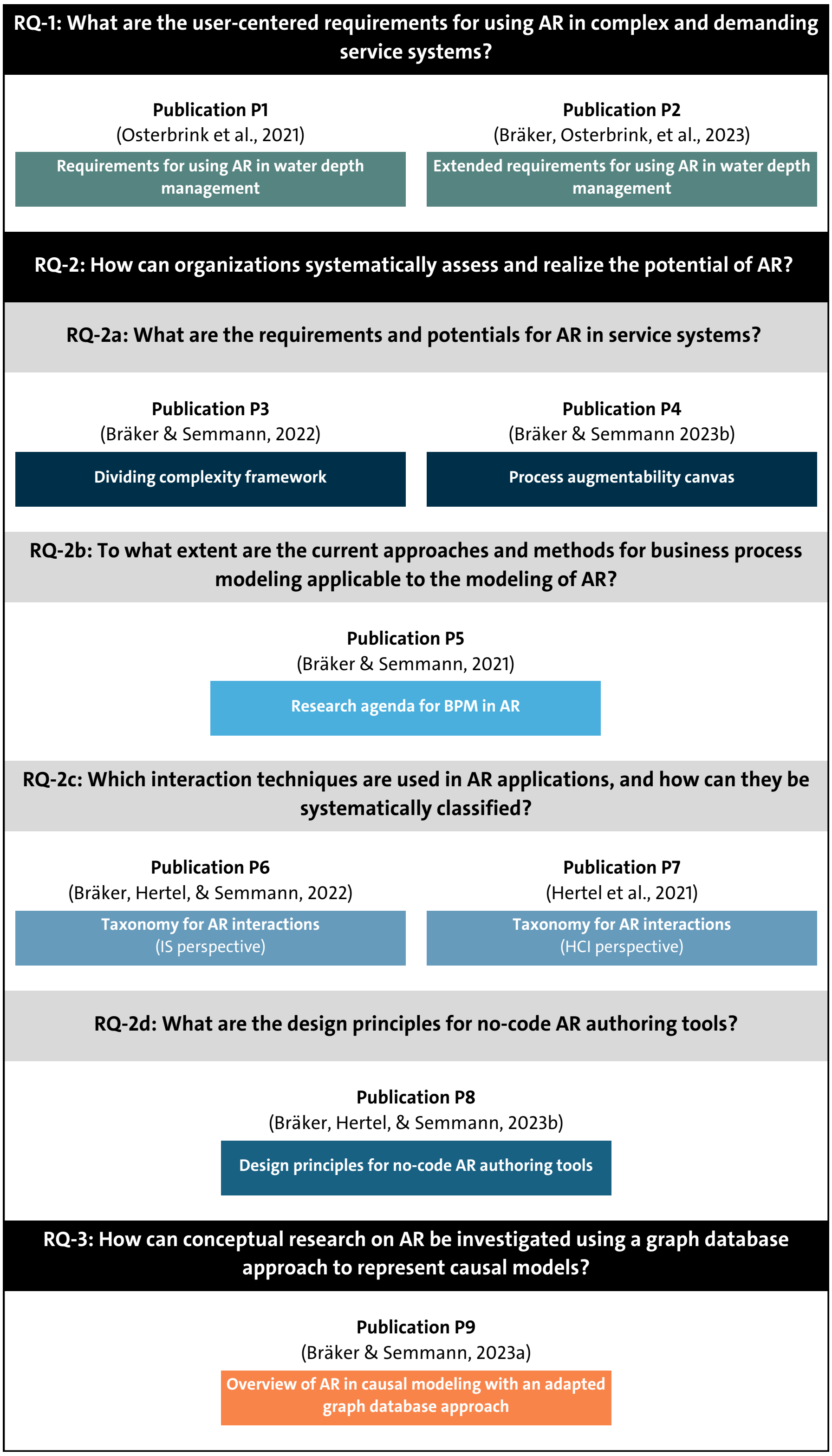
Figure 11 provides an overview of the publications that contribute to each of the three research questions, and shows the artifacts that are presented in each publication (in a color block).

The following sections are structured according to the three research questions. Chapter 5.1 discusses the first research question, which is addressed by Publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023). Chapter 5.2 addresses the second research question to which publications P3-P8 contribute (Bräker, Hertel, & Semmann, 2022, 2023b; Bräker & Semmann, 2021, 2022, 2023b; Hertel et al., 2021). Chapter 5.3 deals with the third research question, which is addressed by Publication P9 (Bräker & Semmann, 2023a).

Additionally, this dissertation contributes methodological knowledge for SSE (see Chapter 5.4) by extending the think-aloud method and integrating first- and third-person video perspectives. Furthermore, a contribution to methodology is made by adapting a graph database approach for exploring and analyzing the literature, and by developing a metamodel for representing AR publications.

5.1 Contribution to the Use of AR in Complex and Demanding Service Systems

When considering the use of AR in service systems, it is crucial to take into account the specific needs and requirements of users and to ensure that the technology is utilized in a way that creates value. From a service systems perspective, it is essential to understand the context and the interactions between actors, technology, and resources in order to apply AR successfully. Design knowledge is necessary for the systematic design, development, and piloting of service systems in accordance with the SSE approach. This dissertation considers a specific real-world use case to investigate the first research question (RQ-1) as an example of how to generate design knowledge.



RQ-1: What are the user-centered requirements for using AR in complex and demanding service systems?

Publication P1
(Osterbrink et al., 2021)
Requirements for using AR in water depth management

Publication P2
(Bräker, Osterbrink, et al., 2023)
Extended requirements for using AR in water depth management

RQ-2: How can organizations systematically assess and realize the potential of AR?

RQ-2a: What are the requirements and potentials for AR in service systems?

Publication P3
(Bräker & Semmann, 2022)
Dividing complexity framework

Publication P4
(Bräker & Semmann 2023b)
Process augmentability canvas

RQ-2b: To what extent are the current approaches and methods for business process modeling applicable to the modeling of AR?

Publication P5
(Bräker & Semmann, 2021)
Research agenda for BPM in AR

RQ-2c: Which interaction techniques are used in AR applications, and how can they be systematically classified?

Publication P6
(Bräker, Hertel, & Semmann, 2022)
Taxonomy for AR interactions
(IS perspective)

Publication P7
(Hertel et al., 2021)
Taxonomy for AR interactions
(HCI perspective)

RQ-2d: What are the design principles for no-code AR authoring tools?

Publication P8
(Bräker, Hertel, & Semmann, 2023b)
Design principles for no-code AR authoring tools

RQ-3: How can conceptual research on AR be investigated using a graph database approach to represent causal models?

Publication P9
(Bräker & Semmann, 2023a)
Overview of AR in causal modeling with an adapted graph database approach

Figure 11. Overview of the publications and artifacts that contribute to each research question

Previous research has demonstrated that AR has the potential to be used in service systems across various sectors, including industry, logistics, healthcare, retail, and education. AR has been proven to enhance performance and increase efficiency (Egger & Masood, 2020; Fiorentino et al., 2014; Kohn & Harborth, 2018). However, it is essential to note that the application of AR in these cases has been limited to primarily linear and relatively simple processes, which restricts its transferability to more complex and dynamic settings. For example, AR has been used in industrial repair and maintenance services, where the user has to follow a set of predefined steps supported by an AR manual (Henderson & Feiner, 2011; Platonov et al., 2006). Similarly, AR has been used in order-picking operations in logistics, where users are required to collect and consolidate materials (Fang & An, 2020).

In order to investigate the use of AR in more complex service systems, the focus is on an example that is more demanding than simple and linear tasks: the hydrographic surveying for measuring water depths in a harbor area. This service is a crucial component of water depth management, and its complexity highlights the potential for AR beyond simple processes. If AR can be successfully applied in this scenario, it could open up new opportunities for AR in various industries. Moreover, it is expected that the findings will be applicable to other cases of comparable complexity.

5.1.1 User-Centered Requirements for Using AR in Water Depth Management as an Example of Complex and Demanding Service Systems

In order to address the first research question (RQ-1) and derive user-centered requirements for the application of AR, it is necessary to investigate the general augmentability of hydrographic surveying. The purpose here is to eliminate the possibility that the reason why such complex and demanding services have not been investigated in previous research is due to the inability to augment such processes. Yeo's (2017) process virtualization theory (PVT) can be used to analyze the general augmentability of hydrographic surveying. Accordingly, the first two publications—P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023)—provide a comprehensive analysis of the augmentability of hydrographic surveying. Publication P1 focuses on sounding (i.e., the measurement of depth below the water surface) with a vessel, and publication P2 extends this by integrating sounding with an autonomous floating drone. The analysis shows that the service of hydrographic surveying meets all four requirements of the PVT: authenticity, 3D visualization, spatial association, and synchronization. This confirms that this process can be augmented. In general, this example indicates that even complex and demanding processes are augmentable. Further information on each aspect is described in the respective publications.

The insight that hydrographic surveying is augmentable means that it is possible to proceed with analyzing the specific user-centered requirements. Based on an in-depth analysis of think-aloud protocol sessions (Boren & Ramey, 2000; van Someren et al., 1994), where skippers were observed and asked to verbalize their thoughts and actions, five requirements for designing an AR solution for hydrographic surveying are identified. The five requirements are (1) real-time overlay, (2) variety in displaying information, (3) multi-dimensional tracking, (4) collaboration, and (5) interaction (Bräker, Osterbrink, et al., 2023; Osterbrink et al., 2021).

Real-time overlay: The first requirement for a real-time overlay arises from the need to display real-time information reliably in the actor's field of view. Such information can be navigation-related or information that influences the measurement task. A real-time overlay, which displays information directly in the actor's field of view, can improve traffic safety in the harbor by improving the situational awareness of skippers, and prevent health issues caused by permanent view shifts between different monitors and the external environment, that would otherwise be required for traffic safety.

Variety in displaying information: Hydrographic surveying requires the skipper to consider a wide range of contextualized information, which is currently displayed on different monitors redundantly because the data sources are not integrated into a single display. This results in inefficient use of available space and view shifts. An AR solution should allow for different representation options, such as filtering by different layers or information types, to prevent visual clutter and exhaustion and only display the information relevant to the specific context.

Multi-dimensional tracking: The setting on the vessel is characterized by a dynamic environment. Because the vessel is moving on the water and the skipper can move within the vessel, tracking is far more complex than in static environments. Accurate tracking is critical, however, because displaying information in a geospatially correctly aligned way ensures navigation safety and high-quality measurement data. Additionally, the tracking system must be robust, as it can be affected by the movement caused by high waves, or by direct sunlight or light reflections. It is important to note that tracking the drone operator is not necessary for the autonomous swimming drone. However, the tracking system must still be robust, as the drone also moves on the surface of the water.

Collaboration: Hydrographic surveying requires constant communication and collaboration between the skipper and the measurement engineer. Communication problems can lead to safety issues or insufficient quality of the measurement data. To ensure traffic safety, communication via radio with other water traffic participants is also necessary. To ensure their shared understanding, the skipper and measurement engineer should have the same visualization of measurement areas and information. For remote collaboration and communication, a hands-free solution is essential because the skipper requires both hands to steer the vessel.

Interaction: For safe navigation and high-quality measurement data, it is crucial to have the ability to interact with the displayed information and selectively show or hide data. This helps to reduce visual clutter and distractions. The interaction technique should not distract the skipper from other tasks required for ensuring navigation safety and task efficiency.

When developing an AR solution to support critical infrastructure services, such as hydrographic surveying, it is important to consider all five requirements. Real-time overlay of the field of view, and visualization of a variety of information can help the skipper deal with the high mental and physical demands. Accurate tracking is necessary to align the information geospatially correctly. Due to the dynamic setting of a vessel moving on water, multi-dimensional tracking is required, which presents a technological challenge. Ensuring non-distracting collaboration and interaction with the AR system is critical too. The five requirements aim to achieve safe navigation, improved situational awareness, support for multitasking and collaboration, and increased efficiency.

The requirements contribute to concrete design knowledge for designing and developing AR solutions for complex service systems. The results contribute to the scientific discourse by combining and extending previous research that only examined individual facets of this case, as there is little to no research in those areas to date. By addressing the challenges related to multi-dimensional tracking that goes beyond the complexity of dynamic environments such as driving or cycling, the results contribute not only to Information Systems (IS) research but also to more technical AR research in the field of Human-Computer Interaction (HCI). Thus, valuable insights are provided for the further advancement of AR technology and its application in real-world scenarios. The requirements open up new opportunities for applying AR in service systems, paving the way for more efficient and user-centric solutions.

5.1.2 Transferability to Other Cases

One question that arises is the extent to which the requirements for AR, developed in the context of hydrographic surveying, are transferable to other cases. Evaluating transferability requires the detailed consideration of the characteristics that make the hydrographic surveying complex and demanding.

Safety-criticality: Safety is of primary importance in all the AR requirements mentioned above. Ensuring safety is particularly relevant when services are safety-critical in a way that failure could endanger human life (Knight, 2002). The above requirements provide guidance for the use of AR under safety-critical circumstances for the maintenance of critical harbor infrastructure. Therefore, the requirements can be transferred to other safety-critical services as well. This includes the maintenance of critical infrastructures (e.g., rail, road, pipelines), or mobility and logistics hubs, such as train stations and airports.

Multitasking and collaboration: The above AR requirements can be transferred to any cases that require a high degree of multitasking, collaboration, situational awareness, and mental load.

Dynamic environment: The requirement for multi-dimensional tracking in dynamic environments is transferable to various scenarios, including unstable or dynamic environments, such as air or water. Therefore, the requirements are transferable to other cases in the maritime industry and cases with a high degree of physical dynamics.

The findings are transferable to a wide range of cases and application domains that are safety-critical, require multitasking and occur in a dynamic environment. Consequently, the requirements offer valuable design knowledge for implementing AR in complex and demanding service systems.

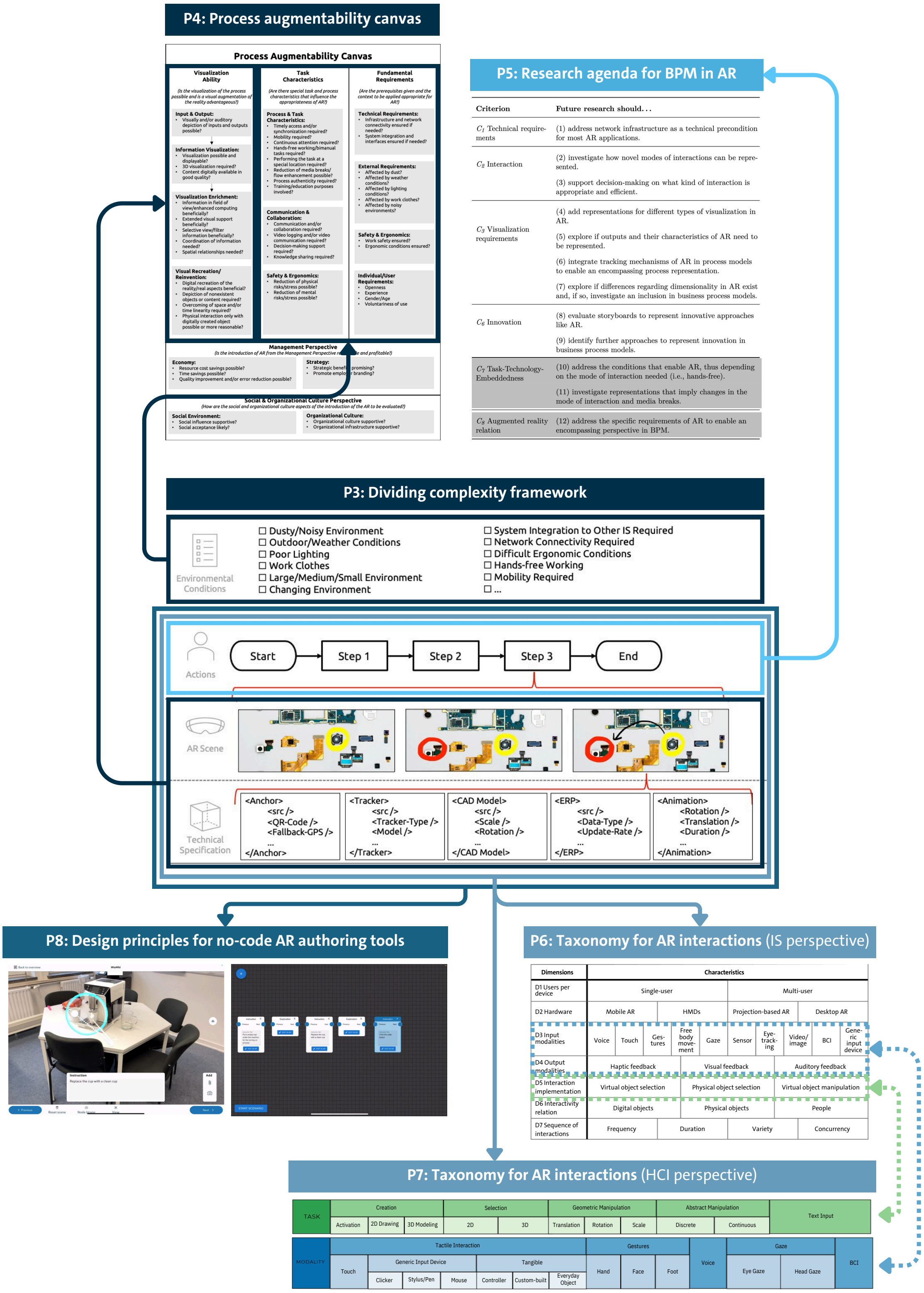
5.2 Contribution to the Systematic Assessment of AR Potentials in Organizations

When organizations consider AR, the question arises as to how to unlock and assess the potential of AR in a systematic way. Especially when organizations have little to no prior experience of AR, they need step-by-step guidance to thoroughly explore its potential and design, and the development and piloting of AR applications. This guidance should assist organizations in identifying areas where AR can add value and making informed decisions about whether to invest in AR technology and how to implement it in the organization.

The research literature on comprehensive approaches to AR assessment is quite fragmented and tends to focus on single problems and specific cases. By adopting a holistic perspective, a contribution is made to understanding how the potential of AR can be systematically assessed and realized on an organizational level. For the second research question (RQ-2) an organization is considered a service system, including its context, actors, technologies, resources, and their interactions.

The following sections examine the journey an organization can take to systematically implement AR, from the first touchpoint with AR to the creation of prototypes using an AR authoring tool that enables development without writing a single line of code. As part of this dissertation, several artifacts have been developed that contribute to design knowledge in this area.

Figure 12 illustrates the interrelationships and synergies of these artifacts. The *dividing complexity framework* presented in publication P3 (Bräker & Semmann, 2022) is a central artifact which is related to the artifacts developed in publications P4-P8. The task characteristics and fundamental requirements of *the process augmentability canvas* presented in publication P4 (Bräker & Semmann, 2023b), are a deep dive into the first layer (environmental conditions) of the dividing complexity framework. Further, the third (AR scene) and fourth (technical specification) layers of the dividing complexity framework are mirrored in the visualization ability of the process augmentability canvas. A zoom-in to the actions level of the dividing complexity framework is presented in publication P5 (Bräker & Semmann, 2021), which evaluates various process modeling approaches for their suitability for modeling AR processes. As the dividing complexity framework does not address AR interaction design extensively, publications P6 (Bräker, Hertel, & Semmann, 2022) and P7 (Hertel et al., 2021) approach AR interactions by developing two taxonomies from different



Process Augmentability Canvas

Visualization Ability
(Is the visualization of the process possible and is a visual augmentation of the reality advantageous?)

Input & Output:
- Visually and/or auditory depiction of inputs and outputs possible?

Information Visualization:
- Visualization possible and displayable?
- 3D visualization required?
- Content digitally available in good quality?

Visualization Enrichment:
- Information in field of view/enhanced computing beneficially?
- Extended visual support beneficially?
- Selective view/filter information beneficially?
- Coordination of information needed?
- Spatial relationships needed?

Visual Recreation/ Reinvention:
- Digital recreation of the reality/real aspects beneficial?
- Depiction of nonexistent objects or content required?
- Overcoming of space and/or time linearity required?
- Physical interaction only with digitally created object possible or more reasonable?

Task Characteristics
(Are there special task and process characteristics that influence the appropriateness of AR?)

Process & Task Characteristics:
- Timely access and/or synchronization required?
- Mobility required?
- Continuous attention required?
- Hands-free working/bimanual tasks required?
- Performing the task at a special location required?
- Reduction of media breaks/ flow enhancement possible?
- Process authenticity required?
- Training/education purposes involved?

Communication & Collaboration:
- Communication and/or collaboration required?
- Video logging and/or video communication required?
- Decision-making support required?
- Knowledge sharing required?

Safety & Ergonomics:
- Reduction of physical risks/stress possible?
- Reduction of mental risks/stress possible?

Fundamental Requirements
(Are the prerequisites given and the context to be applied appropriate for AR?)

Technical Requirements:
- Infrastructure and network connectivity ensured if needed?
- System integration and interfaces ensured if needed?

External Requirements:
- Affected by dust?
- Affected by weather conditions?
- Affected by lighting conditions?
- Affected by work clothes?
- Affected by noisy environments?

Safety & Ergonomics:
- Work safety ensured?
- Ergonomic conditions ensured?

Individual/User Requirements:
- Openness
- Experience
- Gender/Age
- Voluntariness of use

Management Perspective
(Is the introduction of AR from the Management Perspective re[illegible]le and profitable?)

Economy:
- Resource cost savings possible?
- Time savings possible?
- Quality improvement and/or error reduction possible?

Strategy:
- Strategic benef[illegible] promising?
- Promote emplo[illegible]r branding?

Social & Organizational Culture Perspective
(How are the social and organizational culture aspects of the introduction of the AR to be evaluated?)

Social Environment:
- Social influence supportive?
- Social acceptance likely?

Organizational Culture:
- Organizational culture supportive?
- Organizational infrastructure supportive?

Criterion	Future research should. . .
C_1 Technical requirements	(1) address network infrastructure as a technical precondition for most AR applications.
C_2 Interaction	(2) investigate how novel modes of interactions can be represented.
	(3) support decision-making on what kind of interaction is appropriate and efficient.
C_3 Visualization requirements	(4) add representations for different types of visualization in AR.
	(5) explore if outputs and their characteristics of AR need to be represented.
	(6) integrate tracking mechanisms of AR in process models to enable an encompassing process representation.
	(7) explore if differences regarding dimensionality in AR exist and, if so, investigate an inclusion in business process models.
C_6 Innovation	(8) evaluate storyboards to represent innovative approaches like AR.
	(9) identify further approaches to represent innovation in business process models.
C_7 Task-Technology-Embeddedness	(10) address the conditions that enable AR, thus depending on the mode of interaction needed (i.e., hands-free).
	(11) investigate representations that imply changes in the mode of interaction and media breaks.
C_8 Augmented reality relation	(12) address the specific requirements of AR to enable an encompassing perspective in BPM.

☐ Dusty/Noisy Environment
☐ Outdoor/Weather Conditions
☐ Poor Lighting
☐ Work Clothes
☐ Large/Medium/Small Environment
☐ Changing Environment

☐ System Integration to Other IS Required
☐ Network Connectivity Required
☐ Difficult Ergonomic Conditions
☐ Hands-free Working
☐ Mobility Required
☐ ...

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Dimensions	Characteristics									
D1 Users per device	Single-user					Multi-user				
D2 Hardware	Mobile AR			HMDs		Projection-based AR		Desktop AR		
D3 Input modalities	Voice	Touch	Gestures	Free body movement	Gaze	Sensor	Eye-tracking	Video/ image	BCI	Generic input device
D4 Output modalities	Haptic feedback			Visual feedback			Auditory feedback			
D5 Interaction implementation	Virtual object selection			Physical object selection			Virtual object manipulation			
D6 Interactivity relation	Digital objects			Physical objects			People			
D7 Sequence of interactions	Frequency			Duration		Variety		Concurrency		

TASK	Creation			Selection		Geometric Manipulation			Abstract Manipulation		Text Input
	Activation	2D Drawing	3D Modeling	2D	3D	Translation	Rotation	Scale	Discrete	Continuous	

MODALITY	Tactile Interaction							Gestures			Voice	Gaze		BCI
	Touch	Generic Input Device			Tangible			Hand	Face	Foot		Eye Gaze	Head Gaze	
		Clicker	Stylus/Pen	Mouse	Controller	Custom-built	Everyday Object							

Figure 12. Relationships and synergies between the artifacts to answer RQ-2

perspectives. The first is developed from the Information Systems (IS) perspective (Bräker, Hertel, & Semmann, 2022), and the second from the Human-Computer Interaction (HCI) perspective (Hertel et al., 2021). The interaction taxonomies extend the dividing complexity framework regarding the classification and selection of potential interactions when describing the user's actions, the AR scene and its technical specifications.

The AR authoring tool presented in publication P8 (Bräker, Hertel, & Semmann, 2023b) consolidates and evaluates various results from this dissertation and can be seen as a continuation of the framework. P8 implements the actions level by integrating a process modeling view (see also publication P5, Bräker and Semmann, 2021) and enabling AR scene creation using the what-you-see-is-what-you-get (WYSIWYG) principle. This represents the integration of the AR scene with the technical specifications level. Moreover, publication P3 (Bräker & Semmann, 2022) suggests that specific templates for reoccurring tasks could be a useful extension of the framework. Such templates could provide additional guidance for inexperienced users. This issue is partly addressed and discussed in publication P8 (Bräker, Hertel, & Semmann, 2023b), which notes that certain users tend to follow the same patterns for similar tasks. In the following sections describes each artifact and its relation to the other artifacts in more detail.

5.2.1 Approaching AR in Organizations—From the First Touchpoint with AR to the Specification of an AR Prototype

Organizations face major challenges when intending to use AR technologies. The barriers are particularly high for organizations that have little or no experience of AR, and limited knowledge and resources (Stentoft et al., 2019). Without professional consulting, the barriers to using AR are high. To overcome these barriers would require step-by-step guidance for the initial attempts to use AR in an organizational context.

To this very end, publication P3 (Bräker & Semmann, 2022) proposes a framework that provides a systematic approach to support the use of AR, from the initial exploration and towards a step-wise specification for AR implementation. The framework is also referred to as the *dividing complexity framework* and comprises of four layers, each with a different level of abstraction, following a top-down approach.

The framework does not necessitate any technical expertise, thereby enabling experts with domain knowledge to utilize it. Table 15 provides an overview of the layers of the framework, delineating the questions addressed in each layer, its goals and intended outcomes.

Table 15. Overview of the layers of the framework presented in publication P3 (Bräker & Semmann, 2022)

Framework layer	**Guiding questions**	**Goal and focus**	**Result**
Environmental conditions	Which processes are augmentable and, therefore, suitable for AR? How to go about identifying a suitable process?	Understanding of institutional arrangements, working environment, and core resources.	Analyzed and identified processes suitable for AR to make informed decisions about a beneficial process.
Actions	How to model the identified process? Does it need to be remodeled?	Considering the process level as an anchor for the design of AR scenes.	Documented (re)modeled process.
AR scene	What does the AR scene look like?	Describing AR scenes as a representation of the integration of physical and digital resources to fulfill tasks in service systems.	Description of the AR scenes with visualizations and augmentations for each process step as relevant information for later implementation.
Technical specification	What are the technical characteristics of the AR scene?	Addition of technical specifications that define critical resources to enable visualization within the AR scene.	Description of technical implementation details for visualizations and augmentations for each AR scene.

The framework's top-down approach allows organizations to start from scratch and think about processes that could benefit from AR. This starts with an analysis of each process in terms of how it could benefit from AR characteristics, e.g., by AR providing hands-free working. However, it is not only the task itself that determines augmentability. Due to hardware limitations, AR is not suitable for all processes, and the working environment and its conditions determine which hardware would be useful. The first step of the framework is, therefore, to examine the environmental conditions. Understanding the institutional arrangements, environment, and core resources helps to make informed decisions about potentially augmentable processes. As a result, beneficial processes for AR are identified and prioritized.

The actions layer offers guidance for modeling AR processes. Documenting the process helps to establish a shared understanding and identify potential improvements, i.e., the need to redesign the process when integrating AR. In addition, each step of the process helps to prepare the structuring of the later implementation by considering each step as at least one AR scene in the third layer. Structuring and documenting the process beforehand enables a more seamless integration of AR technology into existing processes.

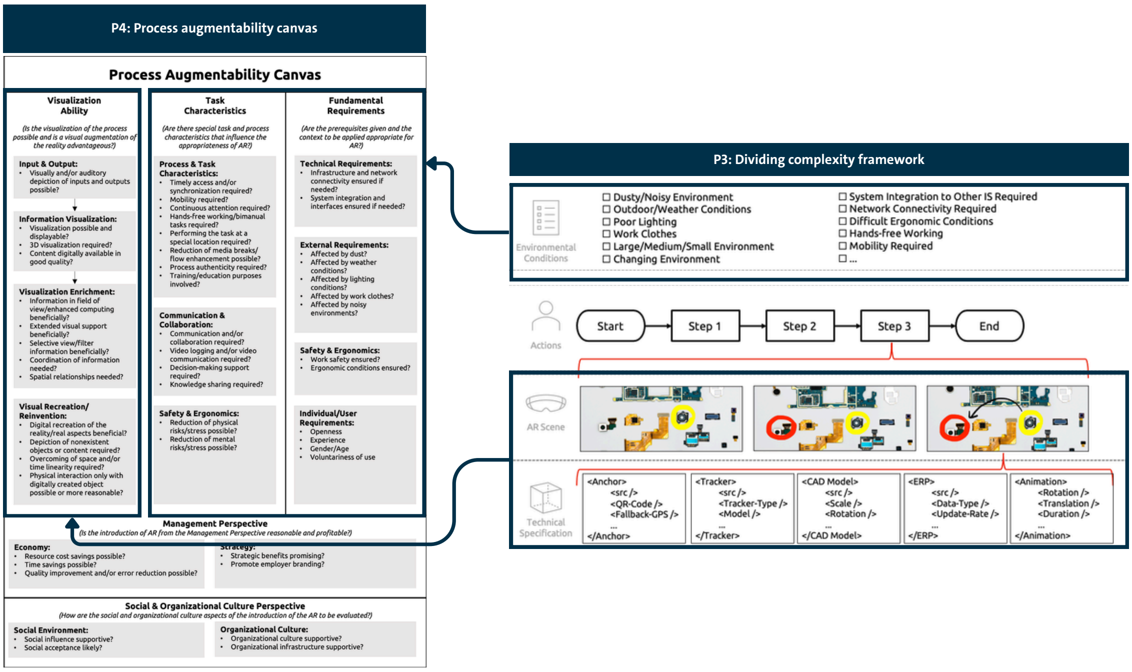
The (re)modeled process documentation enables the visual description of AR scenes and their augmentations for each step. This represents the integration of physical and digital resources to accomplish tasks in service systems. By breaking down process steps into AR scenes, organizations can better understand the flow of AR activities and augmentations.

At the fourth layer of the framework, technical specifications can be added for the characteristics of the AR scene. These specifications define critical resources and their interactions to enable the representation within each AR scene. In addition, they provide a guideline for the implementation of the described AR scenes.

The framework contributes to understanding how AR can be used in organizational contexts. It helps to understand the benefits and requirements for AR in organizations, supports process analysis, use case definition, and understanding of institutional arrangements and work environments, as well as identifying core resources. By specifying the requirements for an AR prototype, it serves as a basis for prototypical implementation. From a theoretical point of view, the framework aims to bridge the gap between more process-oriented IS research and AR research in the HCI community, which typically pays less attention to the socio-technical aspects of AR use. The HCI perspective is reflected in the definition of the AR scene and technical specifications. By specifying attributes that describe the appearance or behavior of the AR scene, this approach comes close to AR development using a game engine like Unity.

5.2.2 Supporting Informed Decision-Making About the Augmentability of Processes—Requirements and Potentials for Using AR in Service Systems

The research question RQ-2a concerns the analysis and evaluation of the requirements and potentials for the use of AR. Two publications in this dissertation contribute to RQ-2a. The first is publication P3 (Bräker & Semmann, 2022), which presents the dividing complexity framework. The second is publication P4 (Bräker & Semmann, 2023b), in which the process augmentability canvas is presented. The two artifacts aim to assist in the analysis, identification, and decision-making regarding the most beneficial use of AR in processes, i.e., to select the most productive, efficient, and effective processes. Both approaches are presented in the form of an easily accessible checklist, which can be used to explore and analyze processes. The first layer of the dividing complexity framework focuses on the analysis of environmental conditions to identify augmentable processes. It also provides examples of how processes can be analyzed. The process augmentability canvas serves as a tool that enables a comprehensive analysis and evaluation of processes in terms of their augmentability. Therefore, it supports structured, criterion-based, and informed decision-making.


P4: Process augmentability canvas

Process Augmentability Canvas

Visualization Ability

(Is the visualization of the process possible and is a visual augmentation of the reality advantageous?)

Input & Output:
- Visually and/or auditory depiction of inputs and outputs possible?

Information Visualization:
- Visualization possible and displayable?
- 3D visualization required?
- Content digitally available in good quality?

Visualization Enrichment:
- Information in field of view/enhanced computing beneficially?
- Extended visual support beneficially?
- Selective view/filter information beneficially?
- Coordination of information needed?
- Spatial relationships needed?

Visual Recreation/ Reinvention:
- Digital recreation of the reality/real aspects beneficial?
- Depiction of nonexistent objects or content required?
- Overcoming of space and/or time linearity required?
- Physical interaction only with digitally created object possible or more reasonable?

Task Characteristics

(Are there special task and process characteristics that influence the appropriateness of AR?)

Process & Task Characteristics:
- Timely access and/or synchronization required?
- Mobility required?
- Continuous attention required?
- Hands-free working/bimanual tasks required?
- Performing the task at a special location required?
- Reduction of media breaks/ flow enhancement possible?
- Process authenticity required?
- Training/education purposes involved?

Communication & Collaboration:
- Communication and/or collaboration required?
- Video logging and/or video communication required?
- Decision-making support required?
- Knowledge sharing required?

Safety & Ergonomics:
- Reduction of physical risks/stress possible?
- Reduction of mental risks/stress possible?

Fundamental Requirements

(Are the prerequisites given and the context to be applied appropriate for AR?)

Technical Requirements:
- Infrastructure and network connectivity ensured if needed?
- System integration and interfaces ensured if needed?

External Requirements:
- Affected by dust?
- Affected by weather conditions?
- Affected by lighting conditions?
- Affected by work clothes?
- Affected by noisy environments?

Safety & Ergonomics:
- Work safety ensured?
- Ergonomic conditions ensured?

Individual/User Requirements:
- Openness
- Experience
- Gender/Age
- Voluntariness of use

Management Perspective

(Is the introduction of AR from the Management Perspective reasonable and profitable?)

Economy:
- Resource cost savings possible?
- Time savings possible?
- Quality improvement and/or error reduction possible?

Strategy:
- Strategic benefits promising?
- Promote employer branding?

Social & Organizational Culture Perspective

(How are the social and organizational culture aspects of the introduction of the AR to be evaluated?)

Social Environment:
- Social influence supportive?
- Social acceptance likely?

Organizational Culture:
- Organizational culture supportive?
- Organizational infrastructure supportive?

P3: Dividing complexity framework

Environmental Conditions

☐ Dusty/Noisy Environment
☐ Outdoor/Weather Conditions
☐ Poor Lighting
☐ Work Clothes
☐ Large/Medium/Small Environment
☐ Changing Environment
☐ System Integration to Other IS Required
☐ Network Connectivity Required
☐ Difficult Ergonomic Conditions
☐ Hands-free Working
☐ Mobility Required
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Figure 13. Relations between the dividing complexity framework from publication P3 (Bräker & Semmann, 2022) and the process augmentability canvas from publication P4 (Bräker & Semmann, 2023b)

The environmental conditions from the dividing complexity framework of publication P3 (Bräker & Semmann, 2022) can also be found in the process augmentability canvas in publication P4 (Bräker & Semmann, 2023b) under task characteristics and fundamental requirements. The AR scene and technical specification layers of the dividing complexity framework are mirrored in the visualization ability of the process augmentability canvas (see Figure 13).

The environmental conditions of the dividing complexity framework are related to the location of the service provision. Location-related aspects that need to be taken into account include a range of factors like, for example, weather and lighting conditions, or noise and dust. Additional factors to consider are the size of the working environment, whether it is a single workbench or an entire warehouse, and whether it is static or dynamic, and whether any protective clothing is required, such as gloves or helmets. When thinking about the use of AR, it is important to take into account technical prerequisites such as system integration and interfaces with other information systems, and factors such as the need for network connectivity. Ergonomic requirements and the need for hands-free working are also relevant. It is important to note that these are just a few examples of the dimensions that should be taken into consideration when using AR.

The process augmentability canvas described in publication P4 (Bräker & Semmann, 2023b) delves deeper into the challenge of identifying which processes could benefit from AR. It takes into account various aspects at individual, task, and organizational levels. The canvas provides a comprehensive representation of the decision needed to identify, access, and realize the potential of AR in an organizational context from multiple perspectives. The process augmentability canvas comprises five categories: (1) visualization ability, (2) task characteristics, (3) fundamental requirements, (4) management perspective, and (5) social and organizational culture perspective. In contrast to the dividing complexity framework, the process augmentability canvas is not limited to environmental conditions. It offers a more comprehensive approach to understanding how AR can be used in organizations. By considering diverse perspectives, the canvas provides a structured way to assessing and improving AR potential, and understanding organizational constraints and requirements. This builds a foundation for informed decision-making. The canvas contributes to understanding the success factors, influential factors, and exclusion criteria for AR.

The five categories of the process augmentability canvas can be summarized as follows:

1. The *visualization ability* category determines whether the process is augmentable and information visualization in AR is possible. If so, visual enrichment could improve the user experience. The visualization ability is a prerequisite for augmentation.
2. The *task characteristics* category analyzes the details of a task. The dividing complexity framework has some overlap with this characteristic, especially in terms of the mobility required during process execution (static vs. dynamic) and hands-free working. However, it also focuses on other aspects, such as communication, collaboration, and stress reduction.
3. The *fundamental requirements* focus primarily on technical aspects such as infrastructure, network connectivity, and interfaces to other information systems. Environmental characteristics, like dust, weather conditions, lighting, protective clothing, noise, and ergonomic conditions, are also important and as such are represented in the dividing complexity framework at the environmental conditions level. Finally, the requirements of individual users, such as their openness to new technologies and prior experience, are also taken into account.

The fourth and fifth categories of the process augmentability canvas are not dependent on the user and task but take a more holistic organizational perspective:

4. The *management perspective* examines augmentability from an economic perspective, taking into account strategic benefits and key performance indicators (KPIs) such as cost and time savings, and quality improvements.
5. The *social and organizational culture perspective* examines how AR applications are impacted by the social environment and organizational culture.

The process augmentability canvas builds on the theory of process augmentability (Yeo, 2017) and enriches it with empirical and literature insights to develop a tool for assessing process augmentability. The canvas considers not only process characteristics but also criteria that are impacted by the entire organization. This helps to identify the potential of AR in entire service systems and provides an understanding of the context, resources, technologies, and challenges involved in applying AR. By integrating the management perspective and the social and organizational culture perspectives, organizations can gain a better understanding of how these factors may influence the applicability of AR. The canvas is an example of a multi-level perspective to enhance the applicability of innovations in real-world scenarios.

By adopting a user-centric approach and perspective, a contribution to the user-centric design of processes is made. This approach ensures that the feasibility of AR is not only evaluated from a technical standpoint but also aligns with the needs of users. While it is important to align tasks and technology, considering a user-centric view can lead to increased user acceptance and adoption of AR applications within service systems. By considering technology acceptance (Davis, 1985; Davis et al., 1989; Venkatesh et al., 2003) and task-technology fit (Goodhue & Thompson, 1995) as important theories, an example of how to use these theories in AR research is provided. The canvas aligns with socially responsible innovation, considering ethical, social, and environmental factors in technology design and deployment. Integrating social considerations underlines the concept that service systems are *socio*-technical systems, emphasizing the importance of social considerations.

Publications P3 (Bräker & Semmann, 2022) and P4 (Bräker & Semmann, 2023b) make a theoretical contribution to the understanding of how AR can be used efficiently in organizational settings. P3 and P4 address the fragmented literature and limited real-world cases in AR applications and consolidate the literature in IS and HCI research. This contributes to the ongoing discourse on embedding innovations in organizations. Furthermore, publications P3 (Bräker & Semmann, 2022) and P4 (Bräker & Semmann, 2023b) contribute to a broader research agenda on digital and organizational change by providing a deeper understanding of the challenges and opportunities of emerging digital technologies. The two artifacts allow for a systematic exploration of AR potential within a service system engineering approach.

5.2.3 Suitability of Current Business Process Modeling Approaches for AR Processes

Research question RQ-2b seeks to identify which process modeling approaches and methods are applicable to AR. Following the logic of the dividing complexity framework presented in publication P3 (Bräker & Semmann, 2022), once the environmental conditions and requirements have been analyzed and a process for applying AR identified, the next step is to model the process to achieve a shared understanding. The dividing complexity framework refers to this as the *actions level*. By modeling and documenting the process, new insights can be gained about whether the process needs to be remodeled. Although the dividing complexity framework does not stipulate any specific recommendations on which process modeling approaches to adopt, publication P5 (Bräker & Semmann, 2021) provides a more in-depth analysis of this aspect.

While numerous process modeling approaches exist in research and practice, none of these focus exclusively on modeling AR processes. The literature review in publication P5 (Bräker & Semmann, 2021) revealed the extent to which state-of-the-art business process modeling reflects AR-based processes. Different criteria are considered for the analysis of the existing literature. Table 16 summarizes each criterion, provides a brief description and the key findings of the literature review. The identified research gaps suggest avenues for future research.

The analysis shows that current business process modeling approaches cover only a fraction of the aspects related to AR. This stresses the need for further research. Publication P5 (Bräker & Semmann, 2021) identifies research gaps and structures them for a research agenda with a holistic perspective, to guide future research and address the need for more comprehensive approaches to incorporating AR into business process modeling. By integrating the technological context into a business process modeling view, a more holistic perspective is achieved. When technology and processes are aligned, they can benefit from each other and enable novel user experiences.

Publication P5 (Bräker & Semmann, 2021) contributes to the ongoing discourse on the impact of digitalization in organizations. It systematically evaluates process modeling approaches regarding their applicability for innovative use cases. The publication contributes to the understanding of AR as a topic highly relevant to the design of service systems.

5.2.4 Systematic Classification of Interaction Techniques in AR Applications

Research question RQ-2c addresses which interaction techniques are used in AR applications and how AR interaction patterns can be systematically classified. Interactions are a crucial aspect to consider when designing AR applications, as they determine how users interact with the AR system, and via which touchpoints. Therefore, it is important to have a clear understanding of interaction techniques and patterns before implementing them.

Publication P3 (Bräker & Semmann, 2022) emphasizes the importance of interaction design yet lacks an overview of potential interaction techniques. Publication P3

Table 16. Analysis of business process modeling approaches for AR

Criterion	Description / central questions	Key findings	Avenues for future research
Technical requirements	Can the technical requirements for AR, such as interfaces to other IS, databases, documents, and network connections, be integrated into process modeling?	Literature covers approaches for requirements such as databases and interfaces. Additionally, measures for selecting hardware are proposed.	Future research should address the fundamental lack of representation of network infrastructure (addressed in publications P3, Bräker and Semmann, 2022, and P4, Bräker and Semmann, 2023b).
Interaction	Can the interaction patterns be represented in the AR application?	Literature covers interactions between actors. However, human-computer interaction is rarely considered.	Future research should investigate the specification of AR interaction patterns and how to support decision-making regarding suitable interaction patterns (addressed in publications P3, Bräker and Semmann, 2022, P6, Bräker, Hertel, and Semmann, 2022, and P7, Hertel et al., 2021)
Visualization requirements	Can inputs, outputs, AR tracking, and the need for 2D or 3D representations be included in the AR process modeling?	Literature covers inputs, outputs, and the integration of documents in business process models. Visualization possibilities are discussed.	Future research should integrate visualization representations in AR and explore the usefulness of such representations for displaying outputs. Further research should integrate tracking mechanisms and explore the need to differentiate between 2D and 3D visualizations. (addressed in publications P3, Bräker and Semmann, 2022, P4, Bräker and Semmann, 2023b, and P8, Bräker, Hertel, and Semmann, 2023b)

Management perspective	Can efficiency criteria such as time savings via timestamps, execution times, durations, and waiting times be represented?	Literature covers timestamps, durations, waiting times, and cost savings by improving execution times and reducing IT bottlenecks.	Already covered in the literature.
Comprehensibility and appropriateness	Is the approach comprehensible and appropriate for organizations with less experience in AR or process modeling?	The literature discusses the comprehensibility and appropriateness of different approaches.	Already covered in the literature.
Innovation	Are there approaches specifically for digital innovations?	Storyboards are rarely used to model innovative processes.	Future research should evaluate storyboards more thoroughly and identify additional approaches to model innovations (addressed in publications P3, Bräker and Semmann, 2022, and P8 Bräker, Hertel, and Semmann, 2023b).
Task-technology-embeddedness	Do approaches represent the steps in which AR plays a role and where media breaks occur?	At the time of the literature review, the topic has not yet been addressed in the literature.	Future research should address which process steps can be supported by AR and the mode of interaction. Additionally, it should investigate how to represent changes in interaction, such as media breaks (addressed in publications P3 Bräker and Semmann, 2022, and P4 Bräker and Semmann, 2023b).

Augmented reality relation	Do process modeling approaches directly address AR?	At the time of the literature review, topic has not yet been addressed in the literature.	Future research should address specific requirements, such as those resulting from increased immersion and new interaction techniques, as well as new demands and challenges for AR in business process modeling.

highlights the need for further elaboration on interactions in AR scenes, and for the specification of AR interaction patterns. Interactions could be embedded at the AR scene level of the dividing complexity framework but were ultimately not considered in more detail due to complexity reasons.

In order to bridge this gap and conduct a comprehensive investigation of AR interactions, two taxonomies are developed as part of this dissertation. Both taxonomies explore AR interactions, but from different perspectives: one from the IS perspective (Bräker, Hertel, & Semmann, 2022), and the other from the HCI perspective (Hertel et al., 2021).

Publication P6 (Bräker, Hertel, & Semmann, 2022) focuses on atomic interactions in AR systems from an IS perspective. A taxonomy for the systematic classification of interactions for AR was developed to support the design of service systems and the development of AR applications. The taxonomy consists of seven dimensions and 29 characteristics (see Table 17). Unlike the approach of Nickerson et al. (2013), not all dimensions are assumed to be mutually exclusive. Due to the multimodality of AR applications, the dimensions of input and output modality are not mutually exclusive. This means that more than one input and output modality can be implemented in AR interactions.

The taxonomy provides a classification of the following aspects: the number of interacting users (D1), the hardware used for the interaction (D2), the modalities used for the input (D3), and accordingly, the senses addressed by the output (D4). In addition, the taxonomy classifies the goal of the interaction (D5), what or who the user interacts with (D6), and how the interactions can be combined in sequence (D7).

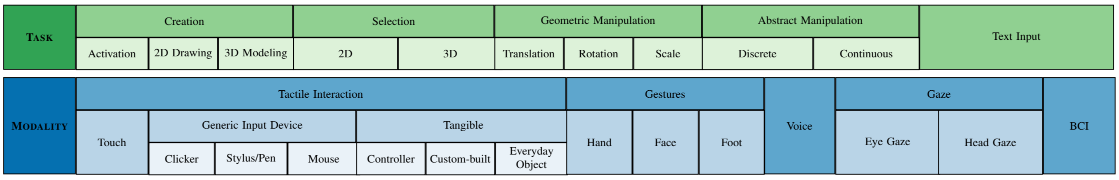
The various taxonomy dimensions allow for a systematic classification of interactions and interaction patterns. This facilitates the analysis and comprehension of interactions used in AR systems, and the selection of interactions for newly developed AR systems. By describing the solution space for AR interactions, the taxonomy

Table 17. Taxonomy of atomic AR interactions (Bräker, Hertel, & Semmann, 2022)

Dimensions	Characteristics									
D_1 Users per device	Single-user	Multi-user								
D_2 Hardware	Mobile AR	HMDs	Projection-based AR	Desktop AR						
D_3 Input modalities	Voice	Touch	Gestures	Free body movement	Gaze	Sensor	Eye-tracking	Video/ image	BCI	Generic input device
D_4 Output modalities	Haptic feedback	Visual feedback	Auditory feedback							
D_5 Interaction implementation	Virtual object selection	Physical object selection	Virtual object manipulation							
D_6 Interactivity relation	Digital objects	Physical objects	People							
D_7 Sequence of interactions	Frequency	Duration	Variety	Concurrency						

contributes to the understanding of AR interactions and guides the design of AR applications. The emphasis on atomic AR interactions highlights common patterns and dimensions that apply to various domains. The taxonomy underlines the evolving complexity of AR inputs and outputs, which is reflected in the non-mutually exclusive dimensions. This demonstrates the increasing prevalence of multimodal input.

This multimodality is also reflected in the second taxonomy presented in publication P7 (Hertel et al., 2021), which is limited to immersive AR interaction techniques and consequently does not include mobile AR, projection-based AR, or desktop AR. Therefore, it can be considered a detailed exploration of the head-mounted display (HMD) hardware dimension explained in the taxonomy in publication P6 (Bräker, Hertel, & Semmann, 2022). Subsequently, two dimensions are derived, namely, task and modality (see Figure 14). The granular tasks used singly or in combination with others, describe the goal of the interaction. The HCI literature generally focuses on more granular interactions, distinguishing between creation, selection, manipulation (geometric or abstract), and text input. Therefore, the taxonomy from the HCI perspective provides a more comprehensive description of the task than the taxonomy from the IS perspective. The HCI taxonomy provides more detailed modalities, allowing for further and more granular classification. The modality characteristics include tactile interaction (involving touch, generic input devices, such as a mouse, and tangible objects), gesture, voice, gaze, and brain-computer interface (BCI). While some of these modalities are reflected in the IS taxonomy, they are clustered differently to provide a better overview.



Task	Creation			Selection		Geometric Manipulation			Abstract Manipulation		Text Input
	Activation	2D Drawing	3D Modeling	2D	3D	Translation	Rotation	Scale	Discrete	Continuous	

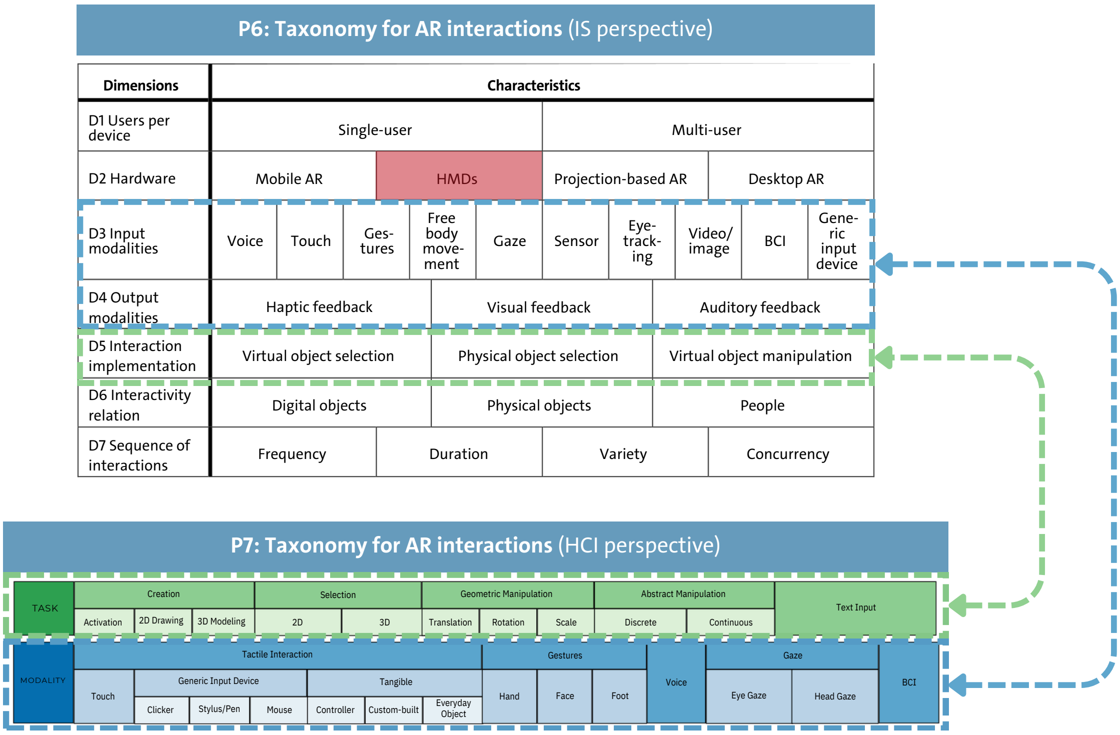
Modality	Tactile Interaction							Gestures			Voice	Gaze		BCI
	Touch	Generic Input Device			Tangible			Hand	Face	Foot		Eye Gaze	Head Gaze	
		Clicker	Stylus/Pen	Mouse	Controller	Custom-built	Everyday Object							

Figure 14. Taxonomy of immersive AR interactions from publication P7 (Hertel et al., 2021)

The HCI taxonomy of immersive AR interactions contributes to research by providing a thorough and fine-grained overview. This overview can serve as a common ground for discussion, identification of related interaction techniques, and evaluation of new ones. Additionally, the holistic view of immersive AR interactions clarifies conflicting definitions in previous research. The taxonomy can guide the development and selection of future AR interaction techniques by identifying emerging interaction trends and research gaps. It also serves as a foundation for future research investigations.

When comparing and relating the two taxonomies (see Figure 15), the HCI taxonomy focuses only on immersive AR, i.e., HMDs as hardware manifestations. In addition, the modality dimension of the HCI taxonomy classifies the input and output modalities of the IS taxonomy in more detail, providing a more extensive specification of generic input devices, including clickers, styluses/pens, and mice. This level of granularity was not found in the IS literature, which only features the term “generic input device”. Additionally, the concept of tangible objects is not mentioned in the IS literature but is present in the HCI literature, which includes controllers, custom-built objects, and everyday objects. While the HCI taxonomy distinguishes between hand, face, and foot gestures, the IS taxonomy goes further by including free body movement, which is not mentioned separately in the HCI taxonomy. Also, sensor inputs are not mentioned in the HCI taxonomy.

The task dimension of the HCI taxonomy is reflected in the interaction implementation dimension of the IS taxonomy. While the IS taxonomy only distinguishes between virtual object selection, physical object selection, and virtual object manipulation, the HCI taxonomy offers more task characteristics. Creation is not discussed in the IS literature but rather in the HCI literature and can be categorized into activation, 2D drawing, and 3D modeling. Selection, according to the HCI taxonomy, can be either 2D or 3D, while the IS taxonomy distinguishes between virtual and physical object selection rather than dimensionality. In the HCI taxonomy, the



P6: Taxonomy for AR interactions (IS perspective)

Dimensions	Characteristics
D1 Users per device	Single-user Multi-user
D2 Hardware	Mobile AR HMDs Projection-based AR Desktop AR
D3 Input modalities	Voice Touch Gestures Free body movement Gaze Sensor Eye-tracking Video/image BCI Generic input device
D4 Output modalities	Haptic feedback Visual feedback Auditory feedback
D5 Interaction implementation	Virtual object selection Physical object selection Virtual object manipulation
D6 Interactivity relation	Digital objects Physical objects People
D7 Sequence of interactions	Frequency Duration Variety Concurrency

P7: Taxonomy for AR interactions (HCI perspective)

TASK	Creation			Selection		Geometric Manipulation			Abstract Manipulation		Text Input
	Activation	2D Drawing	3D Modeling	2D	3D	Translation	Rotation	Scale	Discrete	Continuous	

MODALITY	Tactile Interaction							Gestures			Voice	Gaze		BCI
	Touch	Generic Input Device			Tangible			Hand	Face	Foot		Eye Gaze	Head Gaze	
		Clicker	Stylus/Pen	Mouse	Controller	Custom-built	Everyday Object							

Figure 15. Relations between the two interaction taxonomies from publications P6 (Bräker, Hertel, & Semmann, 2022) and P7 (Hertel et al., 2021)

manipulation of objects can be either geometric or abstract. Geometric manipulation of objects can be achieved through translation, rotation, and scaling. Abstract manipulation can be either discrete or continuous. In the IS taxonomy, virtual object manipulation subsumes any manipulation of virtual content. In addition, the HCI taxonomy concludes with text input, which is not explicitly mentioned in the IS taxonomy.

When comparing the two taxonomies, it becomes evident that the literature in HCI research is much more detailed and focused on specific tasks, while IS literature does not examine tasks and modalities in as much detail but considers the socio-technical environment, e.g., reflected in the number of users per device.

5.2.5 Design of AR Applications and Specification of Requirements for AR Development

When considering how organizations can systematically use AR (see RQ-2), once an appropriate process has been defined, modeled, and documented, the question arises of how to specify and design an AR application for this purpose. The goal is to outline the desired look and feel of the AR application to effectively and easily ensure a shared understanding. Because AR is an immersive technology, prototyping with simple wireframe sketches is not feasible. This raises the question of how organizations can specify, design, and document the design of an AR application.

The dividing complexity framework presented in publication P3 (Bräker & Semmann, 2022) provides an approach for specifying the appearance and technical details of AR scenes. Therefore, the framework suggests describing each process step as at least one AR scene. By using the process steps as a guideline, a seamless experience can be ensured, and no steps are omitted. The AR scene description then contains a visual description of all the AR elements that need to be integrated. It is recommended to describe the AR scenes visually, such as photos of the user's surroundings from a first-person perspective, as this eliminates the need for AR programming skills. For example, a photo can depict a workbench, and users can then easily draw augmentations into this image as if they were wearing an HMD or holding a tablet in front of them.

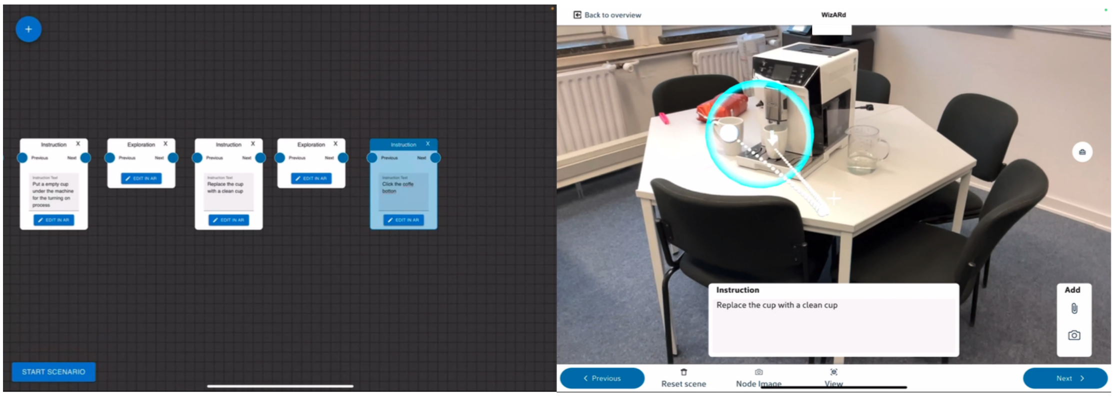
However, static documentation of the user perspective alone may not be sufficient to explain to developers how the AR objects should behave. The technical specification level of the framework from publication P3 (Bräker & Semmann, 2022) aims to describe the behavior and characteristics of the AR elements in each AR scene. Therefore, a markup approach is chosen that represents a clear and easy-to-understand notation that contains all the necessary information about an AR element. However, other forms of notation may also be feasible.

The framework provides a straightforward and accessible method for translating ideas from the mind onto paper. However, it is possible to document processes in a more immersive and interactive way that already looks like the actual finished AR application. This can be achieved, for example, with an AR authoring application that enables the development of AR applications without programming and allows users to drag and drop AR elements directly into reality to see how they look, behave, and feel when interacted with. This concept is explored in publication P8 (Bräker, Hertel, & Semmann, 2023b) and is described in the following section.

5.2.6 Design Principles for No-Code AR Authoring Tools

AR authoring tools allow the creation of AR prototypes without programming knowledge. RQ-2d addresses the design elements and specifications that an AR authoring tool should have in order to serve as a tool for the implementation of AR prototypes without programming knowledge and to improve their accessibility for inexperienced users.

The ability to create and implement AR prototypes without programming skills is a significant advantage for organizations seeking to leverage AR technology. In publication P8 (Bräker, Hertel, & Semmann, 2023b), design knowledge is generated on how no-code AR authoring tools can be designed to improve accessibility for users. Design principles for such AR authoring tools are derived by evaluating a mobile AR authoring application that follows the WYSIWYG principle. The mobile AR authoring application allows the creation and viewing of AR instructions for processes on the same device, even within the same application. It has three main screens: (1) a node editor for modeling the process, (2) an editor for placing AR objects in a scene and creating the AR application, and (3) a preview mode for the created AR instruction.



Put a empty cup under the machine for the turning on process

Replace the cup with a clean cup

Click the coffe botton

Instruction: Replace the cup with a clean cup

Figure 16. Screenshots from the AR authoring tool—node editor (left) and AR editor with several AR elements in the scene (right) (Bräker, Hertel, & Semmann, 2023b)

The node editor screen addresses the need to document process steps as discussed in publications P3 (Bräker & Semmann, 2022) and P5 (Bräker & Semmann, 2021). It uses a simple visualization with one "node" for each step and the ability to connect them to model the sequence of steps. The AR editor provides a more immersive way to select and arrange AR elements for each scene. Following the recommendation of publication P3 (Bräker & Semmann, 2022), a separate AR scene is created for each process step. The AR preview mode allows direct evaluation of the created scene from the user's perspective. Figure 16 shows screenshots of the AR authoring tool with the process modeling view as node editor (left) and the AR scene with AR elements (right).

Fifteen design principles (DPs) were derived from the results of the evaluation of the no-code AR authoring application. They are grouped into eight dimensions that describe how no-code AR authoring applications should be designed (see Table 18). The design principles encompass a multitude of facets, including ergonomic use (DP1), expectation management (DP2), application usage guidance (DP3-4), interaction principles (DP5-7), process modeling support (DP8), AR information encoding (DP9-11), AR element positioning (DP12-13), and tracking (DP14-15).

The design principles encompass a multitude of relevant facets and offer guidance on the design of no-code AR authoring tools. The AR authoring tool has been demonstrated to be a user-centric, lightweight, and seamless means of enhancing processes without requiring programming expertise. The low cost of piloting AR applications allows organizations to gain initial insights into the benefits of applying AR without significant financial investment. Consequently, the design principles contribute to the concrete understanding of such tools and provide design knowledge on how to design and develop them.

5.3 Contribution to the Exploration of Research Areas with Graph Databases—Insights into Conceptual AR Research

The third research question (RQ-3) addresses the investigation of conceptual AR research with the use of graph databases to represent causal models for exploring new areas of research. In publication P9 (Bräker & Semmann, 2023a), a graph database is used to represent paper information from a literature review. The paper information includes metadata and content from structural equation models (SEMs). Causal relationships within one publication and between different publications can be represented as a graph. By integrating paper information and causalities into an overarching graph and storing it in a graph database, novel insights into conceptual AR research can be attained. The methodology is based on preliminary work by Song, Watson, and Zhao (2021) and Song, Watson, Zhao, and Kelley (2021), who propose a graph database approach for analyzing causal models (see Chapter 3.3.10).

Table 18. Design principles for no-code AR authoring tools (Bräker, Hertel, & Semmann, 2023b)

Dimension	**Title of design principle**
Ergonomics	**DP1:** Consider hardware requirements and limitations
Expectation management	**DP2:** Manage and shape expectations for app use and outcomes in the beginning
Guidance	**DP3:** Limit free exploration to guide familiarization with the app **DP4:** Provide tutorials, tooltips, workflow patterns, and best practices
Basic interactions	**DP5:** Consider traditional interaction design and usability patterns **DP6:** Do not let users do unnecessary tasks that can be automated **DP7:** Empower power users
Process modeling	**DP8:** Enable the modeling of complex processes
Extensive information encoding	**DP9:** Enable textual descriptions to enrich AR elements **DP10:** Provide a variety of AR elements and style options **DP11:** Allow adding, editing, and enriching the scene with photos and videos
AR element positioning	**DP12:** Facilitate the spatial perception of AR elements **DP13:** Support precise positioning of AR elements
Tracking	**DP14:** Tracking accuracy is essential **DP15:** Implement object tracking

This was adapted in order to make the approach specific and applicable to AR research. The modifications to the original approach and the revised metamodel are described in detail in Chapter 5.4.3 and in publication P9 (Bräker & Semmann, 2023a).

The graph database approach allows for the identification and visualization of relations and patterns that are not immediately apparent when analyzing literature in a traditional manner. This approach provides a holistic and encompassing view of the research landscape, facilitating the identification of correlations, trends, and research gaps. In this way, a deeper understanding of AR literature and the AR research field can be gathered. Graph databases support the extendibility of the graph by integrating new publications. Moreover, they facilitate the dynamic exploration of data through querying. Graph databases are capable of storing vast amounts of complex data in a structured manner. This adaptability and flexibility make them a valuable approach in the ever-evolving landscape of AR research.

5.3.1 Constructs in Conceptual AR Research

One objective of the analysis of the AR literature using the graph database is to identify the concepts and constructs employed to model causalities in AR. With regard to technologies, mobile AR technology is predominant. Mobile AR offers a convenient and accessible approach for users to engage with. Furthermore, some publications do not even specify the AR technology utilized and describe independent concepts, for instance, focusing on interaction techniques in general. AR glasses and HMDs are rarely mentioned in publications. This indicates a potential research gap regarding the exploration of the benefits and challenges associated with HMDs. Future research could investigate causalities when using HMDs in comparison with other technologies, such as mobile AR.

The main topics were consumer applications related to shopping, retail, and Pokémon Go, which explains the prevalence of mobile AR. The predominance of consumer applications indicates a lack of professional and business-oriented research. Thus, future research could address this research gap. More empirical studies are needed to explore the actual outcomes and benefits of AR implementation in real-world settings. Some publications focus on education and training cases, but only a few address privacy and health implications. Examining how AR affects privacy and health may help decrease concerns and guide further research in this area.

Therefore, publication P9 (Bräker & Semmann, 2023a) contributes to new domain knowledge on AR, such as the predominant use of mobile AR and topics related to consumer environments, and research gaps, like the sparse use of HMDs.

5.3.2 Guiding Theoretical Perspectives in AR Research

The other objective of the analysis was to identify the guiding theoretical perspectives in AR research. It was found that the field of AR research is immature and exploratory. The constructs applied are general rather than AR-specific. Elements of the technology acceptance model (TAM) (Davis, 1985; Davis et al., 1989) are prominent in the SEMs of the publications, which means that it is the most used and influential theory. However, only acceptance in specific cases is examined, and there is no overarching acceptance model for AR. Besides acceptance, the theories applied are quite heterogeneous. The immaturity and exploratory nature of the publications are also reflected in the analysis of the authors, which shows that the field of SEM research on AR is very heterogeneous and diverse.

Publication P9 (Bräker & Semmann, 2023a) contributes to the understanding of the theoretical perspectives that guide AR research. The finding that TAM and acceptance theories are prevalent shows that AR research is dominated by theories that were not natively developed for AR technologies.

5.4 Contribution to Methodology

This dissertation also makes a number of methodological contributions by advancing and specializing methods. On the one hand, the think-aloud method is adapted for use in less lab-driven environments, facilitating the exploration of real-world use cases. On the other hand, the think-aloud method is enriched with screen captures when thinking aloud in an application, integrating IT artifacts more strongly into thought analysis. In addition, the metamodel for the graph database approach for exploring and analyzing literature was adapted for the representation of AR publications.

5.4.1 Thinking Aloud in Non-Standardized Scientific Contexts—Enriching Think-Aloud Protocols with Video Material from the First- and Third-Person Perspective

In scientific contexts similar to laboratory environments, thinking aloud has been shown to be a valuable method for gaining insight into how users perform tasks (Boren & Ramey, 2000; van Someren et al., 1994). Laboratory settings are characterized by their controlled environments, which ideally include a quiet environment and a standardized task for all study participants. However, in some cases, it may not be possible to guarantee a controlled environment, and in such circumstances, the think-aloud protocol may not be appropriate.

However, this methodology still has great potential not only for understanding users and their needs, struggles, and behaviors, but also for generating design knowledge such as user-centered requirements. In service systems engineering, the generation of design knowledge in real-world settings is preferable to that in laboratory settings. Therefore, the question arises as to how the think-aloud methodology can be adapted for use in more challenging work environments characterized by non-standard scientific settings.

In publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023), an enrichment of the think-aloud method was proposed by adapting it to the conditions of the demanding service of hydrographic surveying. As described in Chapter 3.2.2, the hydrographic surveying takes place on a waterborne vessel, where disruptive environmental factors (waves, noise, etc.) can affect the suitability of the think-aloud method, where usually only the spoken words are recorded and transcribed. On the one hand, during soil sounding, the skipper is exposed to noises, whether it be radio conversations with other water traffic participants, or just listening to the radio (comparable to when driving a car). On the other hand, the skipper's behavior is highly dependent on taking in the surrounding context and circumstances, which can vary from task to task.

The think-aloud method was therefore adapted by enriching the transcripts with video material from two perspectives (see Figure 17). To accurately capture the skipper's perspective, a small camera was mounted on the skipper's head to provide a first-person view of the video image. View shifts and changes in the field of view were apparent and could be taken into account during transcription. Since the exact eye movements of the skippers were not required, no eye-tracking equipment was needed. The video footage from a first-person perspective was sufficient for this purpose. Additionally, it was crucial to capture the environment outside the vessel, as the skipper's actions are highly reactive to external stimuli. Observing the skipper's behavior, facial expressions, gestures, and movements provides valuable insight. Therefore, a second camera was installed to capture the skipper from a third-person perspective.

Combining the audio recordings with these two video angles allowed for effective data analysis. This enriched the transcripts with actions that occurred and a description

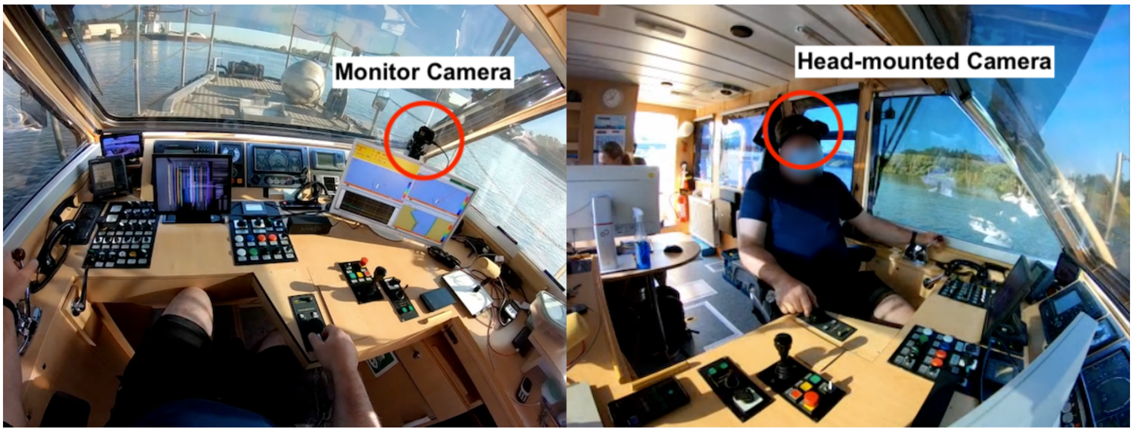


Figure 17. Camera positions for capturing video footage from the first- and third-person perspective (Bräker, Osterbrink, et al., 2023)

of the situation (for example, a ship crossing the path, the ship navigating in a small area, or proximity to the shore), for which special concentration is required. In addition, the audio tracks from two different cameras were used to select the one with the best clarity and to better eliminate noise.

Publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023) contribute to the methodology by enriching the think-aloud methodology and evaluating it in a real-world scenario. The enrichment and adaptation of the methodology have been proven to be highly beneficial, encouraging researchers to use this method in non-standard scientific settings.

5.4.2 Tracking of User Behavior and Interactions with AR Applications—Enriching Think-Aloud Protocols with Screen Captures

In publication P8 (Bräker, Hertel, & Semmann, 2023b), the think-aloud method was adapted and extended to evaluate interactions with AR applications. For this purpose, screen recordings of the user interacting with the AR application were included. This enabled the inclusion of user behavior in the think-aloud transcript, as well as the coding of actions performed while using the application. The use of screen recordings allowed for a more comprehensive understanding of user behavior, which is particularly crucial in the context of AR because, for AR applications, it can be challenging to identify user interactions and pain points. By observing the user's actions, it becomes easier to reconstruct and analyze their experience with the application.

The integration of the interactions with the AR application into the think-aloud protocols contributes to the methodology. The utilization of screen recordings proved to be a valuable tool for gaining insights into the user experience, usability, and interactions with the AR application under evaluation. This enhanced think-aloud methodology improved the overall understanding of user behavior. The facilitation of detailed analysis contributes to the development of a more user-centered approach to understanding and generating design knowledge for AR applications.

5.4.3 Extending a Graph Database Approach by Providing an Adapted Metamodel for Representing AR Publications

The approach of analyzing causal models from publications using graph databases was initially developed in previous work by Song, Watson, and Zhao (2021) and Song, Watson, Zhao, and Kelley (2021) and is described in detail in Chapter 3.3.10. In their approach, however, only a fraction of information from each publication is encoded. This includes information about the publication and the authors, the SEM described in the publication, the associated elements and definitions, and the underlying theory. The initial metamodel by Song, Watson, and Zhao (2021) and Song, Watson, Zhao, and Kelley (2021) is designed to represent SEM publications without any domain context. From a methodological standpoint, the analysis of SEMs with graph databases is highly beneficial, as it facilitates enhanced structuring and simplified information extraction. Nonetheless, for the exploration of the field of AR research it is better to implement a number of modifications to the original metamodel.

The metamodel proposed by Song, Watson, Zhao, and Kelley (2021) is designed to represent publications with SEMs independently of their context. Consequently, there is potential for adapting and refining the metamodel for AR publications. In publication P9 (Bräker & Semmann, 2023a), the metamodel is adapted and refined to represent AR publications more thoroughly. The refined metamodel is shown in Figure 18. It still includes a publication node, which represents the publication's citation and digital object identifier (DOI). As proposed by the original metamodel, one publication is written by one or more authors. The model node was eliminated because it was assumed only to have one relevant SEM within the publication. Consequently, the SEM elements are directly connected to the publication node. The theory node was also refined so that a publication directly applies a theory. In order to enhance the metamodel's specificity to AR, a node was introduced to represent the topic addressed in the publication (e.g., Pokémon GO), and the AR technology it refers to (e.g., mobile AR). By eliminating the model node, the connections between SEM elements and the publication node were streamlined, facilitating easier data extraction and synthesis. Consequently, the refined metamodel provides a more comprehensive and nuanced approach to understanding the relationships between different elements in SEM publications in the field of AR. Thus, it contributes to a more efficient exploration of the vast landscape of AR literature and the different facets of AR publications.

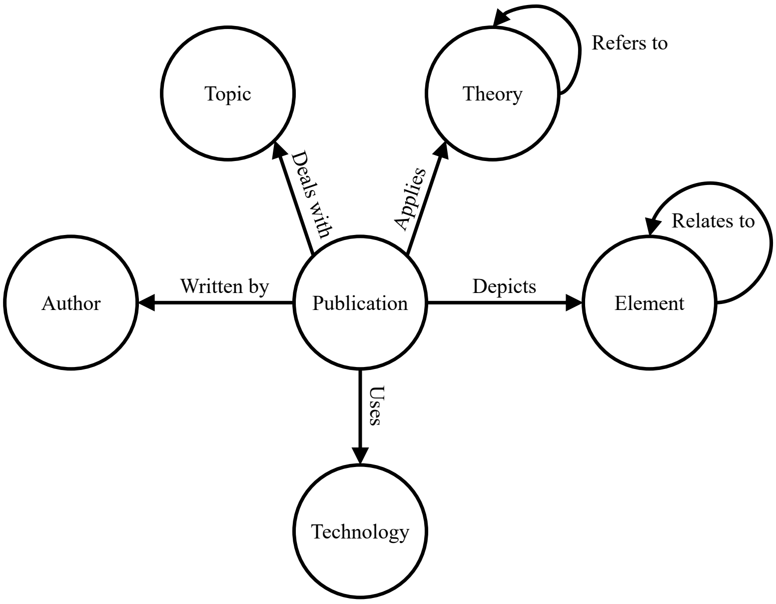


Figure 18. Refined metamodel (Bräker & Semmann, 2023a)

The encoding of SEM publications in the field of AR into a graph database and subsequent querying of this database can provide valuable insights into the current state of the literature. The application of the metamodel offers insight into authors, SEM elements, theories, topics, and technologies used in publications dealing with AR. This facilitates a more comprehensive understanding of AR research and how AR is used in SEM. The in-depth analysis of the body of knowledge reveals the constructs used to explain causalities regarding AR. This approach allows for a comprehensive overview of the prevailing patterns and trends in SEM research on AR. The revised metamodel contributes to the methodology, as graph databases representing publication content are rather uncommon and novel in IS research. Following on from the research of Song, Watson, and Zhao (2021) and Song, Watson, Zhao, and Kelley (2021), a contribution is made through further development and AR specification.

6 Practical Contribution

This dissertation offers several practical contributions, thus aligning with the aim of design science research (DSR), which is to generate design knowledge and integrate theory and practice (Hevner, 2007; Hevner et al., 2004; Peffers et al., 2007). Likewise, this dissertation's theoretical contributions contribute to practice, as each of the developed artifacts provide design knowledge that is relevant to practice and offer solutions for real-world challenges faced by practitioners.

Furthermore, this dissertation offers valuable tools for practitioners, enabling them to explore and realize the potential of augmented reality (AR). The no-code AR authoring tool facilitates the development of proof of concepts without the need to write a single line of code. As the contributions are both user-centric and consider organizational perspectives with actors using technologies and integrating resources, the resulting design knowledge can be applied to the design of service systems. This approach facilitates the integration of research findings into practice, thereby enabling practitioners from diverse industries to benefit from the results and apply the developed artifacts to their specific contexts.

In addition to the design knowledge developed in the publications included in this dissertation, the three publications that were indirectly influenced by this research (see Chapter 4.1) contribute to the practical application of AR in organizations. These three publications are targeted at a more practice-oriented audience, and serve to disseminate the results developed in the publications included in this dissertation in terms of both practice and research dissemination (Bräker, Hertel, Briede, et al., 2022; Bräker et al., 2021; Bräker, Osterbrink, et al., 2022).

6.1 Requirements for Using AR in Complex and Demanding Service Systems

Publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023) that address the first research question (RQ-1) contribute to practice regarding the use of AR in complex and demanding service systems. The developed user-centered requirements provide design knowledge for the use of AR in hydrographic surveying. These requirements serve as a foundation for a prototypical implementation in practice. Consequently, developers can use these requirements as a guide when implementing AR applications and making design decisions. Depending on the use case, environment, and tasks, requirements can be weighted differently and prioritized accordingly for implementation.

The challenge of multidimensional tracking is particularly relevant for AR developers who seek to incorporate tracking mechanisms. Seeing an instantiation of an AR prototype in a dynamic environment on a waterborne vessel can encourage developers to consider new use cases—and edge cases—to improve existing tracking mechanisms.

The insights gained from the study and the requirements are transferable to other cases and thus relevant to a broader audience of practitioners (see also Chapter 5.1.2). The need for multitasking, collaboration, mobile environments, and safety-criticality may characterize these cases. Thus, the results can guide practitioners in a wide range of industries.

6.2 Systematically Assessing AR Potentials in Organizations

The publications P3-P8 (Bräker, Hertel, & Semmann, 2022, 2023b; Bräker & Semmann, 2021, 2022, 2023b; Hertel et al., 2021) that address the second research question (RQ-2) contribute to practice by supporting the systematic assessment of AR potentials in organizations. These publications develop and discuss various artifacts that foster a better understanding and provide guidance on the application of AR in organizations. The reduction of barriers is particularly beneficial for organizations with limited resources and knowledge. By supporting organizations, resources such as money, skills, and knowledge can be saved. The generated design knowledge assists practitioners in efficiently using AR in practice, and can support their decision-making. It also provides a basis for sharing knowledge among different stakeholders, including technical and non-technical experts. The knowledge generated with these publications serves as practical guidance for designers and developers. The combination of these artifacts provides practitioners with a comprehensive and holistic guide on how to exploit the full capacity that AR represents to their organizations.

The dividing complexity framework presented in publication P3 (Bräker & Semmann, 2022) contributes to the successful introduction of AR into organizational contexts, thereby reducing the barriers to AR application. The framework delineates specific steps, represented by the multiple layers that serve as a starting point for applying AR in organizations. The framework contributes to practice by assisting practitioners in understanding AR and guiding them in applying AR in their organization. The step-by-step incremental approach facilitates a systematic yet guided exploration and analysis, as well as the definition of AR use cases. It contributes to understanding the requirements and preconditions for AR, and identifying the benefits and resources needed. The framework allows for the analysis of potential services by multiple actors with diverse backgrounds and expertise. This also enables actors with limited AR experience to approach AR. Further, by enhancing collaboration among actors, the framework provides a basis for shared understanding. When practitioners use the framework to design an AR solution, the outcome serves as a foundation for prototypical implementation. A detailed description of the prototype (i.e., relevant information for a later implementation) is provided, which can be handed over to AR developers for implementation. Overall, the framework reduces the complexity of approaching AR and designing AR solutions.

The process augmentability canvas, described in publication P4 (Bräker & Semmann, 2023b), is a decision-making tool for organizations that supports structured, criterion-based, informed decision-making. By taking a user-centric approach, the canvas encourages organizations to approach AR in a user-centric manner. For organizations with limited resources, the canvas can facilitate an efficient and effective realization of the potential benefits.

The process augmentability canvas is a tool that allows for the evaluation of organizational processes that might be suitable for AR applications. It defines the characteristics that influence their suitability, thereby assisting practitioners in finding an AR “sweet spot”. The canvas also allows for the adaptation of weightings of criteria and specific safety and security measures, often based on regulations. Furthermore, it enhances communication and collaboration, reducing misunderstandings between stakeholders and achieving a shared understanding. The canvas facilitates the alignment of expectations and priorities among various stakeholders, as well as the identification of risks and benefits to be considered when selecting a process to be augmented. Consequently, it contributes to organizational learning and knowledge management by documenting the rationale behind decisions and insights into the application and limitations of AR. The canvas proposes and facilitates two practical modes of analysis. The first is a creative mode, in which business units propose initial processes and identify areas that need adaptation to fulfill criteria for piloting. The second mode of analysis is structured. In this mode, all processes are analyzed and assessed by defining must-have criteria and going through the entire canvas. As a result, all suitable processes are identified.

The publication P5 (Bräker & Semmann, 2021) offers guidance for practitioners seeking a business process modeling approach to model AR processes. It provides insights into what should be considered in AR process modeling and which existing modeling languages are appropriate for AR. The publication emphasizes the importance of aligning the modeling approach with the specific requirements of AR. By following the guidance provided, practitioners can make informed decisions regarding the most effective approach to modeling AR processes. The publication P5 (Bräker & Semmann, 2021) contributes to supporting practitioners in selecting an appropriate method to model and document their processes. For example, simple methods such as flowcharts are stated to be sufficient, which also reduces barriers for organizations because they do not need to adopt a complex modeling language to represent their AR processes. Therefore, it helps to increase the accessibility of AR.

The taxonomies presented in publications P6 (Bräker, Hertel, & Semmann, 2022) and P7 (Hertel et al., 2021) contribute to practice by providing a systematic overview and, thus, a selection catalog for AR interactions. By thoroughly describing the solution space for AR interactions, the taxonomies guide the practical design and development of AR solutions and interactions. The taxonomies can be employed to assess and develop novel interaction techniques. The taxonomy presented in publication P7 (Hertel et al., 2021) is focused on AR tasks. It serves as a foundation for developers to identify common unimodal and multimodal methods for performing specific tasks in AR. The taxonomy presented in publication P6 (Bräker, Hertel, & Semmann, 2022) underscores the importance of selecting the appropriate hardware for any specific use case. Furthermore, it assists in the informed selection of appropriate hardware.

Both taxonomies contribute to practitioners' understanding of AR interactions and patterns.

The design principles described in publication P8 (Bräker, Hertel, & Semmann, 2023b) guide the design and development of no-code AR authoring tools, and address a broad range of facets that practitioners should consider. The AR authoring tool contributes to the broadening of AR applications in practice and the reduction of barriers by providing a lightweight and seamless way to develop AR applications in a no-code manner, without any programming skills being required.

Additionally, it empowers domain experts with no technical or programming knowledge to identify AR potentials and pilot their first AR applications quickly and without much effort, thus reducing the need for a lengthy training period. The AR authoring tool allows for faster prototyping of AR solutions, thereby enabling a diverse range of users to engage in the development of AR prototypes.

The artifacts developed in this dissertation can be combined to cover the entire process, from the initial consideration of using AR to piloting the prototype. The artifacts contribute to practice by providing practitioners with a comprehensive set of tools. Through the synergistic combination of artifacts and their applicability in practice, practitioners are guided along the entire journey of systematically assessing AR potential.

7 Limitations

As with any research project, this dissertation is not without limitations. This section discusses the general limitations of the included publications. The specific limitations of each publication are addressed directly within the publications themselves.

The methodological approaches used in this thesis are subject to several limitations. First, it is important to mention that methodology is always influenced by the researcher's experience, background, and prior knowledge. In other words, the researcher can be biased (Recker, 2021; Yin, 2018). Second, the methodology is constrained by the availability of data, the research participants, the specific circumstances of the case study research, and any organizational requirements that allow external organizations to provide data and resources for research (Yin, 2018).

Methodological limitations regarding the sample of study participants arise in several publications. The think-aloud method applied in publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023), which aimed to gain insights into hydrographic surveying, involved only experienced skippers as participants, due to legal and safety requirements. The sessions took place in a real-world setting during daily water depth measurements. The study participants were experienced skippers with 13 to 15 years of experience in this task. The requirements outlined in these publications may be different for inexperienced skippers with less tactical knowledge and routine. It can be assumed that inexperienced skippers would be even more dependent on augmented reality (AR) assistance to compensate for their lack of knowledge and routine. Therefore, it is reasonable to expect that requirements would increase if the study were replicated with less experienced skippers. However, given the dearth of knowledge about the use of AR in such safety-critical environments, this limitation is considered relatively minor, as this dissertation presents the first requirements for AR in such a demanding and complex scenario.

The user study conducted in publication P8 (Bräker, Hertel, & Semmann, 2023b) is also limited in its sample of participants. The evaluated AR authoring tool aims to support practitioners and technically inexperienced users without programming experience. However, for its first evaluation, it was evaluated with participants from academia, including students and staff from the Department of Informatics. The study was conducted in a controlled laboratory environment that allowed for the collection of both qualitative and quantitative data, including completion time. This controlled environment ensured comparability across participants. The involvement of members of the computer science department facilitated the recruitment of participants. However, the sample remains limited. Expanding the sample to include a broader and more diverse range of participants, including practitioners with limited AR programming experience, may improve the validity of the findings. Additional guidance may be needed for inexperienced practitioners, which could further extend the design principles derived from the study.

Another limitation is that literature reviews, although following a systematic approach, still have shortcomings (vom Brocke et al., 2009; vom Brocke et al., 2015; Webster & Watson, 2002). Although these limitations are well-known in research, they are worth discussing here. Systematic literature reviews were conducted in several publications, including publications P4, P5, P6, and P7 (Bräker, Hertel, & Semmann, 2022; Bräker & Semmann, 2021, 2023b; Hertel et al., 2021). The selection of outlets in all publications was thorough and careful, based on specific criteria. In this way, high-quality journals and conferences were selected for each publication. However, it is important to note that only a fraction of outlets were covered, which limits the scope of the literature considered. Publication P4 (Bräker & Semmann, 2023b) yielded limited results in the literature review. Although expanding the search may have increased the number of articles, it may also have reduced their quality and validity. The same limitations apply to publication P6 (Bräker, Hertel, & Semmann, 2022). However, the ending conditions for the development of the taxonomy were met with the results of the literature review, indicating that the taxonomy is still exhaustive. While the taxonomy from an Information Systems (IS) perspective in publication P6 (Bräker, Hertel, & Semmann, 2022) covers some HCI outlets, the taxonomy from an Human-Computer Interaction (HCI) perspective in publication P7 (Hertel et al., 2021) mainly includes HCI outlets, thus addressing this limitation. However, the HCI taxonomy (Hertel et al., 2021) also has limitations, and the literature review yielded few results. The IS taxonomy is complementary to the HCI taxonomy as it covers more literature in the IS field and expands the scope of articles covered.

A literature review can only consider articles published up to the search date, which represents the extant state of the scientific discourse. More recent results may have been published since, but are obviously not included in the review. However, this time limitation is well-known in the literature (vom Brocke et al., 2009). Similarly, in a literature review, only articles that are discoverable with the selected query can be identified. There are two limitations regarding the query. First, the query may not be comprehensive enough to identify all relevant articles. Second, there is no guarantee that relevant publications use the exact terms and phrases required for discovery. However, this limitation is minimized by systematically conducting the literature search (vom Brocke et al., 2015).

In addition, there is a methodological limitation regarding the literature included in the graph database approach in publication P9 (Bräker & Semmann, 2023a). As the approach only allows the analysis of publications with causal models or structural equation models (SEMs), the literature search was limited to publications containing causal models or SEMs. Thus, the limitation does not lie in the literature search itself but in the graph database approach.

The service systems engineering (SSE) approach recommends the design and piloting of artifacts in real-world scenarios (Böhmann et al., 2014). In this dissertation, artifacts were designed for real-world scenarios, but this approach also has limitations regarding the transferability due to context-dependency of the results. The water depth management case from publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023) was selected due to its special characteristics. As discussed in Chapter 5.1.2, the findings can be assumed to be transferable. However, it is important to note that this is only one single case, and its limitations should be acknowledged. In publication P2 (Bräker, Osterbrink, et al., 2023), the case was extended to include the floating drone, which further demonstrates the transferability and validity of the findings. Publications P3 (Bräker & Semmann, 2022) and P4 (Bräker & Semmann, 2023b) are based on another real-world case in a warehouse of a maintenance, repair, and overhaul service provider. Consequently, the limitations mentioned above remain. While the study offers valuable insights, the transferability of the findings may be limited due to context-dependency.

In conjunction with the aforementioned single-case limitation, there are also limitations regarding potential further evaluations. The artifacts developed in publications P3 (Bräker & Semmann, 2022) and P4 (Bräker & Semmann, 2023b) could benefit from additional evaluations of the final results. The dividing complexity framework (Bräker & Semmann, 2022) requires further application and evaluation in practice by domain experts with limited AR experience, as they are the intended audience for the use of this framework. Therefore, the remaining evaluation represents a limitation. An evaluation by practitioners could enhance the validity of the framework.

This could reveal potential improvements and refine the framework in subsequent further iterations. The process augmentability canvas from publication P4 (Bräker & Semmann, 2023b) also requires evaluation in practice in real-world scenarios with real-world processes by practitioners. This will enhance the validity and usability of the canvas and enable the identification of new insights for improvements.

The participants in the user study conducted in publication P8 (Bräker, Hertel, & Semmann, 2023b) identified usability issues with the prototype due to a priori design decisions that negatively influenced its usability. This indicates a limitation of the maturity of the prototype, which requires further refinement in another iteration. The results, such as the below-average usability, demonstrate the impact of this limitation.

This dissertation has a limitation in that its focus is solely on AR technology. Consequently, virtual reality (VR) and other representations of mixed reality (MR) are not considered in the publications included in the dissertation. For instance, the findings from publications P4 (Bräker & Semmann, 2023b) and P9 (Bräker & Semmann, 2023a) could also be extended to encompass VR and other forms of MR, while the process augmentability canvas presented in publication P4 (Bräker & Semmann, 2023b) is limited to AR processes. However, certain aspects of the canvas may also apply to VR or other forms of MR. It is important to note that this dissertation intentionally only focuses on AR, which is why this limitation is intentional.

Technological limitations constrain this dissertation due to the lack of sufficient maturity of AR hardware. The Microsoft Hololens, for instance, was launched in 2016 and still needs to mature fully. Consequently, limitations resulting from hardware immaturity exist, which can prevent the full potential of AR from being realized and can negatively impact the user experience. The artifacts are developed based on the available hardware on the market at the time, which comes with its inherent features and shortcomings. It is important to note that this dissertation solely addresses the current state of technology, and the rapidly evolving landscape of AR hardware represents a significant limitation.

8 Implications for Further Research

Based on the contribution and limitations of this dissertation, several implications and avenues for further research emerge.

First and foremost, further evaluations of several artifacts are needed to address the limitations of this dissertation (see Chapter 7). As noted in discussing the limitations, certain results might be context-dependent because they are based on a single case study. Further research could evaluate these artifacts in other use cases to improve the transferability and validity of the results. In so doing, the evaluation settings should be selected based on three criteria: (1) real-world scenarios, (2) real processes, and (3) the actual targeted audience.

The user-centered requirements for hydrographic surveying presented in publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023) were derived from the water depth management case. Therefore, it is necessary to address the limitation of context dependency in further research. The requirements could also be evaluated with other use cases in maritime logistics, such as dredging, pilotage in harbor areas, or other logistics cases. Domain experts and augmented reality (AR) developers could evaluate the requirements to validate their technical feasibility, focusing on interfaces, data types, and data quality. Additionally, the study could be replicated with less experienced skippers to investigate whether a lower level of experience would require more process support. Finally, an AR prototype that meets the requirements remains to be implemented. This prototype could be used to evaluate whether supporting the process with AR is beneficial for skippers from a user perspective.

The design of the artifacts developed in publications P3 (Bräker & Semmann, 2022) and P4 (Bräker & Semmann, 2023b) was based on data from a single use case, i.e., the warehouse of a maintenance, repair, and overhaul provider. Further research could evaluate these artifacts in practice in different real-world scenarios and with practitioners who are the target audience. Evaluating the artifacts with domain experts with limited AR experience could improve the validity and usability of the results.

The design principles outlined in publication P8 (Bräker, Hertel, & Semmann, 2023b) were derived in the context of a study in a laboratory setting. Further research could evaluate an improved iteration of the AR authoring tool in a real-world setting with actual processes and practitioners who are the target audience. Additionally, the AR instructions created in the study could be evaluated in further research to test their usefulness. This would provide a better understanding of the benefits of AR in such scenarios.

The immaturity of the AR authoring prototype presented in publication P8 (Bräker, Hertel, & Semmann, 2023b) was causing several issues and limitations in the user study. In order to enhance and refine the AR authoring tool, further research should focus on integrating feedback from the study. Additionally, concepts such as usability heuristics could be integrated, for example in the form of a usability analysis, where usability experts analyze the application based on heuristics to identify usability problems. The study results suggest that further improvements could be made to the prototype, especially of specific features, such as the redundancy of differentiating 3D nodes. Further research could investigate whether the emergence of new business needs and role concepts would influence the need for differentiated 3D nodes, or whether a consolidated 3D node would suffice. Another area for further investigation concerns the complexity level of process modeling. The assumption that linear process models are sufficient to represent processes conflicts with the study participants' need for more differentiated options. Further research should examine in detail the requirements for process modeling options in AR authoring tools.

This dissertation outlines several ideas for extending artifacts designed to assess the potential for AR applications in organizations in a thorough and systematic manner. The dividing complexity framework from publication P3 (Bräker & Semmann, 2022) has the potential for extension regarding the integration of interaction design by elaborating interactions in AR scenes. For instance, the taxonomies' interaction patterns from publications P6 (Bräker, Hertel, & Semmann, 2022) and P7 (Hertel et al., 2021) could be integrated into the framework, considering that the literature currently offers no existing classification of typical AR tasks. The study on the AR authoring tool in publication P8 (Bräker, Hertel, & Semmann, 2023b) found that participants tended to follow certain patterns. However, further research is necessary to gain a more comprehensive understanding of these interaction patterns.

Additionally, future research could explore the integration of CAD data and interactions with trackable objects within the framework. Although publications P6 (Bräker, Hertel, & Semmann, 2022), P7 (Hertel et al., 2021), and P8 (Bräker, Hertel, & Semmann, 2023b) address this topic, there is still room for further elaboration.

Publications P6 (Bräker, Hertel, & Semmann, 2022) and P7 (Hertel et al., 2021) highlight multimodality as an emerging topic. Consequently, further research could revisit multimodal interactions, which are not extensively covered in the Information Systems (IS) literature due to the predominant focus on single interactions. It would be beneficial to elaborate on best practices for combinations of input and output modalities. Furthermore, it may be advantageous to introduce archetypes for interaction patterns. Additionally, the collaborative aspect of AR requires further research. From a more holistic service systems engineering (SSE) perspective, it could be explored how the multitude of tools developed in the second research strand could be integrated for the systematic application of AR in service systems. Therefore, it is necessary to investigate how to combine them effectively to create a valuable tool for SSE which, without being an overloaded, all-in-one solution would still be powerful enough to support the entire process.

Publication P5 (Bräker & Semmann, 2021) has shown that AR is not considered in current business process modeling (BPM) approaches. The proposed research agenda outlines several avenues for further research in this regard. Although this dissertation has addressed some of the areas for further research or, at least, has prepared some of the groundwork, the area of BPM for AR needs to be further explored. The detailed research agenda is outlined in the respective publication in Chapter 13.

The graph database approach employed in publication P9 (Bräker & Semmann, 2023a) could be extended in further research to represent articles that do not contain causal models. It is worth exploring how other artifacts could be represented with graph databases to develop further extensions to the revised metamodel. Additionally, streamlining the encoding process for publications is a promising area for improvement. One potential avenue for future research is the automation of the coding process by using artificial intelligence (AI) mechanisms and tools, including generative AI and natural language processing (NLP), to extract relevant information from publications. This would represent a significant advance over the manual analysis and coding of publications.

While some of its features may also be applicable to virtual reality (VR) or other forms of mixed reality (MR), the process augmentability canvas described in publication

P4 (Bräker & Semmann, 2023b) is limited to AR processes. Further research could extend the canvas to other technologies on the virtuality continuum. This could provide more comprehensive decision support for hardware selection and broaden its practical application. As hardware devices continue to develop and mature, it may be worthwhile conducting further research on extending these to other forms of MR. This aspect likely applies to all artifacts, and it is important to consider which artifacts would benefit from future research that incorporates VR and MR. For example, in publication P9 (Bräker & Semmann, 2023a), the graph database could be expanded to incorporate VR and MR. This would enable the analysis of similarities and differences between the technologies. Additionally, the taxonomies from publications P6 (Bräker, Hertel, & Semmann, 2022) and P7 (Hertel et al., 2021) could be extended to encompass other VR and MR technologies.

With the increasing maturity of AR hardware, several research avenues are emerging. These include addressing the tracking challenges identified in publications P1 (Osterbrink et al., 2021) and P2 (Bräker, Osterbrink, et al., 2023), as well as developing new tracking mechanisms to enable the use of AR in unstable environments, such as on a waterborne vessel. The challenges associated with currently available AR hardware may be further elaborated as new advances in AR hardware come to market. The release of the Apple Vision Pro as a mixed reality display offers new possibilities for AR applications in organizations (Gans & Nagaraj, 2023). On the one hand, it could be explored whether the current challenges and shortcomings are still prevalent with this new type of display. For instance, the Microsoft Hololens' sensitivity to sunlight may not be an issue with the Vision Pro because of its video see-through display. On the other hand, the Apple Vision Pro enables a mixed-reality experience that seamlessly blends AR and VR, allowing for a representation of the entire virtuality continuum. Consequently, a more holistic view of MR is a topic for further research when applying AR in organizations. Therefore, it would be valuable to investigate whether advancements in AR HMDs could impact the implementation and adoption of AR technology in organizations.

Exploring new types of user interfaces that enable new forms of interaction is another potential topic for further research. This could include brain-computer interfaces or eye-tracking mechanisms for interaction. The Apple Vision Pro, for example, allows users to navigate with their eyes, hands, and voice. The eye-tracking feature of the Apple Vision Pro, for example, allows virtual objects to be selected by looking at them. The impact of new interaction mechanisms on the use of AR in organizations and how they (including employees with different abilities) can benefit from it remains to be explored. Another area for further research is interaction with virtual user representations, such as virtual avatars. Future research could explore virtual representations of actors and their interactions in service systems.

Moreover, it would be worthwhile exploring the impact of new technological advances and trends on AR research and applications. In particular, the emergence of generative technologies, such as generative AI, may also influence AR technologies. Imagining the real-time generation and rendering of virtual objects and holograms that are contextually dependent on what the user sees, does, or prefers may be a glimpse into an increasingly connected and digitally revolutionized future. As generative AI technologies are still in the early stages of development, their emergence may create numerous research opportunities.

9 Requirements for Augmented Reality Solutions for Safety-Critical Services – The Case of Water Depth Management in a Maritime Logistics Hub

Osterbrink, A., Bräker, J., Semmann, M., & Wiesche, M. (2021). Requirements for Augmented Reality Solutions for Safety-Critical Services – The Case of Water Depth Management in a Maritime Logistics Hub. *Proceedings of the International Conference on Wirtschaftsinformatik*

Abstract

Augmented reality (AR) is widely acknowledged to be beneficial for services that have exceptionally high requirements regarding knowledge and simultaneous tasks to be performed and are safety-critical. In such services, AR enables to augment service provision by delivering seamless integration of information in the field of view while enabling hands-free usage in the case of head-mounted displays. This study explores the user-centered requirements for AR solutions in the operations of a large European maritime logistics hub. Specifically, it deals with the process of soil sounding. Based on eleven think-aloud sessions during service delivery, two expert interviews, and two expert workshops, we derived five core requirements for AR in soil sounding. Thus, we present the first study on the applicability and feasibility of AR in the maritime industry and identify requirements that impact further research on AR use in safety-critical environments.

Keywords

Mixed reality, service engineering, requirements, think aloud, case study.

9.1 Introduction

In various industries, new technologies are becoming increasingly important in the development and improvement of services, and the use of these technologies has gained attention both in service research and in practice (Ostrom et al., 2015; Wirtz et al., 2018). When using new technologies, the IT resources either complement or improve the effects of non-IT resources on the performance of a process or substitute them (Jeffers et al., 2008). Well-known examples of services that were improved by technology are e-tickets in the airline or event business, electronic check-in and check-out systems in hotels, and electronic money transfer in financial services, etc. (Collier, 1994; Haksever et al., 2000).

As a result, the character of information technology has changed to the extent that it has become the focus of new product and service ideas due to technological developments both in hardware and software (Böhmann et al., 2014). An example of this is the use of augmented reality (AR) head-mounted displays (HMD), through which current challenges, for example, in technical customer services, can be overcome (Niemöller et al., 2019). With the help of HMDs, services can be restructured by enabling information to be displayed directly into the user's field of view under hands-free navigation without media breaks and limited mobility (Niemöller, Metzger, & Thomas, 2017). As a result, HMDs have a high potential to support (Elder & Vakaloudis, 2015) and improve (Metzger, Niemöller, & Thomas, 2017) services such as health care (Klinker et al., 2017), technical customer service (Niemöller, Metzger, & Thomas, 2017), and logistics services (Niemöller, Zobel, et al., 2017; Rauschnabel & Ro, 2016).

While previous studies have largely focused on services in which one task is performed, it is not well understood how AR can support services where two separate tasks are frequently switched. This is the situation in our use case of water depth management where skippers in the service provision of soil sounding simultaneously have to navigate their vessels and measure water depth with high accuracy. Since mistakes or inaccuracies in the performance of the two tasks of the skipper can have serious consequences both directly and indirectly, the use case is a safety-critical service, which can generally be characterized by the fact that a "failure might endanger human life, lead to substantial economic loss, or cause extensive environmental change" (Knight, 2002, p. 547). Especially, for this reason, effective support and improvement of the process of soil sounding are very important as the resulting information is crucial for vessels to navigate harbor areas. Consequently, soil sounding is a key service to ensure safety for all actors that use the harbor infrastructure as this infrastructure is partially dynamic due to tides and currents. An additive complicating factor for an AR application on a vessel is that, in contrast to the already difficult implementation of AR for cycling or driving a car, there is an additional dimension of motion, namely that of the ground, i.e., the water on which the vessel is moving. Against this background, our research is guided by the questions (RQ1) *How amenable is the service process of soil sounding to be supported by AR?* and (RQ2) *What are the requirements for AR solutions to improve the service process of soil sounding?*

To answer the research questions, the paper is structured as follows: First, we give an overview of the application of AR solutions in different service processes, distinguishing between those with a static setting and those where the environmental setting adapts to the user's motion, such as when driving a car. In section 9.3, we introduce the methodology, where we conducted a case study with workshop data, expert interviews, and process tracing using video observations and verbal protocols in the form of think-aloud sessions. In section 4, we present the use case of water depth measurement and analyze it firstly with regard to its augmentability (RQ1). In the second part of the analysis, we use the conducted think-aloud sessions to derive the user-centered requirements for an AR solution for the service process of soil sounding (RQ2). The results and their limitations are discussed in section 6, and in section 7, we summarize the main findings and give an outlook on future research issues.

9.2 Related Work

Innovations in the field of service continue to emerge, with many of the innovations today being digital by integrating resources throughout service systems (Lusch & Nambisan, 2015). In order to apply service innovations and related innovative technologies that can be used to support services, it is important to understand the innovations within the service for which they are to be used, their potential, and the requirements involved (Jessen et al., 2020; Matijacic et al., 2013).

One technology with a very high potential for service innovation is AR. This technology can be used in many different environments that can be distinguished by the degree of dynamics. Environments with little dynamics – here called static environments – can be characterized by the fact that the user's environment does not change because the user does not move in public but is in a limited environment like a room in which objects like machines have a fixed, static place. In those scenarios, there are already insights on applications of AR, such as the design and prototyping of a see-through HMD, which was carried out in the aircraft manufacturing industry to reduce costs and increase efficiency (Caudell & Mizell, 1992). Increased efficiency was also observed for the use of AR-applied devices in the context of maintenance and repair (Henderson & Feiner, 2011; Huck-Fries et al., 2017). In engineering, AR welding guns with cameras to track the exact stud locations were used to support engineering processes (Sandor & Klinker, 2005). Another AR application that was investigated is the use of smart glasses to support the runtime modeling of services, allowing the process to be documented on-site by the service provider during the execution of his activity (Metzger, Niemöller, Berkemeier, et al., 2017). Further applications of AR do exist in the construction industry (Dunston & Wang, 2005), marketing (Yaoyuneyong et al., 2016), education (Kaufmann & Schmalstieg, 2002) as well as healthcare (Klinker et al., 2020a; Sielhorst et al., 2008).

AR use cases in the context of more dynamic mobile settings, on the other hand, have been hardly the subject of research so far. These environments can be characterized by the fact that they are not limited in space and that objects – in contrast to those in static environments – do not necessarily have fixed positions, but the positions of these objects can change due to movements so that a motion emanates from the user's environment. One example is the process of driving a car, where the motion of other traffic participants influences the own process of driving, e.g., when it is necessary to brake because of the car in front brakes. For applications with relatively little or slow movement, head-mounted AR tools, such as HMDs, or other portable devices used for museum tours can be cited to provide audiovisual enhancements to support the tours (Miyashita et al., 2008; Sparacino, 2002). With regard to AR applications in the context of faster movements, the study by Berkemeier et al. (2018), in which requirements for an acceptable smart glasses-based information system to support cyclists in cycling training are identified, can be mentioned. The aim of the study is to augment information such as speed or route details, which would otherwise have to be displayed by other devices, into the cyclist's field of view to promote road safety. There are also studies on cars in which head-up displays or head-mounted displays are used to display relevant information in the driver's field of view in order to reduce risks in road traffic (Heymann & Degani, 2016) or to support driver safety training through simulated dangerous traffic situations (Regenbrecht et al., 2005).

Furthermore, in other safety-critical services, as it is the case in our use case, there are already some investigations on the support potential of AR and how it can be used. For example, the user requirements for an AR-based refinery training tool were determined for an oil refinery in order to develop usable and safe AR applications (Träskbäack & Haller, 2004). Another example is the application of AR in an innovative airport control power, where the aim was to provide the air traffic control operators in the airport control tower with complete head-up information (Bagassi et al., 2020; Balci & Rosenkranz, 2014).

Theoretical accounts have developed concepts to capture how technologies affect service processes. A well-known theory is the process virtualization theory, which is concerned with explaining and predicting whether a process can be performed virtually (Overby, 2008). Examples of virtualized processes include e-commerce, online distance learning, or online banking (Balci & Rosenkranz, 2014; Overby, 2008). The theory has been applied and adapted in many different contexts, e.g. (Balci & Rosenkranz, 2014; Bose & Luo, 2011), and was also examined with regard to augmentation, which led to the idea of the theory of process augmentability (Yeo, 2017), that provides the basis for the analysis of the augmentability of our use case of the soil sounding service.

In contrast to the definition of virtualization, augmentation can be defined as the supplement of a synthetic or physical interaction. As a logical consequence, the four main constructs of the process virtualization theory concerning the potential removal of physical interactions from the process cannot be applied to augmentation. Therefore, one main construct – the authenticity requirement, which is based on the essentialist view of authenticity (Newman, 2016) and the authenticity framework of Grayson and Martinec (2004) – is proposed to have a positive effect on the dependent variable, namely process augmentability. Process augmentability is described as "how amenable a process is to being conducted in AR environments" (Yeo, 2017, p. 5).

Furthermore, three moderating constructs are proposed that are developed from the definition of AR, which is crucial to maintain a sense of hyper-reality (Baudrillard, 1983). By definition, AR must meet three criteria: combine physical and virtual, be interactive in real-time, and be registered in the real world (Azuma, 1997; Yeo, 2017). According to the definition, Yeo (2017) proposed 3D visualization, spatial association, and synchronization as moderating constructs hereafter referred to as characteristics. The proposition of the 3D virtualization characteristic is informed by cognitive load theory (W. Huang et al., 2009). For the characteristic of spatial association, examples were given in Yeo (2017) of how AR uses the geospatial environments to enrich process experiences (Henderson & Feiner, 2011; Sandor & Klinker, 2005; Sielhorst et al., 2008). In terms of the synchronization characteristic, most physical processes conducted in the real world tend to be synchronous, and it is therefore important that the physical movement needs to be connected to maintain the sense of immersion (Overby, 2008).

9.3 Methodology

We conducted a case study (Yin, 2003) to explore the requirements for a user-centered AR solution for safety-critical services in the maritime sector. The use case we investigated was the process of soil sounding, i.e., water depth measurement in a harbor environment, which is carried out during navigation on a vessel.

In order to analyze how amenable the considered use case of the soil sounding process is to be supported by AR (RQ1), we first studied a promotional video of a European harbor operator that provided us with a contextual understanding of the soil sounding process as a foundation for the further analysis. In a second step, we collected data by conducting two semi-structured interviews and two workshops with business and IT experts of the same harbor operator (Table 19). Both the interviews and the workshops were documented by video recording. In addition, more detailed documents concerning the use case were provided by the participants, and additionally, notes were taken during the interview and workshop sessions. To get the first ideas of requirements for AR solutions for the service process of soil sounding (RQ2), we have briefly discussed them in the last part of the workshops with the experts. Since we wanted to identify user-centric requirements, we collected additional data with three skippers who actually perform the process of soil sounding.

Table 19. Data table of sources

#	Source	Format	Duration (hh:mm)	Focus
1	Harbor TV	Video	00:14	Use case context

2	Head of IT Innovation	Interview	01:00	Overview case strategy
3	Deputy Port Hydrographer	Interview	01:00	Deeper understanding of the use case context
4	Deputy Port Hydrographer	Workshop	02:03	Requirements of the use case
5	Project Manager R&D	Workshop	00:57	Process steps and requirements of the use case
6	Soil sounding 1	Think Aloud	01:27	Soil sounding on a shore
7	Soil sounding 2	Think Aloud	01:19	Soil sounding of harbor basin and berths
8	Soil sounding 3	Think Aloud	00:19	Follow-up soil sounding in a relatively small area
9	Soil sounding 4	Think Aloud	01:16	Soil sounding in a side arm with several bridges and an open lock
10	Soil sounding 5	Think Aloud	00:28	Soil sounding of a berth on a quay
11	Soil sounding 6	Think Aloud	00:52	Supplementary soil sounding of a berth within a control measurement
12	Soil sounding 7	Think Aloud	00:47	Soil sounding of recently dredged fields during heavy traffic
13	Soil sounding 8	Think Aloud	00:44	Soil sounding of a dredging field
14	Soil sounding 9	Think Aloud	00:55	Soil sounding of a widened shipping channel
15	Soil sounding 10	Think Aloud	00:36	Soil sounding of a dredging field
16	Soil sounding 11	Think Aloud	00:12	Soil sounding after removal of a ground obstacle as control

In order to gain this central data source, we used the process tracing method (Todd & Benbasat, 1987) of thinking aloud (van Someren et al., 1994), where the skippers were asked to "think aloud" and to explain everything they do while simultaneously engaging in the soil sounding service, in order to analyze which user-centered requirements an AR solution must meet to support the soil sounding process. As the situational features of the service are crucial, we extended the traditional implementation of the method by recording videos from different perspectives. For this purpose, we attached a camera to the skippers' forehead to retrace their field of view and another camera on the monitor to observe the skippers directly. An exact tracking of eye movements of the skippers was not necessary since only the direction of the skippers' view was relevant. With the help of the two recording perspectives and the recorded audio track, we were able to trace the process of soil sounding and derive user-centered requirements for an AR solution. As the service is critical to maintaining harbor operation, only experienced skippers are considered for soil sounding. The think-aloud sessions differ in the type of soil sounding job and its focus as well as the difficulty of the soil sounding, which depends on factors such as the soil sounding environment or traffic volume (see Table 19).

For analyzing the video recordings and verbal protocols of the think-aloud sessions, we used the scanning method, which is one of the four major categories of protocol analysis and the most straightforward one (Bouwman, 1983). We did not perform a verbatim transcription of what was said since the observation of the skippers was the primary object of investigation that we used for our analysis. Instead, the statements of the skippers helped to supplement and explain what was observed. For the identified video sequences in which observed behaviors indicated challenges, we transcribed what was said since this often helped to clarify and support the observation. We analyzed the video and audio material with three independent researchers and initially focused on existing challenges and problems in the process of soil sounding. After identifying all difficulties in the process, we derived problem categories by grouping duplicates and similar ones. Based on these problem categories, we finally derived the requirements described subsequently.

9.4 Use Case of Water Depth Management in a Harbor Environment

In the mobile use cases related to touring, cycling, and driving, two dimensions of motion occur: the motion of the user – which also occurs in static settings – and the motion of the environment. The ground on which the user moves can be described as static because it does not show any motion itself, such as a road. In the case of shipping, however, there is an additional dimension of motion, which is caused by the movement of the water on which the vessel is sailing, e.g., by currents or waves. While already the application of AR in cases with two dimensions of motion is difficult to implement, the application of AR on a vessel with this additional dimension of motion poses a particular challenge that needs to be investigated.

For our analysis, we chose the service process of water depth management in a European maritime logistics hub. Harbor personnel needs to continuously monitor water depth change due to sedimentation and erosion. In order to ensure the safety of vessel traffic and maintain the infrastructure, water depth management must be ensured by continuous soil sounding as well as finding and recognizing nautically critical obstacles on the water ground (e.g., bikes, cars, or shopping carts). Special soil sounding vessels are used that have the technical equipment to monitor water depth and generate a digital landscape model of the water ground live on board (see Figure 19).

Figure 19. Exterior and interior view of a soil sounding vessel

Figure 20 illustrates the measurement depth management cycle to give an overview of the use case context. This states that the measurement of water depths generates knowledge, which in turn causes action, such as deepening a certain area. Since this action causes a change, the changing area must be controlled by measurement.

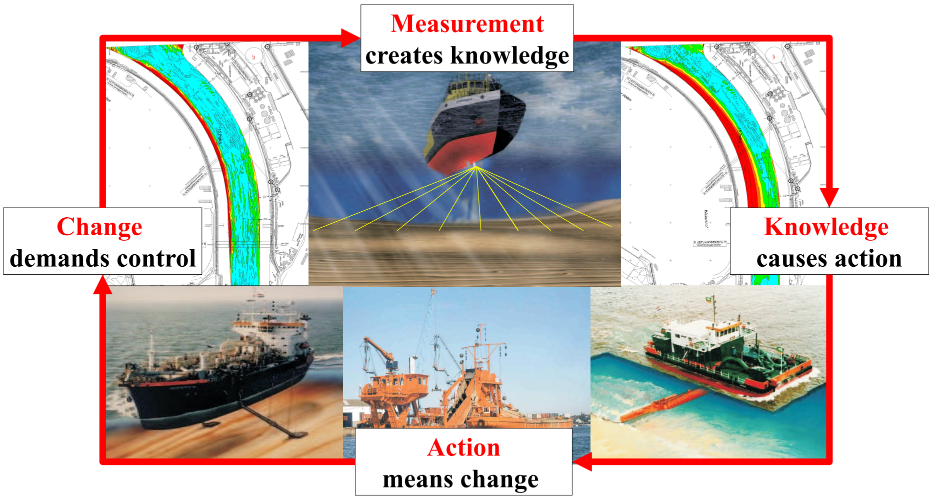


Figure 20. Measurement depth management cycle

The task of measuring water depth is particularly challenging: The skippers of soil sounding vessels use echo sounders to measure the water depths in the harbor while simultaneously paying attention to the vessel's traffic and keeping an eye on a variety of information for measurement on monitors so that they have to permanently switch between the monitors and the view out of the window. This leads to limited safety in vessel traffic, extreme exhaustion due to the constant change of view and context, and several health issues. These side effects of the constant shift of perspective can also be observed in other safety-critical services, such as the air traffic control in an airport control tower (Bagassi et al., 2020). In addition to the simultaneous navigation of the vessel and measurement of data, the skipper needs to interact with a measurement engineer, who is accountable for controlling the quality of the measured data. The measurement engineer is either also on the vessel or works from the home office.

9.4.1 Augmentability of the Use Case

Various attempts have already been made to solve the problem of the exhaustive and safety-critical shift in perspective between the view from the window onto the shipping traffic and the viewing of the data on the monitor. However, for example, the idea of placing the monitor in the windshield at the height of the skipper's eyes so that he no longer has to look down caused the monitor in the windshield to obscure important objects such as other vessels on the water. A further idea to reduce the size of the monitor in the windshield in order to avoid overlaying real objects has, in turn, resulted in the view of the displayed information and data being too small. Since it is important to display information in the skipper's field of view, but a monitor in the windscreen overlays important real objects, the application of AR seems to be a good way to solve the problem. With the help of AR, information can be displayed in the skipper's field of view without completely overlaying real objects. In order to investigate the applicability of AR for the use case, we have analyzed the use case with regard to the four characteristics that – according to the theory of process augmentability (Yeo, 2017) – must be present in a process so that an augmentation of the process is appropriate.

Authenticity. The authenticity characteristic is present in the soil sounding service. The skipper requires an authentic experience to be supported in navigating his vessel and measuring data during the actual soil sounding process. This process cannot be virtualized or simulated due to its high complexity and dependence on the actions and decisions of the skipper. Accordingly, the process can only be performed in reality, and the information and support required by the skipper must correspond to this reality and extend it adequately.

3D visualization. The 3D visualization characteristic is present in the soil sounding process. The skipper requires 3D visualization for an authentic experience because a 2D visualization of obstacles and other ships is too imprecise, making it difficult to estimate sizes and distances, which in turn can affect the quality of the measurement data and traffic safety.

Spatial association. The spatial association characteristic is present in the soil sounding process. It is very important for the skipper that information, such as water depth and currents, as well as obstacles in the water and other vessels, are displayed with geographical accuracy. The skipper requires the possibility to obtain further information about, e.g., displayed objects through interaction with them. For example, if an obstacle or the water depth is not displayed geographically correct, and the skipper does not have access to important information, the vessel may collide with the obstacle or run aground.

Synchronization. The synchronization characteristic is present in the soil sounding process. The 3D objects to be augmented and the collected measurement data, as well as information about boundary conditions such as currents or the tide, must be continuously synchronized and updated, enabling the skipper to use this information to navigate his vessel safely and detect possible obstacles and measurement gaps or errors.

In summary, the soil sounding service is amenable to be supported by AR based on the analyzed characteristics and identified needs of the skipper involved in the process.

9.4.2 Requirements for AR Solutions

Based on the challenges and problems that we have observed in the think-aloud sessions and subsequently analyzed, we identified five requirements for designing AR solutions for service processes such as soil sounding, which we specified together with the experts and skippers of the harbor operator. The identified requirements are (1) real-time overlay, (2) variety in displaying information, (3) multi-dimensional tracking, (4) collaboration, and (5) interaction.

Real-time overlay requirement. In all of the think-aloud sessions carried out, it was observed that during soil sounding, the skipper must be aware of a number of factors that may affect navigation and measurement, such as currents, the actual water level in the soil sounding area, in-water obstacles, general traffic and the data quality of the soil sounding. Since some information can only be acquired with the help of sensors and rapidly changing conditions prevail, the visualization of real-time information is an essential requirement to ensure that the skipper can navigate his vessel safely and, for example, is not in danger of running aground or hitting an obstacle.

Figure 21. Example of the permanent view shift between the sailing window and monitor

During soil sounding on a shore in the first think aloud (soil sounding 1), the skipper explained: “If you like, I’ll probably look 80% here on the monitor and maybe a little out the window”. Therefore, a further challenge, which can impair traffic safety and even lead to health problems, is the constant shift of the skipper’s attention between the sailing window to keep an eye on traffic and his monitors to ensure the quality of the measured data, as seen in Figure 21. To meet this challenge, the elimination of media breaks by overlaying information directly into the user's field of view is required. For example, overlaying real-time information about other vessels, such as their position or direction of navigation, which is received via the Automatic Identification System (AIS) and currently displayed on different monitors, could help to ensure safety.

The real-time overlay requirement, therefore, arises from the need to display information in real-time and to overlay this display in the skipper's field of view in order to improve vessel traffic safety, prevent health issues, and reduce cognitive load. Additionally, such overlay can drastically improve safety during harsh weather conditions that reduce sight while dependence on digital information increases.

Variety in displaying information requirement. In addition to the frequent shifting of view between the vessel's window and the monitors (see Figure 21), a variety of sensor information and data about the soil sounding area is displayed on different monitors, resulting in an additional constant shift between the monitors to ensure the quality of the measurement. Thereby the available space of the monitors is not optimally used, and sometimes even redundant information is displayed (see Figure 22). However, in order to improve usability and thus enable the skipper to execute the measurement efficiently, the skipper requires certain multiple sensor information simultaneously, such as different layers or perspectives of the area of soil sounding, without information and the representation of this information being displayed several times.

Figure 22. Variety of information and monitors on a soil sounding vessel

Another difficulty that also leads to the current use of multiple monitors is that information about the water level in general and the measured areas, which include the quality and density of the data, cannot be overlaid in the current IT system but are both required to ensure both traffic safety and measurement quality. Therefore, a further essential requirement regarding the presentation of information is that different views and representation options of the information should be distinguishable. In this context, we found out during the various think-aloud sessions that it is useful, for example, to have different zoom levels for the maps, since the skipper requires more detail to navigate his ship precisely, for instance, when measuring in narrow shore areas, than in wider water areas where he needs a greater overview. In several sessions, we could also observe that the skippers displayed the required information differently. In some measurement situations, for example, displaying the water depths in the measurement area using different color scales was more helpful than displaying this information as exact numerical values, and vice versa.

The variety in displaying information requirement, therefore, arises from the need to be able to choose different representation options of the information to display on demand in order to improve usability and traffic safety as well as ensuring the quality of the measurement.

Multi-dimensional tracking requirement. Compared to other means of transport such as bicycles or cars, a vessel has an additional dimension of motion since additional movements emanate from the ground, i.e., the water on which the vessel is sailing, making it even more difficult to track the vessel's exact position. However, it is an essential requirement for the navigation of the vessel during soil sounding to track the exact position of the vessel in relation to the environment. On the one hand, an inaccurate position determination can lead to measurement gaps and, accordingly, to a reduced measurement quality and, on the other hand, traffic safety can be impaired by incorrect positioning, since, for example, distances to obstacles or other vessels can no longer be displayed correctly.

Figure 23. Direct sunlight and reflections

Tracking of the vessel's position is also made more difficult by the fact that the skipper is inside the ship and perceives the outside world through glass windows, making it difficult to avoid direct sunlight and reflections (see Figure 23). Although the ships are equipped with sun protection roller shutters, which can attenuate the solar radiation, it is not possible to completely block the sun's rays without restricting the view outside too much by darkening it. Accordingly, the skipper requires tracking that is resistant to sunlight and reflections.

The multi-dimensional tracking requirement, therefore, arises from the fact that the skipper needs an exact positioning of the vessel in order to ensure traffic safety and the quality of the measurement data.

Collaboration requirement. During soil sounding, the skipper has to communicate a lot with other people to ensure traffic safety and quality of measurement. Both in terms of traffic safety and measurement, the skipper has to communicate with other vessels by radio in some situations. With regard to the quality of measurement, however, the collaboration with the measurement engineer, who is responsible for the technical implementation of the depth measurement, such as the configuration of the echo sounders, is most important. Before and during the measurement, the skipper and measurement engineer must continuously coordinate which areas are to be measured, how and when, and when the measuring devices must be activated or deactivated. They have to do this under consideration of different boundary conditions, e.g., the current water level. If the water level is too low, there is the risk of running aground, and if the water level is too high, it is, for example, no longer possible to pass every bridge. But above all, the constant communication about the observation of the live measured values and the flexible adaption of the course to them is of great importance since areas need to be measured again if the data quality is insufficient. A statement made by a skipper (think-aloud of soil sounding 7) summarizes very well the importance of the collaboration between him and the engineer during soil sounding: "If I don't synchronize with him [the measurement engineer], nothing will work".

To support collaboration, the skipper and the measurement engineer require the same visualization of the measuring areas, with additional highlighting of areas being useful because, especially when the measurement engineer is at the home office, it is not trivial to understand what about the other person is talking. It would also be useful to visualize whether the measurement device is activated and in which area it is currently collecting data. In addition, hands-free communication, i.e., without having to pick up a telephone, is required both with other vessels and with the measurement engineer, enabling the skipper to have his hands free for the navigation of the vessel and thus ensure safety.

The collaboration requirement, therefore, arises from the fact that the skipper has to communicate with other vessels and in particular, has to collaborate a lot with the measurement engineer in order to ensure both traffic safety and the quality of the measurement data.

Interaction requirement. The requirement of interaction goes along with the above-mentioned variety of displaying information requirement. Currently, information on the monitor cannot be manipulated by the skipper, or in other words, the skipper cannot interact with the system and is only able to consume information. During several think-aloud sessions, we observed that the skipper wanted to change the views on the monitor. Since the skipper is not able to interact with the system himself, he had to explain the necessary changes to the measurement engineer, who could then make the adjustments. It is therefore not possible for the skipper, for example, to show or hide information or to zoom into a map to get a detailed view if he requires it, e.g., to safely avoid obstacles or close measurement gaps. In order to carry out navigation and measurement more safely and efficiently, the skipper requires an appropriate opportunity to interact with the system.

The interaction requirement, therefore, arises from the fact that the skipper requires to show or hide important information or select detailed views to ensure traffic safety and completeness of the measurement data. Furthermore, the way of interaction should be chosen so that the skipper is not distracted from the navigation of the vessel.

9.5 Discussion

So far, little research on requirements for AR solutions has been done. Since the chosen use case is even more complex than the prior work on application areas of AR, we contribute to the state of research. Prior to investigating what requirements an AR solution must meet to support the service process of soil sounding, we examined the augmentability of the process using the theory of process augmentability (Yeo, 2017). We could determine that all four characteristics – which according to the theory, must be present in a process – are existent in the process of soil sounding so that an augmentation of the process is sensible and could help to facilitate and improve the process. This result is consistent with the taxonomy study by Klinker et al. (2018), who investigated for which processes in logistics an AR application is appropriate. As the process of soil sounding is a difficult case from practice, and therefore laboratory conditions are not given, implementing an AR solution is a big challenge, but it should be tackled to support practice.

In sum, we derived five core requirements from the case of soil sounding for the application of AR, namely (1) real-time overlay, (2) variety in displaying information, (3) multi-dimensional tracking, (4) collaboration, and (5) interaction. In addition, three general underlying requirements emerge related to traffic safety, health, and usability, which are included in all five requirement areas. Compared to the requirements for smart glasses-based AR systems for cycling training (Berkemeier et al., 2018) and to the use of AR in driving situations (Heymann & Degani, 2016; Regenbrecht et al., 2005), there are some similarities because in all these cases, an AR solution has to be applied in a mobile environment and the users act in a traffic situation. Both a failure in road traffic and one in the navigation of a vessel in shipping traffic can have serious consequences. In contrast to cycling or driving a car, however, our use case takes place in an environment where there is a further dimension of motion and consequently more degrees of freedom. Therefore, the multi-dimensional tracking requirement poses an even greater challenge to existing AR hardware as it is in the case of road traffic. Especially for soil soundings, where the measurement had to be carried out in a narrow area or where there was a high volume of traffic, exact tracking is essential. This applies not only to soil sounding vessels but to all other types of vessels as well, whereby the failure tolerance decreases as vessels approach narrow or restricted fairways and increasing traffic density (Gardenier, 1981). Furthermore, the use case of soil sounding gains in complexity since the user has to perform another task in addition to navigating the vessel, namely the service task of depth measurement in order to ensure harbor infrastructure and thus traffic safety. Moreover, from a methodological point of view, our approach contributes to new standards of research. By underpinning the thinking aloud method with video material from various perspectives, we were able to gain the best possible understanding of the spatial implications and requirements for AR. Thereby the enriched thinking aloud material helps to gain further insights and learnings about the user-centered requirements. Additionally, our approach is beneficial in environments that do not meet the standards of typical scientific interviews by being noisy, weather-dependent, and dirty.

However, our approach is not entirely free of limitations. Since we have only focused on one specific use case, that of soil sounding in water depth management, our results are contextual. Nevertheless, we assume a transferability to other use cases. For this purpose, further use cases in the maritime logistics environment could be considered. One possible case is the dredging industry, which is responsible for adjusting and dredging the water depths. Furthermore, use cases in the field of pilotage in the harbor could be considered. Moreover, a floating drone is used for water depth management and soil sounding. Also, in this case, potentials are recognizable, since with the help of AR, for example, the drone operator could take a first-person view in addition to a third-person view regarding the drone.

9.6 Conclusion

In summary, we have shown that the soil sounding service is augmentable in general. Knowing the augmentation potential, we derived five user-centered requirements for the soil sounding process, using the results of the thinking aloud sessions as a foundation: (1) real-time overlay, (2) variety in displaying information, (3) multidimensional tracking, (4) collaboration, and (5) interaction requirement. The requirements for an AR solution, which we have determined with regard to the navigation task of the skipper, correspond to the results of previous research on AR applications in road traffic. However, never before has such a complex process as that of soil sounding been investigated, so we are contributing to the research at this point. On the one hand, the moving vessel in combination with the moving user inside the vessel poses a great challenge in terms of multidimensional tracking possibilities. On the other hand, it is a knowledge-intense process that requires multitasking, i.e. a constant shift between the navigation of the vessel and the measurement of water depth, and collaboration with the measurement engineer. Furthermore, the process is subject to enormous safety critical requirements, which must be considered additionally.

Besides the above-mentioned tracking, future challenges will be to determine whether supporting the process with AR is beneficial for the skipper from a user perspective and, if so, in what form AR can be used to achieve the greatest possible advantage. For this purpose, a prototypical implementation and evaluation will be initiated in the future to explore the subjective usefulness of AR in the soil sounding context. In this context the requirements should be evaluated more detailed with experts from the maritime industry as well as AR solution developers regarding their technical feasibility, whereby the focus should be on interfaces, data types and data quality. Not least, the transferability to other use cases, e.g. in the harbor environment and general industrial as well as logistic scenarios, remains to be investigated.

9.7 Acknowledgements

This research was partly sponsored by the German Federal Ministry for Education and Research and in the project WizARd under the reference 02K18D180 and 02K18D181. Further information can be found under: http://www.wizard.tu-dortmund.de/.

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10 User-Centered Requirements for Augmented Reality as a Cognitive Assistant for Safety-Critical Services

Bräker, J., Osterbrink, A., Semmann, M., & Wiesche, M. (2023). User-Centered Requirements for Augmented Reality as a Cognitive Assistant for Safety-Critical Services. *Business & Information Systems Engineering*, *65*, 161–178. https://doi.org/10.1007/s12599-022-00779-3

Abstract

Augmented reality (AR) is widely acknowledged to be beneficial for services with exceptionally high requirements regarding knowledge and simultaneous tasks to be performed and are safety-critical. This study explores the user-centered requirements for an AR cognitive assistant in the operations of a large European maritime logistics hub. Specifically, it deals with the safety-critical service process of soil sounding. Based on fourteen think-aloud sessions during service delivery, two expert interviews, and two expert workshops, five core requirements for AR cognitive assistants in soil sounding are derived, namely (1) real-time overlay, (2) variety in displaying information, (3) multi-dimensional tracking, (4) collaboration, and (5) interaction. The study is the first one on the applicability and feasibility of AR in the maritime industry and identifies requirements that impact further research on AR use in safety-critical environments.

Keywords

Mixed reality, augmented reality, virtual reality, service engineering, requirements, think aloud, case study, cognitive assistant.

10.1 Introduction

Over the years, human-centered service systems have evolved, and technology has become smarter over time, necessitating the development of improved systems to leverage new technologies (C. Peters et al., 2016). As these new technologies are becoming increasingly important for service development and improvement in various industries, the use of these technologies has gained attention in both service research and practice (Ostrom et al., 2015; Wirtz et al., 2018). When adopting new technologies, IT resources either complement or improve the impact of non-IT resources on the performance of a process or replace them (Jeffers et al., 2008). Well-known examples of services enhanced by technology are electronic check-in and check-out systems in hotels, electronic money transfer in financial services, e-tickets in the airline or event industry, etc. (Böhmann et al., 2014; Collier, 1994). Focusing on the human factor and its capabilities when improving services, so-called cognitive assistance systems, which explicitly aim at enhancing human capabilities instead of replacing them, play an important role (Engelbart, 1962; C. Peters et al., 2016). In this context, cognitive assistants offer the possibility of significantly improving the functioning of complex service systems (C. Peters et al., 2016).

An example of a cognitive assistant that has been studied in various research areas is augmented reality (AR) applications. With the support of AR head-mounted displays (HMDs), for instance, current challenges, such as in technical customer services, can be overcome (Niemöller et al., 2019). HMDs can be used to restructure services by enabling information to be displayed directly into the user's field of view under hands-free navigation without media breaks and limited mobility (Niemöller et al., 2019). As a result, AR cognitive assistants, like HMDs, have a high potential to support and improve (Elder & Vakaloudis, 2015) services such as health care (Klinker et al., 2017), technical customer service (Niemöller et al., 2019), and logistics services (Rauschnabel & Ro, 2016).

While previous studies have primarily focused on services in which one task is performed, it is not well understood how AR cognitive assistants can support services where two separate tasks are frequently switched. This task switch is the situation in our use case of water depth management at a large European maritime logistics hub. As part of the water depth management, deviations in water depths of the port area must be continuously monitored, and if necessary, harbor areas must be dredged to maintain the waterway infrastructure (Bräker, Osterbrink, et al., 2022; Osterbrink et al., 2021). The measurement of water depths is called soil sounding and is provided by special vessels equipped with echo-sounding systems. Floating drones can be used individually or to support vessels to collect supplementary measurement data by being more agile and flexible. Skippers and drone operators are responsible for two parallel tasks during service delivery. First, they must navigate their vessels safely through the harbor area during regular maritime traffic, i.e., taking into account other vessels, water levels, tides, currents and obstacles in the water. Second, the measurement is a task that needs high accuracy and is a collaboration with a measurement engineer. This involves continuously coordinating measurement areas and routes with the measurement engineer, operating the echo sounder system, and checking the data quality of the measured water depths in real time. The measurement engineer, who is likewise on board the vessel, guides the measuring route and controls the quality of the measured real-time data. Since mistakes or inaccuracies in the performance of the skippers and drone operators can have serious consequences, directly and indirectly, the use case is a safety-critical service. These can generally be characterized by the fact that a "failure might endanger human life, lead to substantial economic loss, or cause extensive environmental change" (Knight, 2002, p. 547). Especially for this reason, effective support and improvement of the soil-sounding process are very important, as the resulting information is crucial for vessels to navigate harbor areas. Consequently, soil sounding is a key service to ensure safety for all actors that use the harbor infrastructure, as this infrastructure is partially dynamic due to tides and currents. Besides the two parallel tasks, another distinctive feature of our use case is the setting on the water. In contrast to the already difficult implementation of AR in navigation contexts such as cycling or driving a car, navigation on the water brings further challenges for developing an AR application. The instability of the water surface brings an additional dimension of motion that leads to, among others, much more complex tracking conditions. However, AR applications with an additional dimension of motion have not yet been investigated, so this represents another gap in previous research. Against this background, our research is guided by the questions (RQ1) "How amenable is the service process of soil sounding to be supported by AR?" and (RQ2) "What are the requirements for an AR cognitive assistant to improve the service process of soil sounding?". The results demonstrate how AR can improve operations in an edge case in the context of safety-critical maritime navigation with high requirements. We derived five requirements for such applications that inform future AR solutions in a wide application area. Additionally, we deal with unique tracking challenges that increase the understanding of AR and support systems when dealing with applications for use on the water.

The remainder of the paper is structured as follows: First, we give an overview of the application of AR solutions in different service processes. We distinguish between static settings and those where the environmental setting adapts to the user's motion, such as when driving a car and describe their technological challenges. In Sect. 10.3, we introduce the methodology. We conducted a case study with workshop data, expert interviews, and process tracing using video observations and verbal protocols in the form of think-aloud sessions. In Sect. 10.4, we present the use case of water depth measurement and analyze it firstly with regard to its augmentability (RQ1). In the second part of the analysis, we use the conducted think-aloud sessions to derive the user-centered requirements for an AR cognitive assistant for the service process of soil sounding (RQ2). The results and their limitations are discussed in Sect. 10.5, and in Sect. 10.5.2, we summarize the main findings and give an outlook on future research issues.

10.2 Related Work

Innovations in the field of service continue to emerge, with many of the innovations today being digital by integrating resources throughout service systems (Lusch & Nambisan, 2015). In order to apply service innovations and related innovative technologies that can be used to support services, it is important to understand the innovations within the service for which they are to be used, their potential, and the requirements involved (Jessen et al., 2020; Matijacic et al., 2013). One opportunity to support service is cognitive assistants, enabled or represented by rapidly evolving technologies and innovations. These assistants are primarily characterized by the aim to enhance human capabilities rather than replace them (Engelbart, 1962; C. Peters et al., 2016).

One promising technology that falls into this category of cognitive assistants is AR. As previous research shows, this technology can be used in many different environments. In the context of maintenance and repair, increased efficiency was observed for using AR-applied devices (Henderson & Feiner, 2011). Another AR application that was investigated is the use of smart glasses to support the runtime modeling of services, allowing the process to be documented on-site by the service provider during the execution of his activity (Niemöller et al., 2019). Further applications of AR do exist in the construction industry (Etzold et al., 2014), education (Kaufmann & Schmalstieg, 2002), as well as healthcare (Klinker et al., 2020b). These use cases tend to occur in static environments, i.e., the user does not move significantly, and the environment remains mostly constant.

On the other hand, AR use cases in mobile settings have rarely been the subject of research. These environments can be characterized by the fact that they are not limited in space and that objects – in contrast to those in static environments – do not necessarily have fixed positions, but the positions of these objects can change due to movements so that a motion emanates from the user's environment. Examples of mobile environments include navigation contexts, such as driving a car, where the motion of other traffic participants influences their own process of driving, e.g., when it is necessary to brake because of the car in front. With regard to AR applications in the context of moving environments, the study by Berkemeier et al. (2018), in which requirements for an acceptable smart glasses-based information system to support cyclists in cycling training are identified, can be mentioned. The study aims to augment information such as speed or route details, which would otherwise have to be displayed by other devices, into the cyclist's field of view to promote road safety. There are also studies on cars in which head-up displays or HMDs display relevant information in the driver's field of view to reduce road traffic risks (Heymann & Degani, 2016).

There are additional challenges when using AR in a maritime context compared to use cases in the domain of cycling or driving a car. One of the biggest technical challenges relates to tracking: "A ship is not fixed but will roll, pitch and yaw. So – depending on the use case – we have to determine the movement of the ship relative to the earth and the movement of a person (or device) relative to the ship" (von Lukas et al., 2014, p. 466). This means the vessel can move on the water in six degrees of freedom (DOF) (see Fig. 24). Mainly rotation motions are caused by the movement of the water on which the vessel is sailing, e.g., by currents or waves. In addition, the user can move on the ship in six DOF when wearing an HMD. The combination of the two makes tracking complex and challenging. In addition, harsh weather conditions, reflections from the water, and lack of GPS reception make accurate tracking difficult. For this reason, our use case presents a unique characteristic that raises a research gap that needs to be investigated.

Moreover, in other safety-critical services – as our use case – there are already some investigations on the support potential of AR and how it can be used. For example, the user requirements for an AR-based refinery training tool were determined for an oil refinery to develop usable and safe AR applications (Träskbäack & Haller, 2004). Another example is the application of AR in an innovative airport control power,

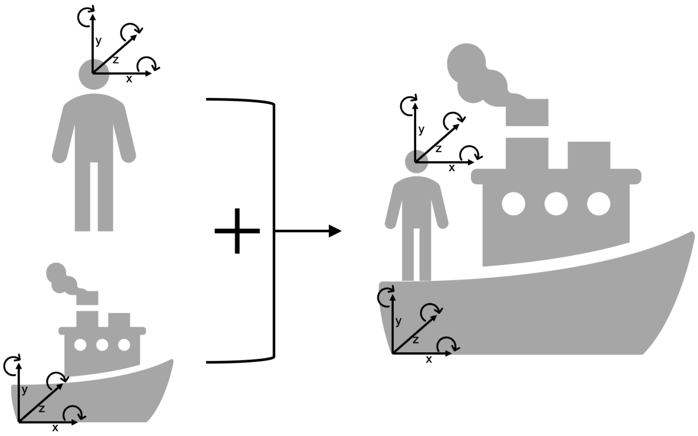

Figure 24. Illustration of the tracking complexity (own representation)

where the aim was to provide the air traffic control operators in the airport control tower with complete head-up information (Bagassi et al., 2020; Balci & Rosenkranz, 2014). All safety-critical services require situational awareness of involved actors. Situational awareness in this regard is defined as "[...] the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995, p. 36). The phenomenon is crucial in many applications and a lever for improved safety (Carroll et al., 2006; Jones et al., 2018; C. Reuter et al., 2019). Especially, AR bears the potential to improve situational awareness, as some recent findings conclude (Coleman & Thirtyacre, 2021). In a user study, J. Y. Lee et al. (2016) investigated how multitasking while driving distracts users and causes misbehavior. Study participants had to solve tasks on a classic infotainment system while driving a car. In particular, the risk of accidents increased when participants made mistakes in the parallel task and were distracted by view shifts and long glances at the infotainment system. Our research addresses a similar situation, albeit not in road traffic but maritime traffic.

Illing et al. (2021) examined in a study to what extent AR can help to support multitasking assembly exercises under time pressure. Especially when two or more tasks are performed in parallel, mental stress and reduced attention can occur. The authors were able to show that AR assistance systems can help to reduce the error rate and the cognitive load and, at the same time, increase the quality and motivation of the actors. The possibility of performing the task hands-free by using AR improves safety and helps users to comprehend the actual task faster. Hands-free working helps to support collaboration with other actors. Especially in mobile settings, where users move around the environment and have to collaborate and communicate at the same time, HMDs bring an advantage (Johnson et al., 2015). Nevertheless, in processes that require situational awareness and hands-free working while collaborating at the same time, AR support brings great benefits. An example of this is the security industry, where security personnel needs to be aware of the environment and simultaneously collaborate with, for example, the police while performing other activities that require hands-free working (Lukosch, Lukosch, et al., 2015).

Theoretical accounts have developed concepts to capture how technologies affect service processes. A well-known theory is the process virtualization theory, which is concerned with explaining and predicting whether a process can be performed virtually (Overby, 2008). Examples of virtualized processes include e-commerce, online distance learning, and online banking (Balci & Rosenkranz, 2014; Overby, 2008). The theory has been applied and adapted in many different contexts (Balci & Rosenkranz, 2014; Bose & Luo, 2011; Osterbrink et al., 2021) and was also examined with regard to augmentation, which led to the theory of process augmentability (Yeo, 2017), which provides the basis for the analysis of the augmentability of our use case of the soil-sounding service. In contrast to the definition of virtualization, augmentation can be defined as the supplement of a synthetic or physical interaction. Consequently, the main constructs of the process virtualization theory concerning the potential removal of physical interactions from the process cannot be applied to augmentation. Therefore, a new main construct – the authenticity requirement – is proposed to affect the dependent variable, namely process augmentability, positively. Process augmentability is described as “how amenable a process is to being conducted in AR environments” (Yeo, 2017, p. 5). The need for authenticity influences process augmentability, meaning that AR offers the possibility to provide authentic experiences, although a process is virtualized. An authentic experience is given if sensory genuineness is needed. Because AR can simulate sensory experiences, processes that require this authentic feeling are amenable to being augmented. Besides, three moderating constructs developed from the definition of AR are proposed to create an authentic experience. By definition, AR must meet three criteria: combine physical and virtual, be interactive in real-time, and be registered in the real world (Azuma, 1997). Accordingly, Yeo (2017) proposes 3D visualization, spatial association, and synchronization as moderating constructs affecting authenticity, hereafter referred to as characteristics. The requirement for 3D visualizations means that three-dimensional objects and overlays enable a more authentic experience. For the characteristic of spatial association, examples were given by Yeo (2017) of how AR uses the geospatial environments to enrich process experiences (Bräker, Hertel, & Semmann, 2022; Henderson & Feiner, 2011; Hertel et al., 2021). The spatial registration of objects in space influences augmentability, and if objects must be spatially anchored for an authentic experience, the process is suitable for AR. In terms of the synchronization characteristic, most physical processes conducted in the real world tend to be synchronous. Therefore, physical movement needs to be connected to maintain the sense of immersion (Overby, 2008). This means that synchronization ensures an authentic experience, i.e., the process is more authentic if no delays can be tolerated.

Based on existing research, our case delineates as follows: we are in a mobile wide-area environment that is constantly changing. At the same time, we are inside a vessel whose interior initially remains static. Due to the vessel's movements on the water, compared to conventional navigation settings, there is an added challenge that the water surface is unstable, and thus the vessel can move in 6 DOF. In addition, our users, the skippers, are performing a safety-critical process where errors can have drastic effects on themselves and others. They must be able to multitask, meaning they perform two parallel tasks and simultaneously collaborate and communicate with other involved parties. The combination of all these characteristics makes our use case a technological edge case, as it is particularly challenging, complex, and thus interesting for research. Likewise, aspects of it are found in loads of other use cases.

10.3 Method

We conducted a case study (Yin, 2003) to explore the requirements for a user-centered AR cognitive assistant for safety-critical services in the maritime sector. The use case we investigated was the process of soil sounding, i.e., water depth measurement in a harbor environment carried out during navigation on a vessel or with the help of a soil-sounding drone.

In order to analyze how amenable the considered use case of the soil-sounding process is to be supported by AR (RQ1), we evaluated to what extent the aspects of the theory of process augmentability (Yeo, 2017) are fulfilled. To assess the degree of fulfillment of the process augmentability criteria, we first studied a use case video of a European harbor operator that gave us a contextual understanding of the soil-sounding process as a foundation for further analysis. In the second step, we collected data by conducting two semi-structured interviews and two workshops with business and IT experts of the same harbor operator (see Table 20). The first interview was held with the port operator's Head of IT Innovation to get an initial overview of the use case. The second interview occurred with the Deputy Port Hydrographer of the same port operator. It gave us a deeper understanding of the use case and the context in which the soil-sounding process is performed. Both the interviews and the workshops were documented by video recording. In addition, the participants provided more detailed documents concerning the use case, such as the depth measurement management cycle (see Fig. 26) and information about and pictures of the soil-sounding vessel and drone (see Fig. 27 and Fig. 28). Two workshops further contributed to the understanding of the use case. In the first workshop, with the Deputy Port Hydrographer, researchers, and port operator personnel, we briefly discussed the first ideas for initial requirements for an AR cognitive assistant for the service process of soil sounding (RQ2).

Table 20. Data table of sources

#	Source	Format	Duration (hh:mm)	Focus
1	Harbor TV	Video	00:14	Use case context and understanding of the soil-sounding process
2	Head of IT Innovation	Interview	01:00	Overview case strategy
3	Deputy Port Hydrographer	Interview	01:00	Deeper understanding of the use case context
4	Deputy Port Hydrographer	Workshop	02:03	Requirements of the use case
5	Project Manager R&D	Workshop	00:57	Process steps and requirements of the use case
6	Soil sounding 1	Think-Aloud	01:27	Soil sounding on a shore (S_A, M_A)
7	Soil sounding 2	Think-Aloud	01:19	Soil sounding of harbor basin and berths (S_A, M_A)

8	Soil sounding 3	Think-Aloud	00:19	Follow-up soil sounding in a relatively small area ($\mathrm{S_A}$, $\mathrm{M_B}$)
9	Soil sounding 4	Think-Aloud	01:16	Soil sounding in a side arm with several bridges and an open lock ($\mathrm{S_A}$, $\mathrm{M_B}$)
10	Soil sounding 5	Think-Aloud	00:28	Soil sounding of a berth on a quay ($\mathrm{S_A}$, $\mathrm{M_B}$)
11	Soil sounding 6	Think-Aloud	00:52	Supplementary soil sounding of a berth within a control measurement ($\mathrm{S_A}$, $\mathrm{M_B}$)
12	Soil sounding 7	Think-Aloud	00:47	Soil sounding of recently dredged fields during heavy traffic ($\mathrm{S_B}$, $\mathrm{M_A}$)
13	Soil sounding 8	Think-Aloud	00:44	Soil sounding of a dredging field ($\mathrm{S_B}$, $\mathrm{M_A}$)
14	Soil sounding 9	Think-Aloud	00:55	Soil sounding of a widened shipping channel ($\mathrm{S_B}$, $\mathrm{M_A}$)
15	Soil sounding 10	Think-Aloud	00:36	Soil sounding of a dredging field ($\mathrm{S_B}$, $\mathrm{M_A}$)
16	Soil sounding 11	Think-Aloud	00:12	Soil sounding after removal of a ground obstacle as control ($\mathrm{S_B}$, $\mathrm{M_A}$)
17	Soil sounding 12	Think-Aloud	02:03	Intermediate soil sounding for a dredging field ($\mathrm{S_C}$, $\mathrm{M_C}$)
18	Soil sounding 13	Think-Aloud	02:08	Intermediate soil sounding for fairway deepening ($\mathrm{S_C}$, $\mathrm{M_C}$)
19	Soil sounding 14	Think-Aloud	00:57	Soil sounding using an autonomous drone in a small area ($\mathrm{D_A}$, $\mathrm{M_D}$)

In the second workshop, the Project Manager R&D, researchers and further port operator personnel participated. During this workshop, we defined the single process steps of the soil-sounding service process and discussed which initial requirements might apply to each process step.

Since we wanted to identify user-centered requirements, we collected additional data with three skippers and one drone operator who performed the process of soil sounding. For simplicity, the common term "actor" is used hereafter for skippers and drone operators when both are meant. We were particularly interested in safety aspects, environmental conditions of the vessel, the cognitive and physical demands of the skipper, the type and intensity of collaboration between the actors, and general challenges and problems encountered by the actors in their daily work. In order to gain this central data source, we used the process-tracing method (Todd & Benbasat, 1987) of thinking aloud (van Someren et al., 1994), where the actors were asked to "think aloud" and to explain everything they do while simultaneously engaging in the soil-sounding service. We used this method to analyze which user-centered requirements an AR cognitive assistant must meet to support the soil-sounding process. As the situational features of the service are crucial, we extended the traditional implementation of the method by recording videos from different perspectives. For this purpose, we attached a camera to the actors' forehead to retrace their field of view and placed another camera on the monitor to observe the actors directly (see Fig. 25). An exact tracking of the eye movements of the actors was not necessary since only the direction of the actors' view was relevant. With the help of the two recording perspectives and the recorded audio track, we were able to trace the process of soil sounding and derive user-centered requirements for an AR cognitive assistant.

As the service is critical to maintaining harbor operation, only experienced actors are considered for soil sounding. The fourteen think-aloud sessions differ in the type of soil-sounding job and its focus as well as the difficulty of the soil-sounding, which depends on factors such as the soil-sounding environment or traffic volume (see Table 20). For each soil sounding, we added anonymized codes for the skipper and the measurement engineer. During the think-aloud sessions, three different skippers ($\mathrm{S_A}$ - $\mathrm{S_C}$), one drone operator ($\mathrm{D_A}$) and four measurement engineers ($\mathrm{M_A}$ - $\mathrm{M_D}$) were involved.

For analyzing the video recordings and verbal protocols of the think-aloud sessions, we used the scanning method, which is one of the four major categories of protocol analysis and the most straightforward one (Bouwman, 1983). We did not perform a verbatim transcription of what was said since the observation of the actors was the primary object of investigation that we used for our analysis. Instead, the actor's statements helped to supplement and explain what was observed. For the identified video sequences in which observed behaviors indicated challenges, we transcribed what was said, which often helped clarify and support the observation. We analyzed the video and audio material with three independent researchers and initially focused on existing challenges and problems in the process of soil sounding. After identifying all difficulties in the process, we derived problem categories by grouping duplicates and similar ones. Based on these problem categories, we derived contextual requirements for each problem. Afterward, we abstracted from the contextual requirement and derived five general requirements for augmenting the soil-sounding service. The detailed results are described in Sect. 10.4.2.

10.4 Use Case of Water Depth Management in a Harbor Environment

For our analysis, we chose the service process of water depth management in a European maritime logistics hub. Harbor personnel must continuously monitor water depth change due to sedimentation and erosion. To ensure the safety of vessel traffic and maintain the infrastructure, water depth management must be ensured by permanent soil sounding as well as finding and recognizing nautically critical obstacles on the water ground, e.g., bikes, cars, or shopping carts. Special soil-sounding vessels and drones are used that have the technical equipment to monitor water depth and generate a digital landscape model of the water ground live on board. Fig. 26 illustrates the depth measurement management cycle to give an overview of the use case context. This states that measuring water depths generates knowledge, which in turn causes action, such as deepening a certain area. Since this action causes a change, the changing area must be controlled by measurement.

The most frequently used technique for measuring water depth is the use of soil-sounding vessels (see Fig. 27). These are special vessels equipped with an echo sounder that enables real-time measurement of water depths under the vessel. Different soil-sounding vessels operate daily in the harbor area, which an autonomous floating drone can optionally support. Each vessel needs to sound different defined areas in the port daily and investigate them for changes and irregularities to ensure safe operations within the harbor. Soil-sounding assignments and allocations are managed centrally by a hydrographic office and prioritized as needed and based on

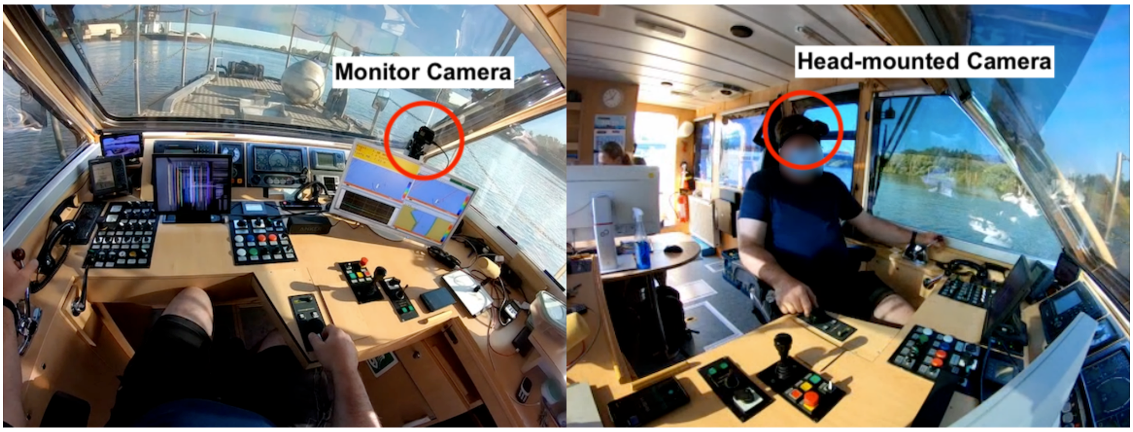

Figure 25. Experimental setup with monitor camera and head-mounted camera

tides. The assignments are usually processed by two people on board each vessel: a skipper and a measurement engineer.

The task of measuring water depth is particularly challenging: The skippers of soil-sounding vessels use echo sounders to measure the water depths in the harbor while simultaneously paying attention to the vessel's traffic and keeping an eye on a variety of information for measurement on monitors so that they have to permanently switch between the monitors and the view out of the window. This leads to limited safety in vessel traffic, extreme exhaustion due to the constant change of view and context, and several health issues. These side effects of the constant shift of perspective can also be observed in other safety-critical services, such as air traffic control in an airport control tower (Bagassi et al., 2020). In addition to simultaneous navigation of the vessel and measurement of data, the skipper needs to interact with the measurement engineer, who is accountable for controlling the quality of the measured data. If the measurement engineer cannot be on the vessel in person, it is possible to work from the home office.

To efficiently perform the measuring tasks assigned by hydrography, the skipper and the measurement engineer need to determine the best possible order of the tasks at the beginning of the workday. This depends on external factors, such as tide, currents or other vessels blocking measurement areas. In addition, the internal prioritization of the hydrographic office is considered. If the order of the assignments has been coordinated, the skipper navigates to the next measuring area. In consultation with the measurement engineer, the skipper either navigates the area at his own discretion and expertise or the measurement engineer places a profile with an outline on the skipper's map view so that the skipper has a point of reference. In addition, the measurement engineer can draw a so-called bearing line for the skipper, which specifies the optimal route through the measurement area. Once the soil-sounding data is available in the appropriate quality, the next measurement area is approached.

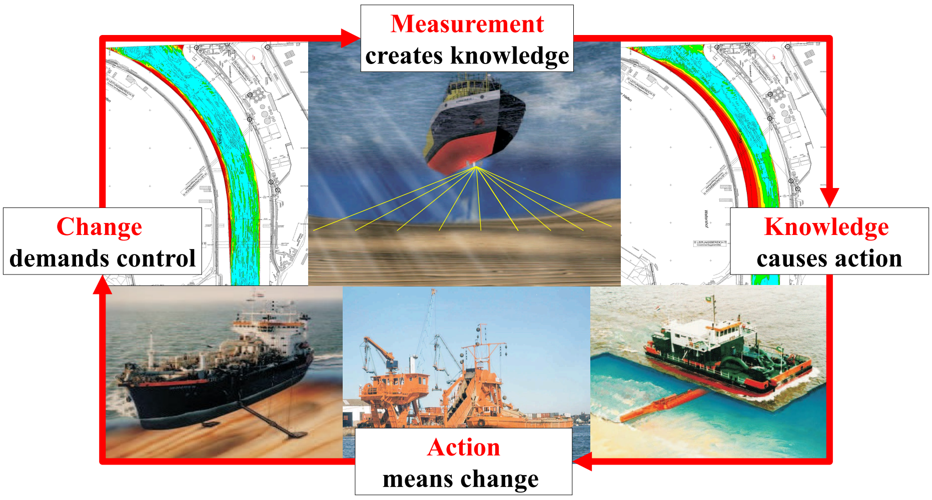

Figure 26. Depth measurement management cycle

In addition to the described approach using special soil-sounding vessels, floating drones can be used for certain use cases (see Fig. 28). The soil-sounding drone is approximately 1.65 m long and is controlled either from land or the soil-sounding vessel. It can be operated manually by a drone operator via remote control or autonomously along a predefined route given by the measurement engineer, which he defines on his monitor. On board the drone – analogous to the soil-sounding vessel – an echo sounder is installed and, in addition, a camera whose image shows the environment from the drone's point of view and is streamed to the monitors of the drone operator and measurement engineer. Compared to the conventional approach of measuring water depth with a soil-sounding vessel, the drone is used for tasks where it would otherwise be too dangerous to use a soil-sounding vessel, for example, because the water is too shallow or maneuvering is difficult. In addition, the drone can be used as an escort vessel to assist in sounding large areas.

The main difference compared to the soil-sounding vessel is the vehicle size and the actor's perspective. In contrast to the skipper, the drone operator can take two perspectives: the perspective from outside the drone and the drone's perspective via the installed camera. Even though the perspective is slightly different from that of the skipper, the same negative side effects occur when controlling and measuring with the drone as when working with a soil-sounding vessel since the drone operator

Figure 27. Exterior and interior view of a soil-sounding vessel

Figure 28. Soil-sounding drone

is also subject to a constant shift between different views. Furthermore, at long ranges, the distances between the drone and other objects in the water and the shoreline are more difficult for the drone operator to estimate. While the drone must always remain in view for safety and regulatory reasons, this can nonetheless be hundreds of meters to several kilometers away from the drone operator in broad harbor basins. Even if the drone operator additionally gets the camera image of the drone streamed to a display, this does not provide a substitute for the outside view of the drone since the image can be disturbed by splash water, for example, and it only visualizes a limited camera image and not a complete 360-degree view at once. Thus, the drone operator also has parallel tasks – first, the safe and precise control of the drone using two different perspectives, and second, the control of the measurement data in collaboration with the measurement engineer. Even in cases where the drone is operating autonomously, the drone operator must maintain full attention, as he or she must always be able to intervene in an emergency. For simplicity, the analysis of the use case uses the common term “vessel” for the soil-sounding vessel and the soil-sounding drone when both are intended.

10.4.1 Augmentability of the Use Case

Various attempts have already been made to solve the problem of exhaustive and safety-critical perspective shift between the window to see shipping traffic and the data on the monitor. However, for example, the idea of placing the monitor in the windshield at the height of the actor’s eyes so that he no longer has to look down caused the monitor in the windshield to obscure important objects such as other vessels on the water. A further idea to reduce the size of the monitor in the windshield to avoid overlaying real objects has, in turn, resulted in the view of the displayed information and data being too small. Since it is important to display information in the actor’s field of view, but a monitor in the windscreen overlays important real objects, the application of AR seems to be a promising way to solve the problem. With the help of AR, information can be displayed in the actor’s field of view without completely overlaying real objects. In order to investigate the applicability of AR for the use case, we have analyzed the use case with regard to the four characteristics that – according to the theory of process augmentability (Yeo, 2017) – must be present in a process so that augmentation of the process is appropriate.

Authenticity. The authenticity characteristic is present in the soil-sounding service. The actor requires an authentic experience to be supported in navigating his vessel and measuring data during the actual soil-sounding process. This process cannot be virtualized or simulated due to its high complexity and dependency on the actions and decisions of the actor. Even if each soil-sounding procedure follows a similar pattern – (1) navigation to the measurement site, (2) navigation of the vessel through the measurement area and execution of the measurement while permanently controlling the quality of the data, (3) completion of the measurement as soon as all data are available – nevertheless each procedure is different. The process of measurement is influenced by the current environmental conditions, e.g., tide, current or wind, but also by other vessels, possible construction sites and obstacles in the water, which are potential sources of danger. In addition, regarding the water depths measured in real-time, the skipper must react quickly and adjust the route according to the current circumstances. Accordingly, the process can only be performed in reality, and the information and support required by the actor must correspond to this reality and extend it adequately.

3D visualization. The 3D visualization characteristic is present in the soil-sounding process. The actor requires 3D visualization for an authentic experience because a 2D visualization of obstacles and other vessels is too imprecise, making it difficult to estimate sizes and distances, which in turn can affect the quality of the measurement data and traffic safety. In addition, a 3D visualization of the real-time measurement results is needed. Analogous to the current map view on the skipper's monitor, certain areas on the water surface could be color-coded in three-dimensional space.

Spatial association. The spatial association characteristic is present in the soil-sounding process. It is very important for the actor that information, such as water depth and currents, as well as obstacles in the water and other vessels, are displayed with geographical accuracy. The actor requires the possibility to obtain further information about, e.g., displayed objects through interaction with them. For example, suppose an obstacle or the water depth is not displayed geographically correctly, and the actor does not have access to critical information. The vessel may collide with the obstacle or run aground in that case.

Synchronization. The synchronization characteristic is present in the soil-sounding process. The 3D objects to be augmented and the collected measurement data, as well as information about boundary conditions such as currents or the tide, must be continuously synchronized and updated, enabling the actor to use this information to navigate his vessel safely and detect possible obstacles and measurement gaps or errors.

In summary, the soil-sounding service is amenable to be supported by AR based on the analyzed characteristics and identified needs of the actor involved in the process. Applying AR, we aim to improve the safety of the vessel traffic, both for the soil-sounding vessel and for other vessels and involved actors. The safety-critical process of soil sounding holds great potential for using AR to overlay specific information into the skipper's field of view, thus increasing situational awareness. For example, by displaying water depths, i.e., how much space is left under the vessel until it runs aground, safety distances, underwater objects, or other vessels. This applies, in particular, to traffic participants who do not have AIS. As harbor areas have to become more efficient in order to fulfill the increasing demands of global supply chains, traffic in the harbor is becoming denser and timed more closely. Given the increased size of vessels and the amount of cargo loaded, slight delays in handling vessels have a huge economic impact. An extreme example of the consequences of such delays was the impact of the vessel Ever Given, which got stuck in the Suez Canal, leading to severe delays on a global scale with an estimated loss of 10 billion $ in trade value per day (Yee & Glanz, 2021).

Furthermore, we aim to relieve the strain on the skipper, who is physically stressed by constant changes of view between monitor and windshield. We want to reduce cognitive stress since the process requires a lot of concentration and attention due to the parallel execution of several tasks using AR. Additionally, the use case is interesting from a technological perspective, as new tracking requirements for AR hardware arise due to the new dimension of motion caused by the water surface. Since the process requires spatial anchoring of objects in the environment and 3D visualizations are needed, accurate tracking is essential in this use case.

10.4.2 Requirements for AR Solutions

Based on the challenges and problems we observed in the think-aloud sessions and subsequently analyzed, we identified five generalized requirements for designing AR solutions as a cognitive assistant for service processes such as soil sounding. We specified the requirements together with the experts and actors of the harbor operator. Table 21 summarizes the results of the think-aloud sessions. We gradually derived the contextual requirements from the observed problems and then abstracted them, resulting in the five generalized requirements. For each contextual requirement, we specify from which think-aloud session, e.g., soil sounding 1 (SoSo1), we derived the requirement. The five requirements are (1) real-time overlay, (2) variety in displaying information, (3) multi-dimensional tracking, (4) collaboration, and (5) interaction.

Table 21. Requirements derived incrementally from the problems and challenges identified in the think-aloud sessions

Problem/challenge	**Contextual requirement**	**Generalized requirement**
Some real-time information is not visible and can only be captured by sensors, e.g., actual water depths, or measurement quality	Visualization / overlay of real-time sensor data (SoSo1, SoSo2)	Real-time overlay
Accuracy and actuality of the visualized data are critical to the safety of the skippers	Ensure reliability, synchronization, and actuality of visualized data (SoSo13)	

On-board AIS information is not always reliable, i.e., not all vessels are shown, positions deviate, the orientation of non-moving vessels is not always correct, software bugs in the IT system exist The skipper must lean forward to view the AIS system on board (small display behind the monitor) Anchored vessels might hinder order planning, resulting in delays. Departure timings can be manually looked up in a sailing list, which is only available on paper	Visualization / overlay of real-time AIS data, including correct position and orientation (SoSo1, SoSo2, SoSo3, SoSo4, SoSo5, SoSo6, SoSo7, SoSo9, SoSo12, SoSo13, SoSo14)
External dependencies, such as tides, currents, wind direction, and wind speed, affect the feasibility of sounding orders and are significant considerations when arranging the order sequence Data is not always available digitally and must be read from printed calendars, which is time-consuming	Visualization / overlay of the real-time tide, current, wind direction, and wind speed (SoSo1, SoSo2, SoSo3, SoSo4, SoSo12, SoSo13)
Real-time water depths are critical for safe vessel navigation as well as assuring measurement quality	Visualization / overlay of real-time water depths (SoSo1, SoSo2, SoSo14)
Real-time safety distance is critical for the vessel's safe navigation Distances to other vessels are difficult to predict without further assistance	Visualization / overlay of real-time safety distances to shore, obstacles, and other vessels (SoSo1)
GPS is not always available, and signal strength is a crucial indicator of both accuracy and safety	Visualization / overlay of the GPS signal, as well as a warning if the GPS signal is insufficient (SoSo1, SoSo4)
The bearing line is critical for proper vessel navigation; however, it is only visible on the monitor	Visualization / overlay of the bearing line and real-time deviations (SoSo2, SoSo6, SoSo8, SoSo14)

Information about the soil-sounding task is usually available but not always accessible in the IT system Because of the multiple measuring ranges, there are frequently overlaps in the measurement data, which is time-consuming and ineffective / inefficient	Visualization of information regarding the soil-sounding field and the task (SoSo3, SoSo4, SoSo13, SoSo14)	
The quality of the measurement data is critical in determining where to measure again or if the route must be corrected	Visualization / overlay of measurement data quality (SoSo1, SoSo2, SoSo4)	
Knowing the soil-sounding vessel's speed is essential for estimating maneuvers For effective navigation, the skipper must be aware of whether the measurement is already enabled or deactivated	Visualization of the vessel's speed and display activation/deactivation of the echosounder system (SoSo12, SoSo13)	
Underwater obstacles can rapidly become dangerous. It is challenging to keep the existing maps up to date due to constantly changing conditions. If a new obstacle is discovered, it is not certain that the map will show it because sometimes it takes years to update it	Visualization of obstacles and ability to add new obstacles to the IT system (SoSo1, SoSo3, SoSo4, SoSo5, SoSo11, SoSo12, SoSo14)	
The skipper must look down to observe critical data on the monitor. Because the monitor must not cover the windshield, it is small and situated far down The skipper needs to frequently switch views between the screens and reality	Overlay the skipper's field of view directly to enhance ergonomic posture and avoid view shifts/media breaks (SoSo1, SoSo3, SoSo4, SoSo6, SoSo7, SoSo9, SoSo10, SoSo11, SoSo12, SoSo13, SoSo14)	
Multiple sensor data from the same area is represented on the screen in separate windows or even on different displays. The available display space is not being used properly, and the same area is being presented redundantly	Simultaneous visualization of several context-dependent information without redundancy (SoSo1, SoSo3, SoSo8, SoSo13, SoSo14)	Variety in displaying information

Because the process necessitates a high level of concentration, too much information might quickly distract attention from possible dangers, etc.	Avoid visual clutter to avoid disrupting the skipper's focus during a safety-critical operation (SoSo1, SoSo14)	
During the measurement process, the position of the vessel is important for navigation. However, the skipper moves around on board the vessel, which might make standard tracking systems difficult to use. Thus, sailing on the water introduces a new dimension of motion for tracking	Tracking the position of the vessel with respect to the environment while the skipper is moving on board the vessel at the same time (SoSo12, SoSo13, SoSo14)	Multi-dimensional tracking
Because the setting takes place on a ship on the water, disturbances in position and rotation, e.g., caused by waves, are unavoidable	Tracking must be resistant to wave motion (SoSo1, SoSo2, SoSo9, SoSo14)	
Because the skipper is inside the ship but perceives the outside world through glass windows, direct sunlight and reflections cannot be prevented Because the measurements are being taken in the harbor area, there may be distracting noise in the surrounding area, such as from building activities	Tracking must be resistant to external sources of interference, such as sunlight, various weather conditions, and noise (SoSo9, SoSo10, SoSo13)	
The skipper and the measurement engineer must collaborate to determine which area to measure in which direction. This can be accomplished through direct dialogue or by the measuring engineer drawing a line or polygon where the skipper must stay on/in. Relying solely on remote communication, such as phone calls, would not work because it is not easy to understand what the other person is saying when working remotely.	Visual support for communication between the skipper and the measurement engineer allows them to gain a shared understanding by viewing the maps from the same position. If they are working remotely, encourage continual auditory communication (SoSo1, SoSo2, SoSo3, SoSo5, SoSo6, SoSo7, SoSo12, SoSo13, SoSo14)	Collaboration

When prioritizing soil-sounding requests, impacting factors such as tide, wind, and current must be considered. Some orders are internally prioritized; therefore, the skipper and measurement engineer must always examine the order in which the orders are processed	Support order planning between the skipper and the measurement engineer by facilitating order discussion and documenting a prioritization (SoSo1, SoSo2)	
Additional communication with other vessels is required during the process. Thus, all vessels involved may maneuver securely. Communication breakdowns and misconceptions can occur	Support and ensure communication with other vessels (SoSo2, SoSo3, SoSo4, SoSo7, SoSo12, SoSo13, SoSo14)	
The skipper needs both hands when he must control the vessel precisely and switch between joysticks quickly. When the measuring engineer is working remotely and connected by phone, or when the skipper needs to use the radio, he must have free hands.	Support for hands-free communication and hands-free working (SoSo1, SoSo7, SoSo12)	
The skipper cannot change the information on the display; in other words, he cannot interact with the system and only consume information. If the displayed content needs to be modified, it must be done by the measurement engineer.	Support the skipper's interaction with the IT system, such as adjusting chart display views (SoSo1, SoSo3, SoSo4, SoSo13, SoSo14)	Interaction

Real-time overlay requirement. In all the think-aloud sessions carried out, we observed that during soil sounding, the actor must be aware of several factors that may affect both navigation and measurement tasks. These include factors such as tides, currents, wind direction and speed, and safety distances. Possible dangers, such as in-water obstacles or general shipping traffic, are also involved, as well as data, such as the actual water level in the soil-sounding area and the measurement data quality. Further information that affects the process of soil sounding is GPS signal strength, speed of the vessel, information about the sounding job, indications of the sounding area and the optimal route across it. Since some information can only be acquired with the help of sensors and rapidly changing conditions prevail, the visualization of real-time information is an essential requirement to ensure that the actor can navigate his vessel safely and, for example, is not in danger of running aground or hitting an obstacle. Other information, such as when high tide is or which ships depart, can currently only be read off paper lists.

The reliability, synchronicity and actuality of the displayed data are furthermore a prerequisite for safe navigation: “I have to be able to rely on this monitor! You have to have trust in the equipment” (SoSo1).

During soil sounding on a shore, the skipper explained: “If you like, I’ll probably look 80% here on the monitor and maybe a little out the window” (SoSo1). Another skipper (SoSo12) even states that he looks at the monitor 95% of the time but always tries to keep an eye on his surroundings. Therefore, a further challenge, which can impair traffic safety and even lead to health problems, is the constant shift of the actor’s attention between the sailing window to keep an eye on traffic and his monitors to ensure the quality of the measured data, as seen in Fig. 29. The elimination of media breaks by overlaying information directly into the user’s field of view is required to meet this challenge. For example, overlaying real-time information about other vessels, such as their position or direction of navigation, which is received via the Automatic Identification System (AIS) and currently displayed on different monitors, could help to ensure safety. One skipper mentioned difficulties occur when not all vessels are detectable in AIS. For example, he needs the vessel’s name to contact it directly by radio (SoSo13). If he does not know the name, he would have to address the vessel by its approximate position, which is not always clearly defined.

The real-time overlay requirement, therefore, arises from the need to display information in real-time and to overlay this display in the actor’s field of view to improve vessel traffic safety and prevent health issues. Especially the permanent alternation between the task of navigating the vessel and the task of measuring the water depths is reflected in constant view shifts, which can be avoided by providing an AR real-time overlay. Additionally, such an overlay can improve safety by enhancing situational awareness, especially during harsh weather conditions that reduce sight while dependence on digital information increases.

Variety in displaying information requirement. In addition to the frequent shifting of view between the vessel’s window and the monitors, a variety of sensor information and data about the soil-sounding area is displayed on different monitors, resulting in an additional constant shift between the monitors to ensure the quality of the measurement. Thereby the available space of the monitors is not optimally used, and sometimes even redundant information is displayed (see Fig. 30). However, in order to improve usability and thus enable the actor to execute the measurement efficiently, the actor requires multiple sensor information simultaneously, such as different layers or perspectives of the area of soil sounding, without information and the representation of this information being displayed redundantly.

Another difficulty that also leads to the current use of multiple monitors is that information about the water level in general and the measured areas, which include the quality and density of the data, cannot be overlaid in the current IT system but are both required to ensure both traffic safety and measurement quality, i.e., the performance of the two parallel tasks. Therefore, a further essential requirement regarding the presentation of information is that different views and representation options of the information should be distinguishable. In this context, we found out during the various think-aloud sessions that it is useful, for example, to have different zoom levels for the maps, since the actor requires more detail to navigate his vessel precisely, for instance, when measuring within narrow shore areas, than in wider water areas where he needs a greater overview. In several sessions, we could also observe that the actors displayed the required information differently. In some measurement situations, for example, displaying the water depths in the measurement area using different color scales was more helpful than displaying this information as exact numerical values and vice versa. Because skippers described navigating the vessel as exhausting and requiring concentration, especially in narrow areas, another requirement is that visual cluttering should be avoided despite the combination of multiple views.

Figure 29. Example of the permanent view shift between the sailing window and monitor

The variety in displaying information requirement, therefore, arises from the need to be able to choose different representation options of the information to display on demand in order to improve usability and traffic safety as well as ensure the quality of the measurement at the same time.

Figure 30. Variety of information and monitors on a soil-sounding vessel

Multi-dimensional tracking requirement. A vessel has an additional dimension of motion than other means of transport, such as bicycles or cars, making tracking the vessel's exact position even more difficult. This means that the tracking system must capture two different types of motion. The first is the movement of the ship on the water's surface, which can be caused to sway by the waves. The other one is the skipper on the ship itself, who can move independently on the ship. It is important for the skipper to be able to change his position during the day. One skipper mentioned (SoSo12, SoSo13) that he has to vary his position to avoid physical discomfort. In doing so, he changes to the steering wheel when driving long distances, for example. When he has to drive short distances, where he must be more concentrated, he prefers to navigate precisely with the joystick.

However, it is an essential requirement for the navigation of the vessel during soil sounding to track the vessel's exact position in relation to the environment. On the one hand, an inaccurate position determination can lead to measurement gaps and, accordingly, to a reduced measurement quality and, on the other hand, traffic safety can be impaired by incorrect positioning since, for example, distances to obstacles or other vessels can no longer be displayed correctly. Although GPS data are available, they are not sufficient for this case since these also change due to the rotation movements of the water surface. The tracking must be very resistant to wave-induced movements. For example, in soil sounding 1, soil sounding 2, and soil sounding 9, there were waves caused by other vessels coming very close to the sounding vessel, and we saw that the vessel was moving a lot, so the skipper had to hold on to the vessel.

In the case of the soil-sounding vessel, tracking is also made more difficult because the skipper is inside the ship and perceives the outside world through glass windows, making it difficult to avoid direct sunlight and reflections (see Fig. 31). Although the soil-sounding vessels are equipped with sun protection roller shutters, which can attenuate solar radiation, it is impossible to completely block the sun's rays without restricting the view outside too much by darkening it. Accordingly, in the case of the soil-sounding vessel, the skipper requires tracking that is resistant to sunlight and reflections.

In the drone use case, there are also two essential tracking instances. First, there is the tracking of the soil-sounding drone itself, which is complicated analogously to the soil-sounding vessel due to the water movement. Second, the tracking of the drone operator's position is relevant. If the drone operator is not on land but on board a vessel, the same tracking problems apply to the operator's position on the vessel as those faced by the skippers on their soil-sounding vessel.

The multi-dimensional tracking requirement, therefore, arises from the fact that the actor needs an exact positioning of the vessel to ensure traffic safety and the quality of the measurement data.

Figure 31. Direct sunlight and reflections

Collaboration requirement. During soil sounding, the actor must communicate a lot with other people to ensure traffic safety and measurement quality. Both in terms of traffic safety and measurement, the actor has to communicate with other vessels by radio in some situations. Since the soil-sounding vessel cannot always adhere to all traffic regulations, depending on the measurement area, it is often impossible for other vessels to estimate which route the skipper will take. For this reason, it is important to clarify by radio which side the two vessels will cross. However, communication by radio is not always trivial, as misunderstandings can occur, radio messages cannot be repeated, and thus some agreements cannot be understood well acoustically. One skipper explained: "On the water, miscommunication is a huge problem, and it can quickly become a serious problem" (SoSo13). Such issues lead to severe problems, as, for example, other ships have a longer braking distance, which can threaten the safety of both involved parties.

Concerning the task of measuring the water depths, the collaboration with the measurement engineer, who is responsible for the technical implementation of the depth measurement, such as the configuration of the echo sounders, is most important: “A good marriage also only works if you talk about everything” (SoSo12). Before and during the measurement, the actor and measurement engineer must continuously coordinate which areas are to be measured, how and when, and when the measuring devices must be activated or deactivated. They have to do this under consideration of different boundary conditions, e.g., the current water level. If the water level is too low, there is the risk of running aground, and if the water level is too high, it is, for example, no longer possible to pass every bridge. However, the constant communication about the observation of the live measured values and the flexible adaption of the course to them is of great importance since areas need to be measured again if the data quality is insufficient. Especially in unknown areas or very narrow areas, permanent communication is required. Furthermore, they have to plan very carefully in advance so that the work is not suddenly wasted and the assignment has to be repeated. A statement made by a skipper summarizes very well the importance of the collaboration between him and the engineer during soil sounding: “If I don’t synchronize with him [the measurement engineer], nothing will work” (SoSo7).

To support collaboration, the actor and the measurement engineer require the same visualization of the measuring areas, with additional highlighting of areas being useful because, especially when the measurement engineer is at the home office, it is not trivial to understand what the other person is talking about. It would also be useful to visualize whether the measurement device is activated and in which area it is currently collecting data. Provided that the measurement engineer is remotely connected, such as during our observations, the communication needs to be supported even more so that the barriers to communication can be reduced. Furthermore, the skipper must pick up a telephone receiver in order to use the radio. In soil sounding 7, we observed how the skipper held the handset of the radio with one hand and used the other hand to communicate via cell phone with the remotely connected measurement engineer (see Fig. 32). Thus, hands-free communication, i.e., without having to pick up a telephone, is required both with other vessels and the measurement engineer, enabling the actor to have his hands free for the navigation of the vessel and thus ensure safety.

The collaboration requirement, therefore, arises from the fact that the actor has to communicate with other vessels and, in particular, has to collaborate a lot with the measurement engineer in order to ensure both traffic safety and the quality of the measurement data.

Interaction requirement. The requirement of interaction goes along with the above-mentioned variety of displaying information requirement. Currently, information on the monitor cannot be manipulated by the actor; in other words, the actor cannot interact with the system and is only able to consume information. During several think-aloud sessions, we observed that the actor wanted to change the views on the monitor. Since the actor could not interact with the system himself, he had to explain the necessary changes to the measurement engineer, who could make the adjustments. It is, therefore, not possible for the actor, for example, to show or hide information or to zoom into a map to get a detailed view if he requires it, e.g., to avoid obstacles or close measurement gaps safely. In order to carry out navigation and measurement more safely and efficiently, the actor requires an appropriate opportunity to interact with the system.

The interaction requirement, therefore, arises from the fact that the actor requires to show or hide important information or select detailed views to ensure traffic safety and completeness of the measurement data. Furthermore, the way of interaction should be chosen so that the actor is not distracted from the navigation of the vessel.

Figure 32. A skipper operates the radio with one hand and talks to the measurement engineer on the other side by telephone

10.5 Discussion

10.5.1 Contribution to Research

Requirements for cognitive assistants are one of the core frontiers of digital service innovation (C. Peters et al., 2016). However, so far, little research on requirements for AR solutions as cognitive assistants has been done in safety-critical services that demand multitasking and collaboration. Especially in maritime navigation, research has so far fallen behind the possibilities that we can contribute to the scientific discourse in different areas here.

Since the chosen use case of soil sounding is mentally demanding, a high degree of situational awareness must be achieved to ensure traffic safety. Soil sounding requires actors to switch views between computer monitors and the real world. This immediately makes it apparent that AR is an excellent technology to support this use case. Coleman and Thirtyacre (2021) have shown that AR can assist pilots of aerial drones by avoiding view shifts and overlaying important information into the drone operator's field of view. Our empirical results show that the constant view shifts and context changes are enormously exhausting and endanger vessel traffic safety and cause mental and physical strain on the skipper. The view shifts occur because the skipper has to perform two tasks in parallel: the service process of soil sounding – i.e., measuring water depths – to ensure the harbor infrastructure and, thus, traffic safety for all traffic participants in the harbor and the navigation of the vessel. Since the safety criticality of the process can also be found in other areas, our results can be applied to other use cases. These can be ports in general, e.g., use cases in the context of control centers, but also other domains such as air traffic controllers, where a high level of concentration and situational awareness is required. In addition, similar requirements may also apply in large factories, e.g., where forklifts or high altitudes create safety-critical conditions.

Moreover, soil sounding demands a high degree of collaboration between the skipper and the measurement engineer, which bears the potential to be supported by AR, e.g., through a shared visual base. Studies have shown that performing two tasks in parallel is much more demanding and results in a significantly higher mental workload (Illing et al., 2021; J. Y. Lee et al., 2016). Our results underline the findings from the literature, as skippers described navigating in narrow areas as very challenging, requiring them to concentrate much more. We propose the real-time overlay requirement to eliminate these view shifts and support situational awareness. The contextual requirements related to real-time overlay provide a guideline for the data that must be overlaid in the field of view in an AR application. One important aspect mentioned by the skippers is the display of AIS data, which includes the exact position and additional information about vessels. A study by von Lukas et al. (2014) shows initial attempts to display AIS data in an AR application. However, the application was limited to displaying the AIS data and did not contain any additional data essential for our case. For example, in addition to the AIS data, skippers for soil sounding need further information about the measurement quality and task, as well as rapidly changing conditions such as currents, tides, or wind direction. The diversity and amount of data the skipper needs to perform the soil sounding leads us to propose the requirement of variety in displaying information. In addition, the skipper must be able to interact with the AR application. The interaction should not interfere with the control of the vessel and should allow for hands-free operation (Johnson et al., 2015; Niemöller et al., 2019). Thus our results are applicable to contexts where multiple tasks are performed simultaneously. In our case, the skipper must navigate the vessel while simultaneously capturing water depth measurement data on the monitor and collaborating with the measurement engineer and other vessels via radio. Especially in navigation settings such as cycling or driving, several parallel tasks quickly occur, e.g., reading information on the navigation device and making a phone call simultaneously while participating in traffic.

Compared to the requirements for smart glasses-based AR systems for cycling training (Berkemeier et al., 2018) and to the use of AR in driving situations (Heymann & Degani, 2016), the commonality remains that in all these cases, an AR solution is used in a mobile environment and the users act in a traffic situation. A mistake in road traffic and a mistake in navigating a vessel can have serious consequences. However, unlike cycling or driving, our use case takes place in an environment with more degrees of freedom with respect to movement, which increases the technological requirements for precise tracking because multiple instances of tracking need to be combined. The multi-dimensional tracking requirement is, therefore, more demanding for AR hardware resource-wise than it is in the case of road traffic. The skipper must be tracked within the vessel, while the information displayed must be relative to the vessel's movement and the skipper's perspective. Accurate tracking is essential, especially for soil soundings where the measurement must be made in a narrow area or heavy traffic. This applies not only to soil-sounding vessels and drones but to all other types of vessels as well, whereby the failure tolerance decreases as vessels approach narrow or restricted fairways and higher traffic density (Gardenier, 1981). However, it is also conceivable that the findings are applicable to navigation in airspace, where movements in 6 DOF are also possible, even if they do not appear at first glance as arbitrary as the movements caused by the water surface. Our use case can be deliberately considered as an edge case, which imposes high requirements. For this reason, a transfer to less demanding requirements is possible. The presented edge case aims to extend our understanding of AR applications from a more general perspective. Consequently, aspects of this use case can be applied in other contexts while not all specific features have to remain constant.

Moreover, our approach contributes to new research standards from a methodological point of view. By underpinning the thinking-aloud method with video material from various perspectives, we were able to gain the best possible understanding of the spatial implications and requirements for AR. Thereby the enriched thinking-aloud material helps to gain further insights and learnings about the user-centered requirements. Additionally, our approach is beneficial in environments that do not meet the standards of typical scientific interviews by being noisy, weather-dependent, and dirty.

10.5.2 Contribution to Practice

The identified requirements for the mobile use case of water depth measurement provide anchors that AR solution developers can use as guidance to develop an application that best supports users in performing their service process in mobile settings with multitasking. In particular, the detailed analysis of the problems and challenges encountered in the soil-sounding service is very practice-oriented, and the contextual requirements derived from it serve as a guide for design decisions in the development of an AR solution. Depending on the use case setting and the tasks to be performed, the requirements are to be weighted differently and prioritized in the implementation. As the process of soil sounding is a difficult case from practice, and therefore laboratory conditions are not given, implementing an AR solution is a big challenge, but it should be tackled to support practice. Once such a complex use case has been solved, it is relatively simple to adapt and scale the principle to other, less complex applications. Specific to our use case, successful implementation of all the requirements in an AR solution for practical use promises to increase safety in shipping, ensure the quality of measurement data, support collaboration, and prevent health problems.

10.5.3 Limitations and Future Research

However, our approach is not entirely free of limitations. Due to safety reasons and legal requirements, we could only conduct the think-aloud sessions with experienced skippers with much tacit knowledge due to their many years in the soil-sounding process. Between our three different skippers, who have seven, 13 and 15 years of experience in the process of soil sounding, there is already some initial evidence that the perception of the requirements may vary depending on experience and tacit knowledge. If the same survey were done with more inexperienced skippers, the requirements for an AR solution would likely have different levels of intensity. Thus, it could be that more inexperienced skippers are even more reliant on AR support to fill the experience gap around the missing tacit knowledge. Furthermore, our results are contextual since we have only focused on one specific use case, that of soil-sounding in water depth management. A first small transfer has already taken place within our use case itself, namely with regard to the use of the soil-sounding vessel and the use of the soil-sounding drone. All five requirements that we were able to derive for the soil-sounding vessel were also determined for the drone use case. Accordingly, we assume transferability to other use cases. In this regard, further use cases in the maritime logistics environment could be considered. One possible use case is the dredging industry, responsible for adjusting and dredging the water depths. Additionally, use cases in the field of pilotage in the harbor could be considered. Not least, the transferability to other use cases in general industry, as well as logistic scenarios, remains to be investigated.

Future challenges will be to determine whether supporting the process with AR is beneficial for the skipper from a user perspective and, if so, in what form AR as a cognitive assistant can be used to achieve the greatest possible advantage. For this purpose, a prototypical implementation and evaluation will be initiated in the future to explore the subjective usefulness of AR in the soil-sounding context. In this context, the requirements should be evaluated in more detail with experts from the maritime industry as well as AR solution developers regarding their technical feasibility, whereby the focus should be on interfaces, data types and data quality.

10.6 Conclusion

Before investigating what requirements an AR cognitive assistant must meet to support the service process of soil sounding, we examined the augmentability of the process using the theory of process augmentability (Yeo, 2017). To answer the first research question (RQ1), we could determine that all four characteristics – which according to the theory, must be present in a process – are existent in the process of soil sounding so that augmentation of the process is sensible and could help to facilitate and improve the process.

Knowing the augmentation potential, we derived five generalized user-centered requirements for the soil-sounding process, using the results of the thinking aloud sessions as a foundation: (1) real-time overlay, (2) variety in displaying information, (3) multi-dimensional tracking, (4) collaboration, and (5) interaction requirement. This answers our second research question (RQ2). The requirements for an AR solution as a cognitive assistant, which we have determined with regard to the navigation task of the actors, correspond to the results of previous research on AR applications in road traffic. However, prior research did not investigate such a complex process in the maritime industry, so we are contributing to the research at this point. On the one hand, the moving vessel, in combination with the moving user inside the vessel, poses a great challenge in terms of multi-dimensional tracking possibilities. On the other hand, it is a safety-critical process that requires multitasking and situational awareness, i.e., a constant shift between the navigation of the vessel and the measurement of water depth, as well as collaboration with the measurement engineer. With the help of these five requirements, we provide practitioners and scholars with a foundation to assist in the development of AR applications in the above environment.

10.7 Acknowledgements

This work has been partly funded by the Federal Ministry of Education and Research of Germany (BMBF) under grant no. 02K18D180 and 02K18D181 ("WizARd – Wissensvernetzung und Kollaboration durch Anwendung erweiterter Realität in produktionsnahen Dienstleistungen"). An earlier version of the manuscript has been presented at the Wirtschaftsinformatik Conference (Osterbrink et al., 2021).

Funding

Open Access funding enabled and organized by Projekt DEAL.

Open Access

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11 Dividing Complexity to Conquer New Dimensions – Towards a Framework for Designing Augmented Reality Solutions

Bräker, J., & Semmann, M. (2022). Dividing Complexity to Conquer New Dimensions – Towards a Framework for Designing Augmented Reality Solutions. *Proceedings of the Americas Conference on Information Systems*

Abstract

Augmented reality (AR) can foster service innovation and thus cope with some of the most urgent challenges in the service science domain, namely supporting frontline workers while ensuring high safety standards. Therefore, the utilization of AR can help to achieve these goals. On the contrary, AR remains a complex technology with specific requirements and preconditions that demand expertise to overcome them. Based on a case study, we derive a framework for designing AR solutions, which helps divide the complexity of designing and developing AR-based services to support the adoption and diffusion of AR applications. Such an encompassing perspective on initial AR explorations helps to transform the acquired information into a thorough proof of concept, pilot implementations and ultimately productive software.

Keywords

Mixed reality, case study, service innovation, value creation.

11.1 Introduction

The transformative character of the last years leads to a new perspective on work and how the workforce should be supported (Ostrom et al., 2021; Wirtz et al., 2018). Especially service research must be aware of these changes, as the service sector is the driver of modern economies. We often focus on highly skilled and educated professionals with desk jobs within service research. However, approximately 75% of the global workforce is frontline workers who partially carry out physical work (Porter & Heppelmann, 2020). Building on this estimate, one of the core priorities of our field is service research. This involves supporting frontline workers in service delivery through technological innovation to save costs and improve the customer experience (Ostrom et al., 2021).

A technology that helps address these issues is augmented reality (AR). AR is a disruptive technology that enables blending the analog world with digital information. AR bears the potential to increase employee productivity while reducing error rates (Porter & Heppelmann, 2020). Despite the transformative nature of existing services, AR is a strategic driver of innovation (Panetta, 2020). By enabling remote access for experts (Obermair et al., 2020) and immersive training possibilities (Büttner et al., 2020), AR is a response to the demand for workforce flexibility through cross-training (Ostrom et al., 2021). In addition to services in industrial settings, the retail, hospitality, and healthcare sectors also benefit from AR (Jingen Liang & Elliot, 2021; Klinker et al., 2020a; Zimmermann et al., 2023). Given these technological potentials, it remains counterintuitive that practical application is still scarce (Steffen et al., 2019). However, digital transformation and the adoption of emerging technologies are not trivial (Grotherr et al., 2019). The realization of the intended benefits often falls behind expectations and requires further lightweight methodological foundations (Semmann & Böhmann, 2015). The barriers between an initial idea to use AR in services and the practical implementation remains significant. Piloting requires analysis and well-advised selection of the use case as well as a customized solution tailored to the organization and the service, which is highly time-consuming and knowledge-intensive. For this reason, the remaining option is often to obtain expertise through external consultations, which is associated with high costs. Alternatively, the organization must develop the competencies itself, which is not less time-consuming and expensive. This makes it challenging to evaluate quick and easy proof of concepts. Limited budgets and lack of technical experience are especially problems for SMEs (Stentoft et al., 2019). As organizations become more aware of the potential of AR as innovative technology and seek to reap the resulting benefits, there is a need for a supporting guideline on how to make piloting AR applications easily accessible to a broad audience.

To bridge this gap, we provide a design framework for systematically developing AR solutions to support its diffusion and adoption. In this regard, we answer the following research question: *How can organizations systematically approach AR as a technology to support services and improve productivity while reducing the initial barriers to AR adoption and diffusion?* To answer this question, we develop a design framework for AR solutions based on qualitative and quantitative data from a case study. The framework aims to enable a comprehensive approach and helps define and analyze AR use cases to support thorough proof of concepts and outline key aspects of an initial prototypical implementation.

The remainder of the paper is structured as follows: in the second section, we lay out related work regarding AR and the adoption of innovation. In the third section, we present our mixed-method approach, including the case study and data obtained. We subsequently develop the design framework and showcase its application using a scenario from the case study. Finally, we discuss the results, draw a conclusion, and outline future research avenues.

11.2 Related Work

AR encompasses scenarios in which virtual, computer-generated objects extend or overlay reality. The components of reality are predominant and are enriched with digital content. Overall, AR can be located on a continuum ranging from the real world to a completely virtual environment. This continuum is known as the virtuality continuum (Milgram & Kishino, 1994). With the help of AR, virtual objects can be blended into reality, while real objects can be removed with graphical overlays (Azuma, 1997). Various hardware alternatives are available for implementing AR. These include head-mounted displays (HMDs) such as AR glasses and hand-held displays such as smartphones or tablets. Projection-based spatial AR uses projectors to superimpose reality with virtual objects (Bimber & Raskar, 2006). Specific hardware requirements, particularly for HMDs, imply several challenges that must be handled. These include resolution, the brightness of the environment, brightness and contrast of the virtual overlays, the field of view, refresh rate and associated delays, as well as safety when wearing an HMD. When developing an

AR solution, the system's portability and the different tracking technologies and interaction patterns should be considered (Azuma, 1997).

Service design and alignment with organizations play a crucial role in service innovation. Especially with rapidly evolving technologies, it is even more important to consider these in service design and service innovation (Ostrom et al., 2015). Rapidly increasing digitalization makes it even more difficult to take advantage of new technologies. Therefore, early support is needed to understand what innovation means in an organizational context. Technochange management combines the use of IT and its organizational impact to optimize business performance (Markus, 2004). It is crucial to align IT and business to achieve the most effective results. At the same time, IT innovation and change in the enterprise are mutually dependent, so new technologies cannot be deployed in isolation from the enterprise context.

11.3 Methodology

Our methodology for developing the framework follows a mixed-method approach (Venkatesh et al., 2016; Venkatesh et al., 2013). To gain initial insights into the use of AR in a service context, we conducted a comprehensive case study (Yin, 2009) at a large European maintenance, repair, and overhaul (MRO) service provider in the aviation sector. We investigated the inventory process in the warehouse of the in-house logistics service provider. In the given use case, the inventory process must be performed daily to record current inventory levels continuously. We chose different approaches to identify the different actors and resources involved as well as understand the value creation of the service and existing barriers to AR adoption.

First, we began with a qualitative approach, conducting observations at four different warehouses and the inventory coordination office to follow the service delivery of inventory directly in the field. We documented the observations using ethnographic field notes (Emerson et al., 2001, 2011). Because we did not intervene during the observations, we conducted additional qualitative, non-standardized interviews to gain further insights into the challenges during service delivery. We interviewed the logistics service provider employees who carry out the inventory service themselves or coordinate it and the associated IT department that maintains the logistics IT applications for a technically oriented impression. Moreover, we interviewed the healthcare management, the works council, and the coordinator responsible for the communication between the IT department and the logistics service provider. Last, we talked to the person responsible for mixed reality technologies to capture the organization's current state of AR usage. We documented the interviews using hand-written notes (Rubin & Rubin, 2011).

To investigate the use of AR in a concrete example, we conducted a user study with 33 employees in which we piloted a prototypical AR application. The application assists in the inventory process by guiding wayfinding in the warehouse, overlaying important clues, and enabling the input of recorded quantities. Using questionnaires, we collected quantitative data that was further strenghtened by the think-aloud method (van Someren et al., 1994) during the user study. Participants were asked to think aloud and verbalize everything that came to their minds during prototype use. To further enrich our findings, we conducted two workshops at the MRO service provider with seven experts from the MRO's IT department and the logistics service provider. The workshops were based on the design-thinking approach and focused on assessing the suitability of various services for the use of AR. We analyzed the documentation of the observations, interviews, workshops, and user study questionnaires and derived the requirements for environmental conditions for AR use. We consolidated similar requirements and enriched the data with insights from established ISO standards to ensure better generalizability. The results contribute significantly to the first level of the AR design framework.

To further develop the AR design framework, we built on existing prior work (Bräker, Hertel, & Semmann, 2022; Bräker & Semmann, 2021) and conducted two additional workshops with a panel of experts. The expert panel consisted of five experts, three from academia in the field of human-computer interaction and information systems and two from practice, more specifically from one of the leading companies for custom AR applications in the industry. The focus in the third and fourth workshops was no longer on a specific use case but dealt with the development process of AR applications as well as its challenges in general. During the third workshop, we developed an initial user journey for the service design process of an AR application with the expert group. The results of the user journey are mainly reflected in the four levels of the framework. After creating a first version of the framework, we evaluated our results from different perspectives during a second workshop with the same group of experts. We used the results to develop the final framework, which we present in the following section.

11.4 Result – Conceptualizing the Design of Augmented Reality Solutions

To make the entry and use of AR in an organizational context as effortless as possible, we have developed the framework for the design of augmented reality solutions. As shown in Figure 33, our model is built on different levels of abstraction and follows a top-down approach. This way, we ensure that organizations, especially SMEs, can create and pilot AR applications by proceeding from the general requirements of the service context to technical details. The user's AR experience and technical expertise are irrelevant when applying the framework. Both technical and domain experts are empowered with this tool to pave the way for AR adoption.

Environmental Conditions. Our case data (observations, interviews, user study, workshops 1-4) suggest that when identifying and analyzing services, several requirements are essential for a use case to benefit from AR. These requirements are also covered in international guidelines such as the ISO standards ISO/IEC 25010 and ISO 6385, which explicitly address general software quality requirements and ergonomic principles (International Organization for Standardization, 2004; International Organization for Standardization/International Electrotechnical Commission, 2011).

Under environmental conditions, we subsume general factors in the service environment, which can relate to the entire service process or only to individual process steps. If the service occurs under changing environmental conditions, this can be annotated at the first level. The information documented here is used to evaluate the process's general suitability for augmentation. Subsequent decisions, such as selecting suitable hardware or tracking technology, can be supported by the information collected. In the context of environmental conditions, the location of service provision should be investigated in terms of technical prerequisites, location-related aspects, and potential interferences. Particularly in an industrial context, it may be noisy or dusty environments. In other contexts, the process may be exposed to challenging weather conditions, non-optimal or changing lighting. The need to wear work clothing, such as work gloves and the size of the environment play a role in the design of the AR application. For example, a small environment, such as a single workbench, has different requirements than a larger environment, such as an entire warehouse. Further, the distinction between changing and static environments has an impact. System integration and interfaces to other information systems, as well as technical factors such as the need for a permanent network connection, should be captured. It may be documented if the process is subject to special ergonomic requirements or demands hands-free or mobile working. There are specific service domain aspects in some cases, such as healthcare hygiene requirements (Klinker et al., 2020a).

We propose a checklist approach for the environmental conditions to keep things simple. The result of this level can assist in selecting hardware and interaction techniques. Although our framework can support the recommendation of different hardware options, we do not force hardware decisions. One reason for this is the rapidly evolving hardware. On the other hand, our main focus is on how the intended information is displayed in an AR application, not on the hardware used to display that content. Nevertheless, hardware requirements, such as hands-free working or weather resistance, can be derived from the framework. In addition, we support technology and platform independence so that the augmentation can be displayed on a tablet as well as on an HMD or projection-based solution. In this way, we strive for a high degree of flexibility. Hardware selection, if the needed skills are not available in the organization, can be supported by experienced consultants who are knowledgeable about the technological state-of-the-art. Questions that can be answered based on the environmental requirements include: does the AR hardware need to be head-mounted? Is it required to fit beneath a helmet? What input capabilities are required, e.g., controller input, hand tracking, eye tracking? Is a video see-through device required for clearly visible augmentations, or does the work environment necessitate a latency-free, optical see-through display? Is it necessary for the device to be able to track itself in 3D space? Although these questions are reasonable, for the sake of this paper, we do not focus on them and refer to prior work on interaction classification (Bräker, Hertel, & Semmann, 2022; Hertel et al., 2021) and hardware selection options (Bräker et al., 2021).

Actions. At the actions level, we look at the service process and its actions. Existing process models, e.g., BPMN (Object Management Group, 2011) or service blueprints (Bitner et al., 2008), can form the basis for this, but simple modeling using flowcharts can also be sufficient. One result of the analysis is to answer whether AR can be integrated into the existing process or whether it must be redesigned. In the case of established services, whether a process change provides value should be evaluated. As a recent study shows, no specific and widely acknowledged approach to business process modeling for AR exists, although the analysis of the process, in the beginning, is a success factor (Bräker & Semmann, 2021). For this reason, the process modeling presented in our design framework for AR solutions should rather be seen as a placeholder. The third and fourth expert workshops confirm the importance of

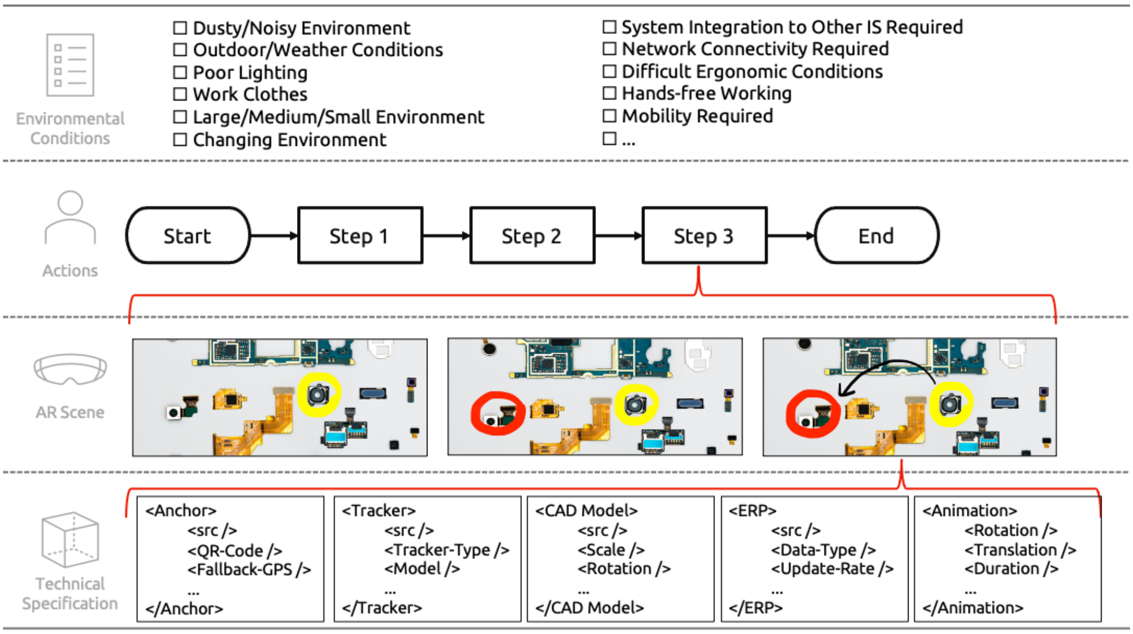


Figure 33. Design framework for AR solutions

process understanding. Furthermore, it was examined that less complex forms of notation, such as flowcharts, should be investigated for their suitability for modeling innovations and AR specifically, as these promote accessibility, especially for SMEs (Bräker & Semmann, 2021). Since most AR processes are relatively simple, sequential, and straightforward, we instantiated an example process using flowchart notation in Figure 33. In doing so, we encourage broader use in practice, as the flowchart notation is quite comprehensible. When multiple actors are involved in the service process, the framework can be applied and filled out for each process participant.

AR Scene. The design and content of the AR application are mapped on the AR scene level. The AR elements are documented, and, depending on the level of augmentation required, it is possible to specify one or more AR scenes for each process step. The data of the third and fourth workshops show that a direct annotation of photos is an accessible way for inexperienced users to visualize their idea of the AR scene. An image of the actual scene or the workplace can be used as a starting point. This way, it is easy to get a shared understanding of the goal. If an image of the scene is not available, a simple sketch is also appropriate.

The result is a storyboard that defines one or more AR scenes for each process step. For example, in Figure 33, a specific part of a construction kit to be assembled is first highlighted. Then a second part is highlighted, and an arrow indicates that both components are to be assembled. However, the augmentation should not be limited to these two functions and can, for example, include text fields, buttons, or links to documents. Interactions between the user and the AR application can also be examined in this step (Bräker, Hertel, & Semmann, 2022; Hertel et al., 2021). Such a representation can simplify the technical implementation enormously because widely used development platforms such as Unity are also scene-based (Unity Technologies, n.d.-b), so a transfer of the information to a Unity scene can be done quickly.

Technical Specification. Technical specifications can be defined for each AR scene at the final level. They are closest to implementation and refer to the attributes of the virtual objects or augmentations. If the user is unaware of the technical parameters or does not have the required technical knowledge, they are not compulsory, although beneficial. The relevance of the technical specification was confirmed in the third and fourth expert workshops, as it is the most precise kind of information for developers and authors of AR applications. For notation, we propose an XML-based approach, such as the augmented reality markup language (ARML 2.0) (Open Geospatial Consortium, 2015). However, any form of notation can be used here that fits the state-of-the-art technological approaches. Thus, current frameworks like Google's ARCore or Apple's ARKit could be embedded in this layer. Tracking information such as anchors, i.e., the localization in reality, or tracking types such as markers or object-based tracking are specified here. If CAD models are helpful for the augmentation, these can be specified here as well. However, CAD models are not always mandatory, even if the data is available. Simple augmentations are often sufficient for simple and easy prototyping, so more details are not necessarily profitable. If virtual objects such as 3D models, documents, or text fields should be integrated, the user might specify these attributes. Furthermore, the specification of animations, e.g., the duration or type of animation, can be helpful for the later development of the AR application. However, data from information systems within an organization, e.g., data from an ERP system, could also be specified. We argue to define the technical specifications per AR scene and describe all augmentations in as much detail as possible.

Subsequently, using the data collected via the framework, the implementation of the AR application can begin. Due to the many implementation possibilities, our framework focuses on the steps before implementation and aims to provide a comprehensive description of the AR application. The development can be automated by entering the content into an appropriate authoring platform, or the application is developed manually. Following the development of the application, a piloting phase can be entered, in which its usefulness is evaluated. This may yield new information that can be utilized in a future iteration of the AR application. Finally, after piloting, the advantages and disadvantages can be weighed at the management level, and if the piloting is successful, the application can be transferred into practice.

11.5 Showcasing the Design Framework for Augmented Reality Solutions

To demonstrate the framework, we apply the model to the exemplary service of stock inventory in a warehouse. The process described below occurs in the context of a large European MRO service provider in the aviation sector, more precisely at their in-house logistics service provider. A so-called permanent inventory is performed daily to record the current stock levels in the warehouse. As shown in Figure 34, the service is delivered within a large environment that underlies changes, and work clothes must be worn. In addition, an interface to the data of the warehouse management system is essential, e.g., to retrieve current inventory orders or enter the quantities of the items. Furthermore, the process is subject to special ergonomic conditions, as materials must be moved and taken out. These are especially challenging when the user needs to operate a forklift. Since some materials are counted and recorded directly at the storage location, working hands-free is advantageous. The service delivery requires mobility because the materials are distributed over the entire warehouse. The service is also subject to special safety-critical requirements, as storage locations that are sometimes difficult to access are served with a forklift truck.

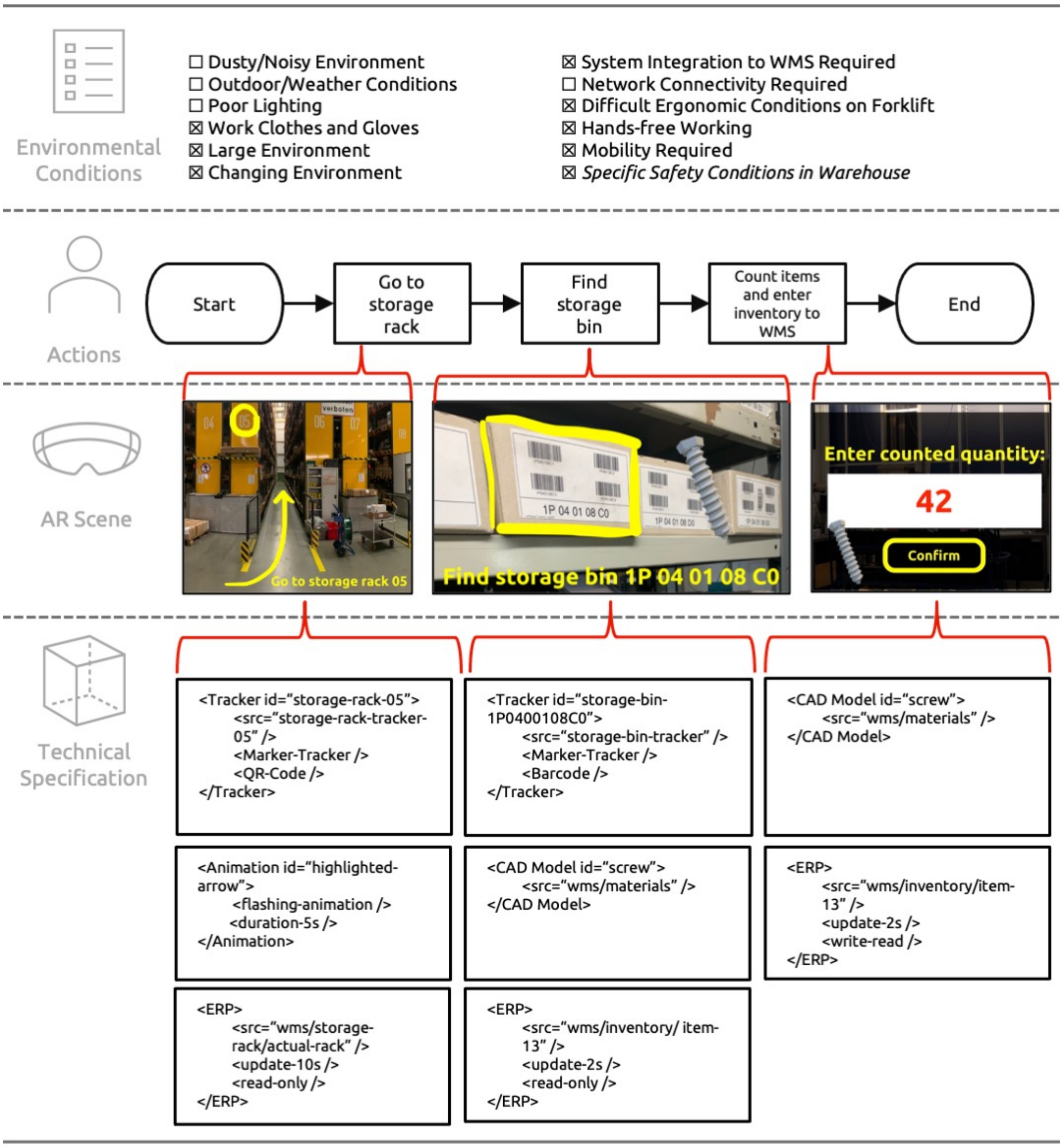
The inventory process itself is designed relatively simple. In the beginning, the user searches for the corresponding storage rack. Afterward, the user looks for the correct storage location in the storage rack where the material is located. Finally, the material must be counted, and the quantity is checked and stored in the warehouse management system (WMS). Throughout the entire process, the environmental conditions described above apply.

The next step at the AR scene level is to visualize the process augmentation. Navigation to the destination is helpful, but instructions on what to do next can support the process. In this example, the user must first go to the rack with the number five. Then the user can be navigated to this rack using an arrow, and the shelf number is highlighted. Once in the rack aisle, the task is to find the corresponding storage location. This can also be highlighted by the augmentation and supplemented by the textual display of the storage location. In addition, the material is displayed as a 3D representation in the form of a CAD file to avoid errors. Finally, the user receives an input mask to transfer the existing quantity to the WMS directly.

The last level contains the technical specifications. Here, the properties of the virtual objects can be defined for each AR scene if the information is available. For example, in the first scene, marker tracking in the form of a QR code is used to detect the storage rack. In addition, the arrow has an animation that lasts for five seconds and flashes. Furthermore, data from the WMS is needed to show the current storage rack. This data is updated every 10 seconds, and the interface only needs to be given read access to retrieve the information. In the second scene, tracking is also used, but this time through the already existing barcodes. In addition, the source of the CAD model of the material to be counted is defined. In order to display the correct storage location, access to the WMS is required, which is updated every two seconds and needs read-only access to retrieve the data. In the third and last scene, the 3D model of the screw is used again to prevent errors. Write access to the WMS is now required to enter the counted quantity and, if necessary, read access to compare the entered data.

To showcase another exemplary application of the framework, we applied it to an example from the consumer shopping sector, the IKEA Place app, released in 2017 (Ozturkcan, 2021). This AR application allows customers to view IKEA furniture in their own house before purchasing and assembling it. The application of our framework to this app can be imagined as follows: Because the environment is comparatively less demanding and usually not exposed to dust, disturbing weather conditions, or workplace safety conditions, the environmental conditions are relatively simple and have minimal impact on the subsequent steps. The process and user actions are relatively straightforward. Objects can be selected and placed in the room. The user must select a piece of furniture and choose a position in the room to accomplish this. In that position, the piece of furniture should be placed in the room, aligned in the correct size. This requires a tracking mechanism that reliably recognizes the room's structure, such as the floor. Furthermore, lightweight CAD models of the furniture components are required, and synchronization of the associated data from the IKEA Shop system.

Another use case for the framework is an assembly and maintenance process in an industrial context. AR is already used successfully in these areas, but the development of customized applications still involves a great deal of effort (Mourtzis et al., 2017). To map an assembly process, the environment must be analyzed



☐ Dusty/Noisy Environment
☐ Outdoor/Weather Conditions
☐ Poor Lighting
☒ Work Clothes and Gloves
☒ Large Environment
☒ Changing Environment

☒ System Integration to WMS Required
☐ Network Connectivity Required
☒ Difficult Ergonomic Conditions on Forklift
☒ Hands-free Working
☒ Mobility Required
☒ *Specific Safety Conditions in Warehouse*

```
<Tracker id="storage-rack-05">
      <src="storage-rack-tracker-
      05" />
      <Marker-Tracker />
      <QR-Code />
</Tracker>
```

```
<Animation id="highlighted-
arrow">
      <flashing-animation />
      <duration-5s />
</Animation>
```

```
<ERP>
      <src="wms/storage-
      rack/actual-rack" />
      <update-10s />
      <read-only />
</ERP>
```

```
<Tracker id="storage-bin-
1P0400108C0">
      <src="storage-bin-tracker" />
      <Marker-Tracker />
      <Barcode />
</Tracker>
```

```
<CAD Model id="screw">
      <src="wms/materials" />
</CAD Model>
```

```
<ERP>
      <src="wms/inventory/ item-
      13" />
      <update-2s />
      <read-only />
</ERP>
```

```
<CAD Model id="screw">
      <src="wms/materials" />
</CAD Model>
```

```
<ERP>
      <src="wms/inventory/item-
      13" />
      <update-2s />
      <write-read />
</ERP>
```

Figure 34. Application of the design framework for AR solutions for the inventory service at an MRO logistics provider

initially. For example, if it is a factory floor, the requirements for the specific case must be given. Especially during assembly, a hands-free operation is critical. If a plant is imagined to be located outdoors, the process is sensitive to weather conditions and changing lighting circumstances. If work clothes, such as work gloves, are worn, and the user has to visit various stations on an outdoor site, we have entirely different requirements than with the IKEA app. However, the process is usually relatively straightforward, with few variations and ramifications in the process. It would then be important in the augmentation that parts to be assembled or maintained are highlighted, and the user can see the steps of the instructions. In this way, the user does not have to carry extra instructions and receives all the information for the respective work step, depending on the context. This also requires tracking on the technical side, which could be object-based in this case. In addition, the associated CAD models and the work steps from the user manual are required.

11.6 Discussion

Applying the design framework for AR solutions presents that a comprehensive overview of AR scenes helps identify the benefits of innovative solutions for services. The framework enables an incremental development of an understanding of how AR can be applied and what is needed to support services. An initial assessment of the environmental conditions allows to reflect the institutional arrangements of service and delineate critical resources. Building upon and extending the resources applied, the process behind the service is laid out as an anchor for the design of AR scenes. These scenes represent the integration of physical and digital resources to fulfill tasks in a service system. The actual implementation of the service is represented in the technical specification that defines crucial resources technically to enable a representation within the AR scene.

Based on this understanding of developing a framework for AR in services by applying the design framework for AR solutions, further specifications within the framework need to be considered. First, the interplay of actions and AR scene levels could be further elaborated. It could be beneficial to specify the types of interaction users take in an AR scene. As the purpose of the framework is to provide an accessible tool as a starting point for the application of AR that should enable end-users to assess their services regarding the applicability of AR, we did not add individual interactions in the framework. Such specification would require a perspective with expertise in AR to define what interaction would fit the purpose within the AR scene. In the same regard, a professional assessment is needed to evaluate if representations and interactions in an AR scene are needed and beneficial for service delivery. Representing too much information in an AR scene could lead to information overload, as C. C. Yang et al. (2003) described for the internet. A solution could be to guide inexperienced users with examples and interaction patterns typically applied in AR scenes. This could lead to an increase in the maturity of the AR scene descriptions that build the foundation of prototypical implementations of the service with AR.

Another aspect to consider is interactions with trackable objects. Such interactions increase the complexity of AR scenes as CAD data need to be integrated and manipulations on the objects are performed. Maintenance and repair services (Metzger et al., 2018) or remote services (Aleksy et al., 2014; Mourtzis et al., 2017) are typical examples. Such services can be represented within the framework but rather as a rough estimate than a full-fleshed conceptualization. In addition, specific templates for reoccurring tasks could be integrated into the framework. These tasks could include, for example, the search and discovery of specific objects and points of interest. However, data input or tasks like communication and collaboration can be prefilled exemplarily. So far, there is no standard for typical AR tasks in the literature, so future research should aim for a classification.

Finally, there are limitations to our approach. First and foremost, an application and evaluation in practice are needed to refine the framework further and validate its usability by domain experts with limited AR experience. Additionally, it would be beneficial to gain a deeper understanding of the actual influence of AR on value creation and the perception of the service by customers and service providers.

11.7 Conclusion

Based on a guiding case study, we aimed to reduce the barriers to utilizing AR for improved services, especially for SMEs. Therefore, we propose the design framework for AR solutions that enables actors with limited experience in AR to establish a proof of concept and follow a pilot AR implementation. This is enabled by dividing the complexity of AR applications into smaller sections that can be tackled step by step. Following the levels of the framework, services are assessed comprehensively at multiple levels and potentially by multiple actors with ideally a diverse set of backgrounds and expertise. By doing so, key information is gathered about institutional arrangements, the working environment, and core resources. By laying out the resource integration within the AR scenes, relevant information for a later implementation is given by simultaneously providing a better understanding of the AR-based solution.

The lightweight approach reduces the barriers for organizations to explore use cases for AR and guides this process aiming to design an initial proof of concept that easily can be extended towards prototypes and, in the long run, to productive AR solutions for services. From a research perspective, our framework bridges the gap between more process-oriented IS research to more interaction and AR scene-driven research in the area of human-computer interaction.

11.8 Acknowledgments

This research was partly sponsored by the German Federal Ministry for Education and Research in the project WizARd under the reference 02K18D181. Further information can be found under: http://www.wizard.tu-dortmund.de/.

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12 The Process Augmentability Canvas – How to Find the Sweet Spot for Augmented Reality

Bräker, J., & Semmann, M. (2023b). The Process Augmentability Canvas – How to Find the Sweet Spot for Augmented Reality. *Proceedings of the European Conference on Information Systems*

Abstract

The adoption of augmented reality (AR) has been one of the defining technological trends of the past decade. While AR has experienced significant growth in consumer electronics, its potential for professional use still needs to be explored. Despite the growing interest in AR, determining its feasibility and potential to satisfy business needs remains challenging. To address this gap, we used a mixed-method research approach to create a guiding framework called the process augmentability canvas. Drawing on a comprehensive case study of a major European maintenance, repair, and overhaul service provider, as well as state-of-the literature, we present a canvas that allows scholars and practitioners to evaluate AR's applicability for a given process thoroughly. By providing a structured approach to analyzing AR solutions, the process augmentability canvas contributes to a better understanding of how AR can be used efficiently in organizational settings.

Keywords

Augmented reality, canvas, service innovation, service design.

12.1 Introduction

Digital technologies have transformed the possibilities available to organizations in improving service provision and operational efficiency. However, assessing the applicability and usefulness of digital technologies in organizational contexts remains challenging. This is particularly true for augmented reality (AR), which has already become a commodity from a customer's perspective. Especially through the use of AR on mobile devices, as demonstrated by popular mobile applications like Pokémon GO (Lintula et al., 2017) and IKEA Place (Ozturkcan, 2021), AR has become popular. In services, AR provides benefits through process support, enabling hands-free working and training possibilities (Bräker, Osterbrink, et al., 2023; Klinker et al., 2020a; Placencio-Hidalgo et al., 2022). Despite the enormous potential of AR for digitization in industrial settings, its adoption in these areas remains scarce. This scarcity may, in part, be due to a lack of understanding regarding the key challenges and success factors involved in implementing AR technologies (Masood & Egger, 2020). While previous research has explored the challenges and requirements in specific services (El-Shamandi Ahmed et al., 2023; Hobert & Schumann, 2017; Osterbrink et al., 2021; Prilla et al., 2019; Zubizarreta et al., 2019), little attention has been paid to identifying services that benefit from AR (Bräker & Semmann, 2022; Steffen et al., 2019). In particular, small and medium-sized enterprises (SMEs) with limited resources and knowledge require more decision-making assistance. As such, guidance is needed to help organizations identify services best suited for piloting and implementing AR. To bridge this gap, we propose a mixed-method approach to answer two research questions:

RQ1: What criteria determine the suitability of AR for services?

RQ2: How can processes be identified that benefit from AR?

To achieve this, we introduce the process augmentability canvas. It is a framework that supports practitioners and scholars in identifying the sweet spot of AR by defining process characteristics and environmental variables that influence the suitability of AR. Our canvas proposes a representation of decisions needed to identify, assess and realize the potential of AR in practice. We build on the wide acceptance and application of such canvas tools as prominently introduced with the business model canvas (Antunes & Tate, 2022; Osterwalder & Pigneur, 2010).

In the following sections, we first introduce related work to lay the foundation regarding AR and the effects of aligning task and technology characteristics. We then describe our research design, which is based on a comprehensive case study at a large European maintenance, repair, and overhaul (MRO) service provider in the aviation sector and a literature review. Afterward, we present the result, the process augmentability canvas. Finally, we discuss the implications of our findings and conclude the paper.

12.2 Related Work

Augmented reality, blending virtual computer-generated overlays with reality (Milgram & Kishino, 1994), has been extensively studied for decades (Sutherland, 1968). AR has three main characteristics: First, it "combines the real and the virtual" (Azuma, 1997, p. 2), usually by extending or overlaying virtual elements onto reality. Reality and computer-generated virtual objects are perceived simultaneously in this manner. Second, AR is "interactive in real time" (Azuma, 1997, p. 2), enabling real-time interactions with the system. Finally, virtual content is "registered in 3-D" space (Azuma, 1997, p. 2). Virtual objects have a registered location in the real world. They can be controlled through interactions and behave similarly to real objects. AR applications can be implemented using different hardware technologies, such as head-mounted displays (HMDs) or hand-held displays like tablets or smartphones. Spatial AR uses hardware detached from the user's body, like projection-based spatial AR that overlays real objects using projectors (Bimber & Raskar, 2006).

In IS research, various models have been developed to determine whether a technology is suitable for a task. The task-technology fit (TTF) model (Goodhue & Thompson, 1995) and the technology acceptance model (TAM) (Davis, 1985, 1989) are examples of such models that aim to explain technology usage. The unified theory of acceptance and use of technology (UTAUT) is an extension of the TAM, which provides more specific factors affecting technology use and their moderators (Venkatesh et al., 2003). Four factors influence the behavioral intention to use a system, and hence the actual user behavior: (1) performance expectancy, meaning that the system supports job performance, (2) effort expectancy, which is accordingly to ease of use of TAM, (3) social influence, and (4) further facilitating conditions. Moderating factors such as gender, age, experience with the technology, and the voluntariness of use also play a significant role. The TTF model has also been applied to determine the feasibility of AR for specific use cases, such as in the architecture, engineering, and construction industries (Shin & Dunston, 2008). Therefore, to ensure high process performance, user acceptance, and adoption, as well as efficient system usage, aligning task and technology characteristics is critical when evaluating the suitability of AR for processes.

When new technology is introduced, it often results in the virtualization of processes. The process virtualization theory (PVT) (Overby, 2008) seeks to examine the virtualizability of processes. Virtualizing a process involves removing physical interaction between the user and other objects or individuals. Virtualizability is measured by the quality of outcome or user acceptance. According to PVT, four key constructs negatively impact process virtualizability. The first aspect, sensory requirements, involves the user's sensory experiences during the process, including human senses such as sight, smell, hearing, touch, and taste. Virtualizing the process reduces the experience's richness, negatively impacting the process virtualizability. The second construct, relationship requirements, refer to the degree of interaction with others. Social interactions with other people lead to knowledge acquisition and personal ties. The need for physical in-person interaction negatively influences the process's virtualization ability. The synchronism requirement refers to quickness and allowed delays in the process. A process with a high demand for synchronicity is less amenable to being virtualized. Lastly, identification and control requirements refer to the need for unique user identification. If the process requires control through secure user identification, the process is less virtualizable. A thorough analysis of the process is necessary to determine which processes are suitable for AR. A recent study has investigated the extent to which conventional process modeling approaches and tools are suitable for modeling AR processes and concluded that there is still a research gap regarding the applicability of AR in practice (Bräker & Semmann, 2021).

12.3 Research Design and Methodology

In this research, we adopt a mixed-method approach (Venkatesh et al., 2016; Venkatesh et al., 2013) to identify criteria that describe the suitability of AR. Our approach combines quantitative and qualitative data to validate that our findings are relevant for practitioners and researchers. We combine specific knowledge from a use case with generalized knowledge from literature (Greene et al., 1989).

Our case study is based on a leading European MRO service provider in the aviation sector with its own logistics service provider. Specifically, we focus on a use case in their logistics warehouse – the inventory process. This process represents one of the typical processes in a warehouse (ten Hompel & Schmidt, 2007). The inventory is performed daily to check the current stock levels. Mobile hand-held scanners record the inventory and transfer the counted quantity to the warehouse management system. Depending on the storage location, employees have to walk further distances within the warehouse or – in the case of smaller materials – can request that all materials are delivered directly to their workstations. Our focus was on the suitability of the inventory process for utilizing AR, the criteria that determine the suitability, and what we can learn from this example to make more general statements about the applicability of AR. Through observations, interviews, a user study, and workshops, we explored how AR can enhance this process and what criteria determine its suitability. Figure 35 illustrates our research design, which consists of five steps.

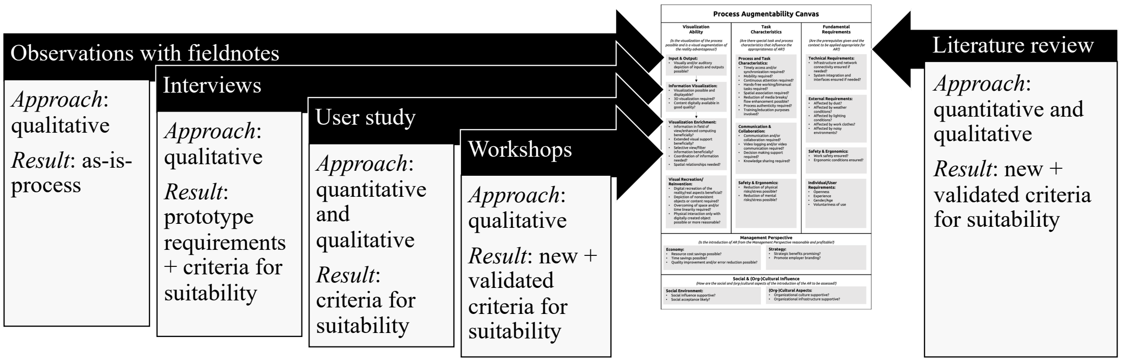


Figure 35. Research design

12.3.1 Literature Review

We began our research by reviewing the literature to establish an initial theory-driven framework version. In order to draw on fundamental knowledge from previous research, we conducted a structured literature review (vom Brocke et al., 2009). The primary goal was to identify existing models or frameworks that outline which processes are suitable for AR digitization. We performed a keyword search, which included several high-quality information systems journals, including the "Senior Scholars' Basket of IS Journals". We added the "International Conference on Information Systems" and the "European Conference on Information Systems" as IS conferences. Additionally, we searched through human-computer interaction-focused outlets, including the "AIS Transactions on Human-Computer Interaction", "ACM Transactions on Computer-Human Interaction", and the "CHI Conference on Human

Factors in Computing Systems", as AR is a prominent research topic in this field. We did not restrict the time frame and examined all articles related to AR, along with models or frameworks in the title, keywords and abstract. Our search query was: ("augmented reality" OR "virtual reality" OR "mixed reality" OR "smart glass*" OR "data glass*" OR "extended reality" OR "assisted reality") AND ((digitisation OR digitization OR digitalisation OR digitalization OR digitizing) OR (criteria OR model OR concept OR design OR framework OR "design principles" OR process)). We reviewed a total of 270 papers and narrowed it down to ten relevant to our research as they discussed models or frameworks that guide the application and requirements for AR implementation (see Table 22). Two independent researchers were involved in the review process. Additionally, we added two papers by Klinker et al. (2018) and Venkatesh et al. (2003), covering a broad range of relevant aspects, to serve as valuable additions to the relevant papers.

Table 22. Literature review

	AIS Electronic Library	**EBSCO Business Source Complete**	**ProQuest**	**ACM Digital Library**	**Science Direct**	**Sum**
Hits	43	34	3	190	0	270
Relevant	8	2	0	0	0	10

12.3.2 Case Study

Observations with fieldnotes: Preliminary qualitative research was undertaken to investigate the inventory process at the logistics service provider. This research involved six field observations in four different warehouses and an inventory coordination office, whereby ethnographic fieldnotes were taken (Emerson et al., 2001, 2011). Each observation session lasted approximately one hour. We assumed a relatively passive observer role in the environment to avoid any interference with the logistics service provider's employees. The main objective was to observe and document how the actual inventory process is carried out to identify potential areas for improvement. As a result of this initial step, we have documented and analyzed the actual inventory process and gained insights into performance challenges.

Interviews: Ten qualitative interviews were conducted to explore additional insights, collect requirements, and identify relevant criteria when utilizing AR. The interviewees comprised logistics employees from the warehouse and inventory coordination, healthcare management, workers' council, coordinators responsible for communication between the MRO service provider, as well as unit members technically responsible for AR and virtual reality (VR) technologies and logistical applications. The non-standardized interviews were based on guiding questions and lasted approximately 30 minutes each. We documented them with handwritten notes (Rubin & Rubin, 2011). The insights from the interviews provided preliminary requirements for an AR prototype. We identified specific criteria that are critical for the successful implementation of AR in the inventory process.

User study: We developed a prototype for the inventory process using Microsoft Hololens. The prototype facilitates wayfinding in the warehouse, correct materials identification, and inventory stock entry into the warehouse management system. We conducted a user study acquiring qualitative and quantitative data to evaluate the use of AR within a concrete example. The study employs the thinking-aloud method during prototype use (Boren & Ramey, 2000; van Someren et al., 1994). We additionally used established questionnaires to gain more quantitative data, including the NASA task load index (NASA-TLX), to evaluate subjective workload and stress levels (Hart & Staveland, 1988). The system usability scale (SUS) (Brooke, 1996) and the short version of the user experience questionnaire (UEQ-S) (Schrepp et al., 2017) were used to evaluate usability and user experience. A questionnaire was used to measure technology acceptance using the TAM model (Davis, 1989; Davis et al., 1989) and the UTAUT model (Venkatesh et al., 2003). Open questions were included to solicit participants' feasibility estimations and feedback qualitatively. The objective was to gain further insights into the AR application's suitability, identify strengths and weaknesses, and thus determine criteria that influence the suitability of the AR technology. Our study included 33 manufacturer and logistics service provider employees, with a heterogeneous age distribution and male and female participants. The study lasted four days, with each participant spending 15 to 20 minutes on average using the prototype. We instructed the participants to use the AR prototype for the inventory process and communicate their thoughts loudly according to the thinking-aloud approach (Boren & Ramey, 2000; van Someren et al., 1994).

Workshops: We leveraged the design-thinking approach to conduct two workshops to identify additional practical criteria for implementing AR (Brown, 2008). Seven participants attended the workshops, including employees from the logistics service provider and the manufacturer's IT department. Each workshop was designed to last approximately 1.5 hours. To guide the workshops, we posed two central questions:

(1) Which process steps or tasks would most benefit from AR integration? (2) Which existing processes can be digitized using AR technology? The workshop began with a diverging brainstorming phase, during which we aimed to collect all of the appropriate processes and subtasks for utilizing AR. Next, we structured the ideas by clustering them and evaluated them in a converging phase to identify three core ideas. In the following diverging phase, we collected and documented criteria for these core ideas. The documentation was done in the form of a process profile. The participants recorded the technology's requirements, advantages, risks, interrelationships, and support capabilities to develop this process profile. Finally, we re-clustered the criteria and used them as input for the following stages of the study.

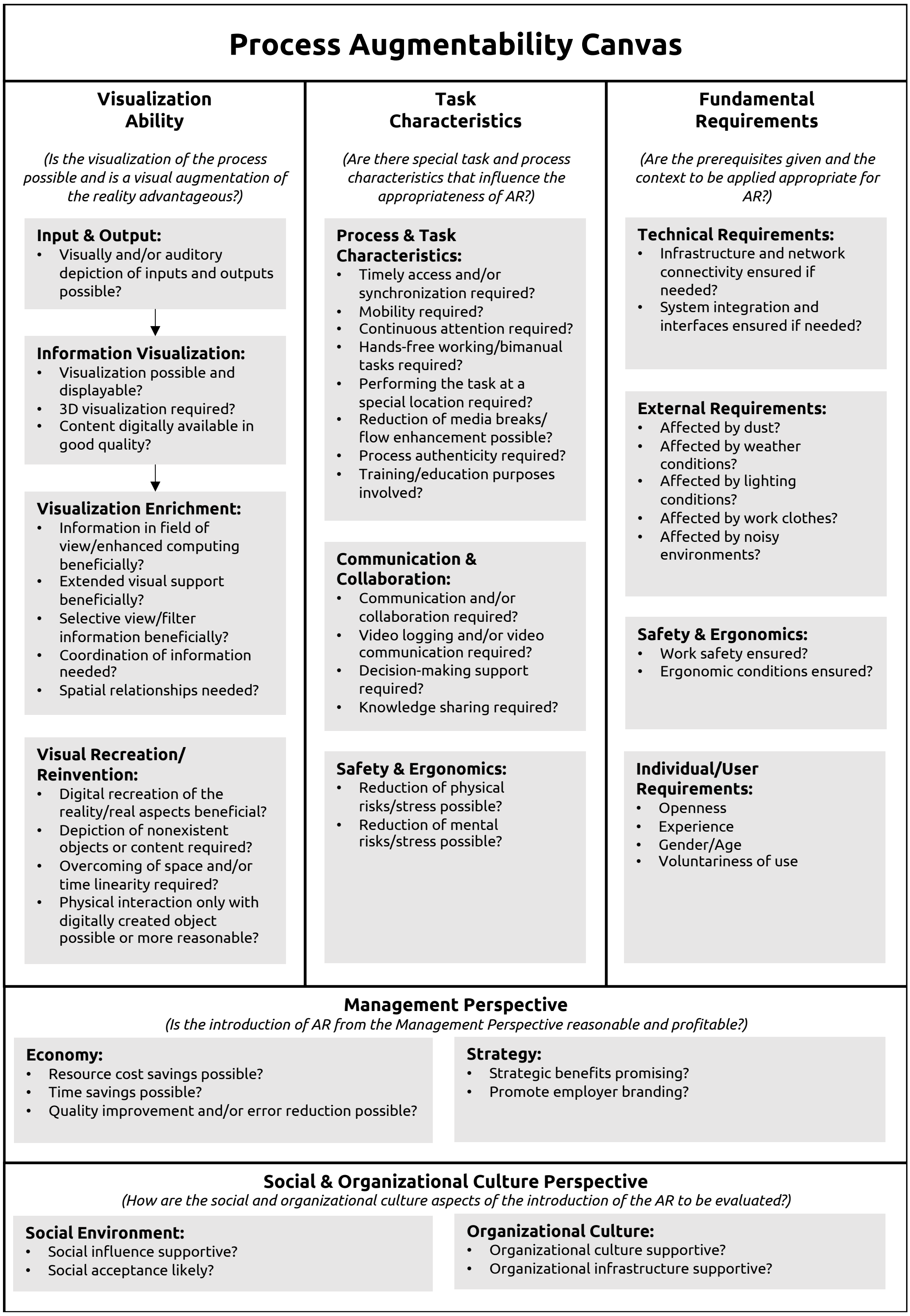
12.3.3 Data Analysis and Framework Development

To develop the framework, we conducted a data analysis combining the literature review findings with our case data. We began by reviewing the literature to establish an initial theory-driven version of the framework. Two independent researchers coded relevant publications by searching for keywords that described the applicability and suitability of AR. This process allowed us to derive 42 criteria from the literature, which we supplemented with data from our case study. We analyzed the data from the case study by coding the empirical material analog to the literature coding. In addition to keywords describing the applicability and suitability, we mainly looked for requirements, challenges and improvement possibilities in the empirical data. Based on this, we developed 24 criteria shaped by practical experience. Of these 24 criteria, 17 confirmed or extended the findings from the literature, while seven entirely new criteria shaped by the practice were discovered. The same two researchers thematically clustered these criteria to create the final framework. After removing duplicates and merging similar criteria, the framework's foundation consists of 49 criteria divided into 15 groups. To make the canvas useful for organizations assessing their processes and making decisions regarding the use of AR, we aimed to build the canvas with a process-oriented approach. We expand the process characteristics to include preconditions for AR and a more abstract view of the management and the social and organizational culture perspective. We conducted a second clustering to summarize the groups further, resulting in five primary categories. The final framework is described in section 12.4.

12.4 Result – Guiding Framework to Assess Processes for the Applicability of Augmented Reality

The resulting framework, called process augmentability canvas (see Figure 36), provides guidance and decision support for the application of AR in service contexts. The canvas format offers immediate access to all categories, groups, and criteria without imposing a strict order for user exploration. The five main categories of the canvas align with the analysis results. The first category, *(1) visualization ability*, deals with visual representations and requires vision enrichment as a precondition. AR is effective only when information is visualizable, and this ability involves three interdependent sequential phases. These include, at first, the depictability of visual and auditory inputs and outputs. Second, the information needed for the process should be analyzed to determine whether visualization is achievable. The visualization should also enrich the user's experience in the third step.

The second category, *(2) task characteristics*, represents the outcome of the activities and processes and serves as the canvas's fundamental goal. Therefore, this category occupies the central position of the canvas. Processes meeting one or more of the process and task criteria are well-suited for initial AR application. AR also supports communication and collaboration activities by enabling remote collaboration through AR devices. Moreover, AR can help reduce physical and mental stress. The third category, *(3) fundamental requirements*, refers to technical and environmental aspects and constitutes a precondition for AR use. This category includes technical and external requirements, work safety and ergonomics, and individual and user requirements. We suggest evaluating technical and external requirements and assessing safety and ergonomic benefits if the preconditions are achievable. Finally, we recommend analyzing the user target group to ensure technology acceptance. Two additional perspectives abstracted from a strict process perspective are included at the lower part of the canvas. The *(4) management perspective* provides insights into economic and strategic benefits, such as profitability. In contrast, the *(5) social and organizational culture perspective* encompasses the impact of social environments and organizational culture on AR assessment. Detailed descriptions of the different areas of the canvas and their sources are presented in the following.



Process Augmentability Canvas

Visualization Ability

(Is the visualization of the process possible and is a visual augmentation of the reality advantageous?)

Input & Output:
- Visually and/or auditory depiction of inputs and outputs possible?

↓

Information Visualization:
- Visualization possible and displayable?
- 3D visualization required?
- Content digitally available in good quality?

↓

Visualization Enrichment:
- Information in field of view/enhanced computing beneficially?
- Extended visual support beneficially?
- Selective view/filter information beneficially?
- Coordination of information needed?
- Spatial relationships needed?

Visual Recreation/ Reinvention:
- Digital recreation of the reality/real aspects beneficial?
- Depiction of nonexistent objects or content required?
- Overcoming of space and/or time linearity required?
- Physical interaction only with digitally created object possible or more reasonable?

Task Characteristics

(Are there special task and process characteristics that influence the appropriateness of AR?)

Process & Task Characteristics:
- Timely access and/or synchronization required?
- Mobility required?
- Continuous attention required?
- Hands-free working/bimanual tasks required?
- Performing the task at a special location required?
- Reduction of media breaks/ flow enhancement possible?
- Process authenticity required?
- Training/education purposes involved?

Communication & Collaboration:
- Communication and/or collaboration required?
- Video logging and/or video communication required?
- Decision-making support required?
- Knowledge sharing required?

Safety & Ergonomics:
- Reduction of physical risks/stress possible?
- Reduction of mental risks/stress possible?

Fundamental Requirements

(Are the prerequisites given and the context to be applied appropriate for AR?)

Technical Requirements:
- Infrastructure and network connectivity ensured if needed?
- System integration and interfaces ensured if needed?

External Requirements:
- Affected by dust?
- Affected by weather conditions?
- Affected by lighting conditions?
- Affected by work clothes?
- Affected by noisy environments?

Safety & Ergonomics:
- Work safety ensured?
- Ergonomic conditions ensured?

Individual/User Requirements:
- Openness
- Experience
- Gender/Age
- Voluntariness of use

Management Perspective

(Is the introduction of AR from the Management Perspective reasonable and profitable?)

Economy:
- Resource cost savings possible?
- Time savings possible?
- Quality improvement and/or error reduction possible?

Strategy:
- Strategic benefits promising?
- Promote employer branding?

Social & Organizational Culture Perspective

(How are the social and organizational culture aspects of the introduction of the AR to be evaluated?)

Social Environment:
- Social influence supportive?
- Social acceptance likely?

Organizational Culture:
- Organizational culture supportive?
- Organizational infrastructure supportive?

Figure 36. The process augmentability canvas

12.4.1 Visualization Ability

Visual representations play a significant role in AR applications. In order to augment a process, it must be ensured that the relevant information and data can be visualized and that the visual augmentation of reality provides benefits. Hence, the visual representation of inputs and outputs should be possible (Klinker et al., 2018). Moreover, audio elements such as voice commands can be incorporated to enrich the visual elements. Once it is confirmed that the inputs and outputs of the system or application are represented, the necessary information must be visualized and displayed (Klinker et al., 2018; Kortekamp et al., 2019). If the process requires or benefits from 3D information, AR is a viable option (Kortekamp et al., 2019; Yeo, 2017). High-quality digital content is a prerequisite for visualization (Klinker et al., 2018).

Provided that the first two requirements are met, the visualization should be advantageous and regarded as enrichment, allowing the process to profit from AR. Visual enrichment can be accomplished by enriching the user's field of view with additional (Steffen et al., 2017; Steffen et al., 2019) or filtered information (Kortekamp et al., 2019; Steffen et al., 2017; Steffen et al., 2019). Additionally, AR is helpful when a process involves coordinating a significant amount of complex information (Oesterreich & Teuteberg, 2017; Steffen et al., 2019) or when visualizing spatial relationships is beneficial (Steffen et al., 2019; Yeo, 2017). AR also permits the visual recreation and reinvention of objects. When real objects are recreated in a virtual environment, they mimic reality (Steffen et al., 2017; Steffen et al., 2019), which can serve various purposes, such as cost reduction or risk reduction. If the necessary objects do not exist in the real world, reality must be reinvented (Steffen et al., 2017). In some cases, such as time travel or empowering physically disabled persons, spatial or temporal linearity must be overcome (Steffen et al., 2017; Steffen et al., 2019). AR is recommended when the process refers to non-existent elements or when it is simpler to mimic reality. This is also true if the process benefits from interacting with digitally created objects (Steffen et al., 2019). However, a simplistic augmentation of reality can still hold significant value.

Table 23 summarizes the criteria mentioned above and provides a brief overview of their sources. To improve readability, we have included the sources within the description where *I* are interviews, *L* is literature, *O* is field observations, *U* is user study, and *W* is workshops.

Table 23. Visualization ability

Group	Criterion	Description
Input & output	Visually and/or auditory depiction of inputs and outputs possible?	Is it possible to visually or auditory depict the inputs and outputs of the process? Possible inputs could be photos, videos, text, or speech commands. Possible outputs could be photos, videos, text, or audio. (*U; W; L* (Klinker et al., 2018))
Information visualization	Visualization possible and displayable?	Is content visualization possible, and can the required information be displayed? (*U; W; L* (Klinker et al., 2018; Kortekamp et al., 2019))
	3D visualization required?	Is the 3D visualization of the information required? (*L* (Kortekamp et al., 2019; Yeo, 2017))
	Content digitally available in good quality?	Is the required content digitally available? Is it available in good quality? (*U; W; L* (Klinker et al., 2018))
Visualization enrichment	Information in field of view/enhanced computing beneficially?	Does the process benefit from representing the information in the user's field of view? (*L* (Kammler et al., 2019; Steffen et al., 2019))
	Extended visual support beneficially?	Does the process benefit from extended visual support, e.g., by enriching additional information? (*L* (Kammler et al., 2019; Kortekamp et al., 2019; Steffen et al., 2019))
	Selective view/filter information beneficially?	Does the process benefit from a selective view, e.g., in the form of filtered information? (*L* (Kortekamp et al., 2019; Steffen et al., 2017; Steffen et al., 2019))
	Coordination of information needed?	Does the process coordinate many or complex information? Does the process benefit from improved structuring and a better overview of this information? (*L* (Oesterreich & Teuteberg, 2017; Steffen et al., 2019))
	Spatial relationships needed?	Does the process benefit from a visualization of spatial relationships and spatial positioning? (*L* (Steffen et al., 2019; Yeo, 2017))

Visual recreation/ reinvention	Digital recreation of the reality/real aspects beneficial?	Does the process benefit from a recreation of existing aspects to mimic reality? (L (Steffen et al., 2017; Steffen et al., 2019))
	Depiction of nonexistent objects or content required?	Does the process benefit from the possibility of creating aspects that do not exist in reality? (L (Steffen et al., 2017))
	Overcoming space and/or time linearity required?	Does the process require going beyond time and space, e.g., traveling back in time or visiting other places? (L (Steffen et al., 2017))
	Physical interaction only with digitally created object possible or more reasonable?	Does the process benefit from interacting with digitally created objects? (L (Steffen et al., 2019))

I = interviews, L = literature, O = observations, U = user study, W = workshops

12.4.2 Task Characteristics

The task characteristics play a critical role in determining the suitability of AR as an appropriate technology solution (see Table 24). While AR can support generic process tasks, certain task characteristics provide enhanced benefits when using AR. For instance, when timely access to information is required, or specific information needs to be synchronized in real-time, AR can be recommended (Klinker et al., 2018; Yeo, 2017).

Mobility is another factor that influences the appropriateness of AR, particularly when users are required to be mobile due to changing or flexible workplaces. AR is also appropriate when continuous user attention is required, such as driving a vehicle or performing bimanual tasks (Kammler et al., 2019; Klinker et al., 2018). The spatial allocation of virtual objects is an important consideration, especially when the process performance is location-based (Yeo, 2017). AR can be highly recommended when virtual objects or information can be arranged spatially or related to a specific location. AR can also be used to reduce media breaks and improve workflow.

Table 24. Task characteristics

Group	Criterion	Description
Process & task characteristics	Timely access and/or synchronization required?	Is timely access to the information required? Does the information need to be synchronized in real time? (*L* (Klinker et al., 2018; Yeo, 2017))
	Mobility required?	Does the process require the user's mobility? (*U; W; L* (Klinker et al., 2018; Steffen et al., 2019))
	Continuous attention required?	Does the process require the continuous attention of the user? (*L* (Klinker et al., 2018))
	Hands-free working/bimanual tasks required?	Does the process contain bimanual tasks? Does the process benefit from hands-free working? (*U; W; L* (Kammler et al., 2019; Klinker et al., 2018))
	Performing the task at a special location required?	Does the process require performance at a specific location and thus the spatial assignment of the information or the visualized objects? (*L* (Yeo, 2017))
	Reduction of media breaks/flow enhancement possible?	Does the process have many media breaks? (*O; W*)
	Process authenticity required?	How important is the authenticity of the process? To what extent should the process meet the expectations of reality? (*L* (Yeo, 2017))
	Training/education purposes involved?	Does the process involve training or education aspects? (*L* (Kohn & Harborth, 2018; Kortekamp et al., 2019; Sommerauer & Müller, 2018; Steffen et al., 2019))
Communication & collaboration	Communication and/or collaboration required?	Does the process involve communication or collaboration with other people? (*O; W; L* (Kortekamp et al., 2019; Steffen et al., 2019; Weigel et al., 2021))
	Video logging and/or video communication required?	Does the process involve or benefit from video logging or video communication? (*L* (Klinker et al., 2018; Kortekamp et al., 2019; Steffen et al., 2019))

	Decision-making support required?	Do decisions have to be made during the process? Can this decision-making process, e.g., benefit from visualization and coordination of information or supported communication? (*L* (Chaturvedi et al., 2011; Oesterreich & Teuteberg, 2017))
	Knowledge sharing required?	Is knowledge sharing essential for the process, e.g., between different people and departments? (*L* (Chaturvedi et al., 2011; Kortekamp et al., 2019; Sommerauer & Müller, 2018; Weigel et al., 2021))
Safety and ergonomics	Reduction of physical risks/ stress possible?	Is it possible to reduce physical stress or risks? (*U; W; L* (Oesterreich & Teuteberg, 2017; Steffen et al., 2017; Steffen et al., 2019))
	Reduction of mental risks/stress possible?	Is it possible to reduce mental and emotional stress or risks? (*U; W; L* (Oesterreich & Teuteberg, 2017; Steffen et al., 2017; Steffen et al., 2019))

I = interviews, *L* = literature, *O* = observations, *U* = user study, *W* = workshops

Authenticity is another critical factor determining AR's appropriateness for specific processes (Yeo, 2017). AR can be useful when training situations or educational aspects are involved (Kohn & Harborth, 2018; Kortekamp et al., 2019; Sommerauer & Müller, 2018; Steffen et al., 2019). AR can assist communication and collaboration processes (Kortekamp et al., 2019; Steffen et al., 2019; Weigel et al., 2021), particularly in instances such as video logging, video communication, or remote support (Klinker et al., 2018; Kortekamp et al., 2019; Steffen et al., 2019). AR can aid in decision-making processes (Chaturvedi et al., 2011; Oesterreich & Teuteberg, 2017) and knowledge sharing (Chaturvedi et al., 2011; Kortekamp et al., 2019; Sommerauer & Müller, 2018; Weigel et al., 2021), and promote empathy (Steffen et al., 2019) in all of these instances. Additionally, AR can reduce physical, mental, or emotional risks, thus improving safety and ergonomics (Oesterreich & Teuteberg, 2017; Steffen et al., 2017; Steffen et al., 2019). This also includes diminishing negative aspects of reality (Steffen et al., 2017; Steffen et al., 2019). Therefore, identifying and assessing task characteristics is a critical step in determining the appropriateness of AR in a given context.

12.4.3 Fundamental Requirements

The fundamental requirements are critical for the successful implementation of AR in organizations. Such requirements encompass various aspects of the application's context, including technical and external prerequisites, as well as concerns related to safety and ergonomics (see Table 25). Individual and user requirements that affect technological acceptance, such as openness, experience, and voluntariness of use, should also be taken into account. In cases where the application requires network connectivity or relies on specific technical infrastructure (Klinker et al., 2018), the required conditions for the use of AR should be thoroughly established. The same applies to interfaces and system integrations.

In addition, external factors that influence the workplace and the environment, such as dust, weather conditions, lighting, work clothing, or noisy surroundings, must be considered (Klinker et al., 2018; Kortekamp et al., 2019). Moreover, compliance with company and legal requirements for work safety and ergonomics should be prioritized (Oesterreich & Teuteberg, 2017).

Specific individual and user requirements that affect technology acceptance and adoption, such as demographic factors like gender and age, should also be considered. For instance, younger people are deemed more likely to use new technologies, and users with greater experience are more likely to embrace the technology, as demonstrated by Venkatesh et al. (2003) UTAUT model. Furthermore, voluntary adoption of AR technology is more likely to result in higher levels of acceptance among users. Overall, AR is beneficial if the technical and external requirements, workplace safety and ergonomics guidelines are met, and the potential group appears reasonable.

Table 25. Fundamental requirements

Group	**Criterion**	**Description**
Technical requirements	Infrastructure and network connectivity ensured if needed?	Does the process require network connectivity? Are all requirements fulfilled regarding the infrastructure? (*W; L* (Klinker et al., 2018))
	System integration and interfaces ensured if needed?	If integration with other systems is necessary, can this be achieved? If interfaces are required, can they be implemented? (*W*)

External requirements	Affected by dust?	Is the hardware exposed to dust or similar? If so, can it be eliminated? (*O, U; L* (Klinker et al., 2018))
	Affected by weather conditions?	Is the hardware exposed to weather conditions? Can these be controlled to ensure the hardware is not damaged? (*I; O; U*)
	Affected by lighting conditions?	Can the lighting conditions be adapted to the hardware requirements? (*O; U; W*)
	Affected by work clothes?	Do users have to wear work clothes? If so, is it ensured that the work clothing does not affect their use? (*O; U*)
	Affected by noisy environments?	Does the process occur in a noisy environment, so the process benefits from visually displaying the information? (*L* (Kortekamp et al., 2019))
Safety & ergonomics	Work safety ensured?	Can work safety be ensured according to business and legal requirements? (*I; O; L* (Oesterreich & Teuteberg, 2017))
	Ergonomic conditions ensured?	Can ergonomic use be ensured depending on the business and legal requirements? (*I*)
Individual/ user requirements	Openness	Are potential users open to new technologies? (*U*)
	Experience	Are the potential users experienced using new technologies in general or AR in particular? (*U; L* (Venkatesh et al., 2003))
	Gender/age	Can potential users be assigned to specific gender/age groups? (*L* (Venkatesh et al., 2003))
	Voluntariness of use	Do the potential users feel that the use of AR is voluntary? (*L* (Venkatesh et al., 2003))

I = interviews, *L* = literature, *O* = observations, *U* = user study, *W* = workshops

12.4.4 Management Perspective

From a managerial standpoint, the application of AR must be evaluated based on economic efficiency and strategic benefits (see Table 26). The decision to adopt AR should be made when it is possible to save on resource costs (Oesterreich & Teuteberg, 2017; Steffen et al., 2017; Steffen et al., 2019) or when time savings are expected (Kammler et al., 2019; Kohn & Harborth, 2018; Oesterreich & Teuteberg, 2017). Both short-term and long-term economic gains should be considered. Another facet of economic efficiency is quality improvement and error rate reduction (Kohn & Harborth, 2018; Oesterreich & Teuteberg, 2017). It is also essential to consider the strategic benefits of AR through digitization (Oesterreich & Teuteberg, 2017), which may positively impact employer branding (Dabirian et al., 2019). Therefore, AR is recommended if economic benefits can be realized and strategic benefits, such as increased employer branding, are anticipated.

Table 26. Management perspective

Group	Criterion	Description
Economy	Resource cost savings possible?	Is digitizing the process possible to save resources (and therefore costs) in the long or short term? (*I; W; L* (Oesterreich & Teuteberg, 2017; Steffen et al., 2017; Steffen et al., 2019))
	Time savings possible?	Is digitizing the process possible to save time (and therefore costs) in the short or long term? (*U; W; L* (Kammler et al., 2019; Kohn & Harborth, 2018; Oesterreich & Teuteberg, 2017))
	Quality improvement and/or error reduction possible?	Is it possible to improve quality or reduce error rates by digitizing the process? (*L* (Kohn & Harborth, 2018; Oesterreich & Teuteberg, 2017))
Strategy	Strategic benefits promising?	Can strategic benefits be achieved by digitizing the process? (*L* (Oesterreich & Teuteberg, 2017))
	Promote employer branding?	Can employer branding be promoted by digitizing the process using AR? (*I*)

I = interviews, L = literature, O = observations, U = user study, W = workshops

12.4.5 Social & Organizational Culture Perspective

The final category focuses on the social environment and organizational culture (see Table 27). Specifically, the user's social environment plays a vital role in shaping the social adoption of an AR application, with supportive social networks positively affecting acceptance (Klinker et al., 2018; Venkatesh et al., 2003). However, the impact of the organizational culture and infrastructure on AR's appropriateness is likewise significant. For instance, the UTAUT model identifies organizational infrastructure as a facilitating condition for technology adoption (Venkatesh et al., 2003). Thus, using AR to support processes is recommended if user acceptance and social acceptance of the technology can be fostered. Moreover, if the organizational culture and infrastructure are supportive, then optimal conditions for AR adoption prevail.

Table 27. Social & organizational culture perspective

Group	**Criterion**	**Description**
Social environment	Social influence supportive?	Can social influence be expected as supportive? (*L* (Venkatesh et al., 2003))
	Social acceptance likely?	Can the social acceptance of the users and their environment be ensured? (*U; L* (Klinker et al., 2018))
Organizational culture	Organizational culture supportive?	Does the organizational culture support the use of AR? (*I*)
	Organizational infrastructure supportive?	Does the organizational infrastructure support the use of AR? (*L* (Venkatesh et al., 2003))

I = interviews, L = literature, O = observations, U = user study, W = workshops

12.4.6 Application of the Process Augmentability Canvas

As the proposed framework aids in the augmentation of processes through the utilization of AR, the question arises how the framework can be applied in practice. For a practical application, any business process can be selected, and each canvas section can be explored. The analysis should begin with the upper part of the canvas, emphasizing the visualization ability and fundamental requirements. For each category, the process can be evaluated against each criterion to determine whether the requirements are met or can be met in the future. This enables a comprehensive evaluation of the advantages and disadvantages of using AR. Moreover, it provides a solid foundation for informed decision-making. For instance, if it is determined at the beginning that both the visualization ability and the fundamental requirements are satisfied, we recommend continuing to evaluate the task characteristics. The process selected and its tasks can be examined more closely. This is an advantage if a clear recommendation can already be made based on these characteristics. However, it is not necessarily a disadvantage if this is not possible. Either way, an initial evaluation based on rough prototypes of AR solutions is beneficial. As the maturity of solutions and the potential to become the standard mode of operation increases, the process should be reviewed from the perspectives of management and social and organizational culture. Once the canvas is completed, a solid foundation should be established to determine whether a process can benefit from AR. It is important to note that the canvas is not primarily a checklist that must be completed in its entirety. Rather, it serves as guidance and assistance for the initial assessment of a process's suitability for the application of AR. It is a supplementary tool for practitioners in organizations and serves as a benchmark for comparing different processes. It is important to acknowledge that not every process can satisfy every criterion. Therefore, it is still the responsibility of the respective organization to weigh the suitability of different processes.

12.5 Discussion

The proposed process augmentability canvas represents a significant step forward in enabling organizations to leverage the potential benefits of AR for services. It provides a structured, criterion-based approach to decision-making, which is particularly relevant given the complexity of the issues involved. We have drawn on existing research in designing the canvas, consolidating fragmented coverage and integrating key insights to create a coherent, comprehensive framework.

Our approach reflects a user-centric perspective, which is critical to overcoming organizational barriers and realizing the intended benefits of AR (Lusch & Nambisan, 2015; L. D. Peters, 2016). We have based our canvas on the state-of-the-art concerning technology acceptance and task-technology fit, ensuring that it supports a user-centric approach. Nevertheless, this approach does bear the risk of not leveraging the potential of novel technologies. Thus, a technology-driven approach can be taken to identify areas for application initially. The canvas can contribute to the user-centric design of processes as it tackles all relevant aspects to approach AR solutions.

The canvas enhances communication and collaboration among stakeholders, facilitating alignment of expectations and priorities, reducing misunderstandings and conflicts, and fostering a shared understanding of the benefits and risks of AR. It also supports organizational learning and knowledge management by capturing decision-making rationale and providing valuable insights into the application and limitations of AR. This work contributes to the broader research agenda on digital innovation and organizational change, deepening understanding of the challenges and opportunities of emerging digital technologies. Moreover, the user-centric approach to evaluating AR aligns with the trend toward socially responsible innovation, emphasizing ethical, social, and environmental factors in technology design and deployment. Thus, this work is relevant to practitioners and researchers interested in the implications of digital transformation.

Two main modes of analysis using the canvas are intended to support organizations that aim to pilot AR solutions. The first involves a structured analysis and assessment of all processes using the canvas, allowing organizations to define must-have criteria (e.g., safety and ergonomics) to identify processes that can be augmented. Further analysis should help narrow down potential processes based on the augmentation's expected value, usefulness, and seamlessness. This approach enables organizations to develop a prioritized list of processes and identify processes for piloting that would benefit most from augmentation. Accordingly, as more processes use AR, the economic break-even can be reached more quickly, ultimately leading to organizational changes by shifting towards a more open organizational culture regarding innovation.

The second mode is an approach more driven by business units that seek to explore possibilities of AR or digital units that seek to pilot AR with business partners. Therefore, initial processes can be proposed, and with the help of the process augmentability canvas, areas can be identified that need to be adapted to ensure the criteria are fulfilled to pilot the augmentation. Especially in such a creative exploration mode, guidance to fulfill safety and ergonomics criteria is crucial. At the same time, criteria related to the tasks are assessed by the domain experts themselves. Therefore, a positive assessment within this mode ensures a good task-technology fit. Solely by taking care of these aspects, the results of a piloting phase can lead to applicable and valid results for the organization. Thus, only such results can inform decision-making.

While our work represents a significant contribution to the field, some limitations exist. Our literature review produced relatively few results, and we recognize that broadening the search could increase the number of relevant articles. However, this would potentially decrease the quality and validity of those articles. Additionally, our canvas is based on a single case organization. Thus, the canvas builds on in-depth insights but is nevertheless limited in its transferability. This should be tackled in future research to evaluate the general applicability of the canvas. Finally, while the canvas in its current state focuses on AR, several aspects do indeed apply to VR and mixed reality more broadly. Given the claim to support informed decision-making, further research and validation of the canvas are needed.

12.6 Conclusion and Outlook

In conclusion, our proposed process augmentability canvas offers valuable contributions to theory and practice by addressing the fragmented literature and limited real-world cases in AR applications. Through consolidation of the state-of-the-art literature in IS and HCI on characteristics of processes to be augmented, we contribute to the ongoing discourse on AR regarding embedding innovations in organizations. Additionally, we propose an example for applying a multi-level perspective to enhance the applicability of innovations in real-world scenarios. Because the process augmentability canvas has been enriched and validated within a real-world organization, it has already proven its applicability and usefulness. Therefore, it enables practitioners to cope with the complex decision-making regarding the application of AR in their organizations and find the sweet spot for AR application. The canvas allows for adapted weightings of criteria and specific, often regulation-dependent, safety and security measures. Even more, the canvas enables an explorative approach to applying AR and experiencing the benefits and potential shortcomings. SMEs that are rather limited in resources can benefit from the canvas in realizing benefits quickly and efficiently.

Based on the process augmentability canvas, various avenues for further research emerge. First and foremost, evaluating the canvas in diverse real-world scenarios would further improve the validity of the artifact. Second, deciding to what extent virtualization and augmentation are the most promising within the virtuality continuum remains challenging. Thus, extending the canvas to guide the decision for the technical degree of augmentation would be important, especially considering broader applicability in SMEs. This includes the type of AR, from HMDs to spatial augmentation and VR.

12.7 Acknowledgements

This research was partly sponsored by the German Federal Ministry for Education and Research in the project WizARd under reference 02K18D181. Further information can be found at: https://wizard.tu-dortmund.de/. Additionally, we thank Lufthansa Technik AG for the support and the opportunity to acquire comprehensive empirical data.

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13 How Does Business Process Modeling Reflect Augmented Reality-Based Processes?

Bräker, J., & Semmann, M. (2021). How Does Business Process Modeling Reflect Augmented Reality-Based Processes? *Proceedings of the Pacific Asia Conference on Information Systems*

Abstract

Process modeling is broadly agnostic concerning the technology used for inputs and outputs, despite the choice of technology significantly determines and influences processes. Given the maturation of augmented reality and its increasing application in services, we seek to explore whether business process modeling can support such emerging and immersive technologies. To determine if current process modeling approaches are suitable for this purpose, we conduct a criteria-based assessment of the literature based on a thorough literature review. As a result, we identified several shortcomings and propose a research agenda to guide further development of process modeling to cope with the increasing adoption of augmented reality for service design and service innovation in organizations. Thus, we contribute to the understanding of augmented reality as a matter of service design and increase the accessibility of augmented reality for small and medium enterprises.

Keywords

Service design, business process management, mixed reality, literature review.

13.1 Introduction

The maturation of augmented and virtual reality leads to vast opportunities for organizations to leverage these technologies to support and even evolve their processes. Thus, augmented reality (AR) can alter service design and especially field services (Elder & Vakaloudis, 2015; Herterich et al., 2015; Hobert & Schumann, 2017; Niemöller, Zobel, et al., 2017). AR has the potential to foster changes in processes by enabling the visualization of ad-hoc information throughout a process (Wang et al., 2020) or the hands-free performance of service tasks (Cha et al., 2019; Klinker et al., 2020a; Prilla et al., 2019). AR can thus guide and support processes (Zubizarreta et al., 2019). Despite these valuable use cases and further benefits, organizations and, especially, small and medium enterprises (SMEs) do not lever these potentials because the barriers to integrating AR into service processes are relatively high. Several reasons for this lack of adoption are already discussed in academia (Adenuga et al., 2019; Chandra & Kumar, 2018; Elshafey et al., 2020; Jung et al., 2020). Consideration of AR technologies early in the modeling process, e.g., in the service design of a process, has not received much attention. The representation and integration of AR in widely applied process modeling techniques have not yet been prioritized. Because process modeling seeks to represent organizational practice and fosters stringency, it is broadly applied in organizations (Dumas et al., 2018; van Der Aalst, 2012). Process models are an institutionalization of organizational practice and need to reflect the current state of business practice, where new technologies and trends, such as augmented reality, may be used. Accordingly, the question arises whether business process modeling can keep up the pace of technological advancement. This is particularly the case for AR, as it has, on the one hand, the potential to heavily impact service processes and, on the other hand, imposes requirements regarding work environment, available data, and interaction (Herterich et al., 2015; Niemöller, Zobel, et al., 2017). Based on these requirements, we answer the following research question within this paper: *To what extent are current business process modeling methods and techniques able to support the modeling of augmented reality-based processes in businesses, and which facets of AR do those existing modeling approaches represent?*

To answer this question, we performed an extensive literature review to assess the state of the art of business process modeling regarding AR. The analysis is based on eight facets that constitute the requirements for modeling AR processes. Based on the review, we propose key findings and a research agenda to further advance the representation of AR specifically and mixed reality more generally. By bridging the identified gaps, a significant impact on assessing business processes' potential for AR can be made as it responds to tools organizations already use. Thus, a comprehensive representation would enable a broader consideration of AR and a more convincing evaluation of its adequacy and potential.

The remainder of the paper is structured as follows: in the second section, we introduce related work in AR and business process modeling. Subsequently, we describe our research design based on a thorough literature review. We analyze the results in section four and derive implications for further research based on our analysis in section five. We close with concluding remarks and a broader perspective for further research.

13.2 Related Work

13.2.1 Business Process Modeling

Business Process Management (BPM) enables organizations to identify potentials for saving costs, reducing execution times and error rates, improving productivity, and gaining competitive advantages through innovation (Dumas et al., 2018; van Der Aalst, 2012). Business process modeling languages are essential to standardize and formalize the way processes are visualized and described (Dumas et al., 2018). There are a variety of modeling languages widely used in service research, such as flowcharts, Unified Modeling Language (UML), Event-driven Process Chains (EPCs), Petri nets or Business Process Model and Notation (BPMN) (Dumas et al., 2018; van Der Aalst, 2012). Another more customer-centered approach is service blueprinting (Bitner et al., 2008). In addition to the initial design of a process, existing processes can be analyzed. Business process reengineering (BPR) intends to improve performance, cost, quality, and speed (Dumas et al., 2018; Hammer, 1990). Further, business process innovation (BPI) can pave new ways of working and performing processes (Davenport, 1993). A critical enabler and catalyst for business process innovation and reengineering are new information technologies (Anand et al., 2013). An example of one of those new and innovative technologies is augmented reality.

13.2.2 Foundations and Potentials of Augmented Reality

Augmented reality is classified as a variation of virtual reality (VR), both of which are manifestations of mixed reality (MR). MR consolidates a range of displays that combine real and virtual environments. The extent of mixed reality can be summarized in a continuum between reality and virtuality, called Virtuality Continuum (Milgram & Kishino, 1994). The continuum ranges from a completely real environment on the one side to a solely virtual environment, the virtual reality on the other side. If the virtual part is predominant, but the real environment is partly involved, the term augmented virtuality (AV) is used. If the real environment is predominant but extended by virtual objects, it is called augmented reality. AR is characterized by three key features. First, it combines real and virtual elements. Second, it allows interactions in real-time, and third, virtual objects are registered in three-dimensional space (Azuma, 1997). Three conventional display technologies are distinguished for the representation of AR (Bimber & Raskar, 2006): (1) head-attached displays, also known as head-mounted displays (HMDs) or smart glasses, (2) hand-held displays such as tablets or smartphones, and (3) spatial AR which is detached from the user's body, e.g., using projectors.

Augmented reality has also been adopted in services, service systems, and service innovations. Maintenance, repair, and assembly tasks are, for example, a typical field of application, and the use of AR can lead to increased performance and efficiency (Henderson & Feiner, 2011; Palmarini et al., 2017; Platonov et al., 2006; Webel et al., 2011). However, also in the area of aircraft manufacturing (Caudell & Mizell, 1992), engineering processes (Sandor & Klinker, 2005), the construction industry (Dunston & Wang, 2005), logistics services (Berkemeier et al., 2019), and healthcare (Sielhorst et al., 2008), AR is already used. The application of AR thus also creates entirely new potentials such as hands-free working (Cha et al., 2019; Klinker et al., 2020a; Prilla et al., 2019) or the support and guidance of tasks (Zubizarreta et al., 2019), which should also be regarded. Although the vast potential is evident, there are still several challenges associated with the use of AR. In the literature, the tracking and object registration in the three-dimensional space (Azuma, 1997; F. Zhou et al., 2008), delays which can result from network connectivity problems (Azuma, 1997), or the selection of appropriate hardware AR devices (Azuma, 1997; F. Zhou et al., 2008), are discussed. Also, the blending of real and virtual objects (Azuma, 1997), new forms of interaction (F. Zhou et al., 2008), and the right degree of immersion (Yuen et al., 2011) are mentioned. With the introduction of AR to an organizational context, these challenges and requirements do not necessarily disappear and must be considered.

13.3 Methodology

To conduct our research, we initially derive an analytical framework based on literature and case studies on the application of AR in service processes. This leads to a multidimensional perspective on the characteristics of AR in services and thus on the aspects to be considered when modeling AR processes. Based on this framework, we conduct a literature review that aims to identify scientific papers with a strong foundation in business process modeling that address the proposed criteria.

13.3.1 Deriving an Analytical Framework

To provide a methodological foundation for the literature review, we first defined criteria for selecting and analyzing potential papers. The resulting eight criteria will be used to evaluate existing process modeling approaches concerning their applicability to augmented reality. This preliminary framework guides the analysis of the identified papers but will be iteratively adjusted during the process if needed.

Since AR is a new technology, the use of AR in organizations depends on hardware selection, interfaces, and network conditions. Therefore, one criterion that determines AR use should concern the ***technical requirements*** ***(C_1)*** for AR. We search for options to include interfaces to other IS, databases, and documents as preconditions, but also a way to illustrate for which process steps a network connection is obligatory to be correctly executed (International Organization for Standardization, 2004; International Organization for Standardization/International Electrotechnical Commission, 2011; Klinker et al., 2018).

Furthermore, patterns and possibilities of ***interaction*** ***(C_2)*** should already be representable in process modeling. Since AR requires new forms of interaction, e.g., touch, voice, or gesture interactions, we are looking for representations for interaction techniques in the analysis. For the modeling of AR processes, we are interested in the process steps that involve interactions with the AR system, or interaction patterns, e.g., in the form of touch, gestures, or voice commands.

For augmented reality applications, visual representations of information are fundamental. Therefore, we include visualizability in our analysis to ensure that ***visualization requirements (C$_3$)*** are already considered in business process modeling. The requirements for visualization include, for example, the representability of inputs, as well as their characteristics and formats. The outputs that emerge from the AR system and their characteristics should also be considered to ensure seamless integration into existing IT landscapes. Furthermore, requirements regarding the visual tracking of real-world objects are essential. For process modeling, it is of interest which process steps require object tracking and a precisely positioned AR overlay and which information can be depicted without tracking. As a visualization requirement, it can also be considered which information benefits from three-dimensional representations and which process steps, in contrast, are sufficient for two-dimensional representations (Klinker et al., 2018; Kortekamp et al., 2019; Steffen et al., 2019; Yeo, 2017).

In addition, we examine the process modeling approaches from the ***management perspective (C$_4$)***, focusing on efficiency criteria, such as time savings. Aspects of being analyzed are whether the process model or modeling language contains timestamps, execution times, durations, and waiting times (International Organization for Standardization, 1998; Kammler et al., 2019; Kohn & Harborth, 2018; Oesterreich & Teuteberg, 2017; Steffen et al., 2017; Steffen et al., 2019).

Moreover, aspects of ***comprehensibility and appropriateness (C$_5$)*** of the process model are important. Especially for SMEs that do not have much experience in either process modeling, augmented reality, or both, simple access is beneficial.

Finally, we look at possible references to ***innovation (C$_6$)*** and digital trends. As AR has been a trend in recent years (Panetta, 2019), we anticipate that this criterion describes the applicability of business process modeling approaches to innovative technologies and trends.

The use of AR in business processes, particularly the use of HMDs and smart glasses, is accompanied by new requirements, e.g., the putting on and taking off of AR glasses or the change of attention between reality and augmented reality (Osterbrink et al., 2021). For this reason, the analysis includes a criterion that deals with the ***Task-Technology-Embeddedness (C$_7$)***. Possible questions with relevance to the domain of process modeling refer, for example, to process steps to be executed in parallel with the use of the AR application, media breaks, and their visualization, but also to the possibility of identifying process steps that require or benefit from hands-free working.

Since we aim to identify business process modeling languages, notations, and tools suitable for modeling AR processes, we include a criterion called ***augmented reality relation (C_8)*** that evaluates if AR is addressed in a paper and the underlying business process model.

13.3.2 Reviewing of Extant Literature

To investigate the applicability of existing modeling languages and process model notations for the modeling of AR processes, we conducted a structured literature review based on Webster and Watson (2002) and vom Brocke et al. (2009). We did not limit the review process to service-specific approaches to have more encompassing results that could be adapted towards service specifics. However, to ensure transferability to the application domain, we conducted the search mainly to the IS community. Therefore we did a keyword search within the "Senior Scholars' Basket of IS Journals" with several additional outlets; the IS Journals "Business & Information Systems Engineering", "Communications of the AIS", "Information & Management" and "Journal of Information Technology Theory and Application", as well as the IS Conferences "International Conference on Information Systems", "European Conference on Information Systems", "Hawaii International Conference on System Sciences", "Americas Conference on Information Systems", "Pacific Asia Conference on Information Systems" and "International Conference on Wirtschaftsinformatik".

Since we did not get appropriate results searching for the terms "modeling language" or "process model" in combination with AR, to find approaches explicitly designed to model AR processes, we expanded the search terms to get broader literature related to business process modeling in general. We searched for ("business process modelling" OR "business process modeling") in title, abstract, and keywords. We had no time restrictions and included only peer-reviewed articles. We generated the search queries using LitSonar (litsonar.com), and the included databases were (1) AIS Electronic Library (AISeL), (2) EBSCO Business Source Complete (EBSCO), (3) IEEEXplore (IEEE), (4) ProQuest (PQ), (5) ScienceDirect (SD) and (6) ScholarSpace (SchS). To verify our search strategy, we used Google Scholar to search for "modeling language" or "process model" in combination with AR as well as "business process modeling" combined with AR in the title. Only eight articles resulted from this additional Google Scholar search, none suitable for our analysis.

We reviewed a total of 229 papers. To be considered relevant at first, the paper had to focus on business processes mainly and, in addition, fulfill at least one of the

Table 28. Literature review

Database	**1^{st} round**	**2^{nd} round**	**3^{rd} round**	**Relevant**	**Relevant for AR-criteria**
AISeL	134	55	42	23	11
EBSCO	3	2	1	1	0
IEEE	25	10	7	2	1
PQ	6	3	2	2	1
SD	1	1	1	-	-
SchS	60	10	6	1	1
Total	229	81	59	29	14

following criteria: In the paper (1) business process modeling languages are developed, extended, combined, or evaluated, (2) case studies applying business process modeling languages are discussed or (3) business process modeling is considered in the context of augmented reality, virtual reality or mixed reality. Furthermore, the full text had to be available. As shown in Table 28, we have conducted the literature review process over three rounds. We reviewed the title, abstract, and keywords of all 229 papers for the first selection round. We scanned the remaining 81 Papers during the second selection round and were able to sort out another 22 papers. Afterward, we analyzed the remaining 59 papers in the third round and finally identified 29 papers that meet at least one of our three relevance criteria mentioned above. With these 29 papers, we continue with the in-depth analysis looking for criteria C_1 to C_8 from section three. Within the in-depth analysis, no new criteria were identified nor any need for adaptations. Since we did not encounter any paper dealing with the ***Task-Technology-Embeddedness (C₇)*** and ***augmented reality relation (C₈)***, we dropped both categories for the analysis. Sorting out all papers that do not address any of the criteria, the criterion-based analysis results in 14 highly relevant papers that address one or more of the criteria. Accordingly, we can assume that these 14 papers are highly relevant to the modeling of AR processes.

13.4 Analysis

The analysis shows that ten of the 14 papers introduce new process modeling languages and notations or extend existing ones. Four papers evaluate, analyze, or compare existing approaches to gather insights. Table 29 summarizes the criteria-based analysis results by presenting the papers' scope, focus, and methodology, showing the modeling languages and extensions used and indicating the criteria addressed in each paper. In the following, we summarize the findings from the literature based on the individual criteria.

Table 29. Analysis of the literature review results

Source	**Scope/ focus**	**Applied Methods**	**Modeling language/ starting point**	**Extension**	**Criteria**
Bajaj and Ram (1996)	New model	Informal framework specification	Independent	-	C_4
Becker et al. (2010)	New DSL for banking sector (case study)	Action research (interviews, literature reviews, document analysis, evaluation)	SBPML	Adaption DSL	C_3/C_4
Fedorowicz et al. (2005)	New extension (Internet payment platform use case)	Interviews, document analysis	BPMN	BPMNe	$C_1/C_2/C_3$
Figl (2017)	Comprehension of process models	Literature review	Independent	-	C_1/C_5
Jonnavithula et al. (2015)	Inventory of concerns and research directions	Scoping review	Independent	-	$C_1/C_2/C_4/C_5$
Koliadis et al. (2006)	New combination of languages	Constrained development methodologies	BPMN, i*	-	C_2

Legner and Wende (2007)	Research agenda for inter-organizational relationships	Explorative research (workshops, discussions)	Seven modeling languages	-	**C_1/C_2**
Merunka et al. (2009)	New model	Business Object Relation Modeling (BORM)	BORM	-	**$C_1/C_2/C_3$**
Miron et al. (2019)	New method/ modeling tool	Action design research (interviews, workshops, focus groups, questionnaires)	BPMN, Storyboards	-	**C_6**
Muehlen and Ho (2008)	BPMN constructs to start process modeling with (case study)	Action research (notes, voice recordings, design artifacts)	BPMN	-	**C_2**
Oberweis (2010)	New metamodel and extension	Formal description of a resource metamodel	BPMN	BPMN competence extension	**C_2/C_4**
del-Río-Ortega et al. (2019)	Extension of BPMN with PPIs	Design science research methodology (literature review, scenario analysis, evaluation)	BPMN	VISUAL PPINOT	**$C_1/C_3/C_4$**
Rittgen (2000)	New extension (new connector, modification of a join)	Formal description of the new extension	EPC	XORAND, Modified OR join	**C_3**

Rittgen (2006)	Language mapping framework	Mapping, integrating two empirical studies	DEMO, UML	-	***C₂***

Technical requirements *(C₁)*: Regarding the technical requirements, the analysis shows that data stores can, for example, be depicted using traditional flowcharting database symbols. Furthermore, it can be distinguished between electronic data stores and physical or paper data stores (Fedorowicz et al., 2005). Another possibility of involving data stores and interfaces is to visualize them as separate process participants, similar to human process participants. They also regard the IT structure, which helps transition the business process model to the later software design and development (Merunka et al., 2009). Besides data stores, another essential aspect relates to interfaces. Especially in inter-organizational business process design, the interfaces with other organizations and the organizational boundaries should be described (Legner & Wende, 2007). Furthermore, the integration of process performance indicators (PPIs) can potentially guide selecting appropriate tooling and hardware. One example could be supporting the selection between AR glasses and traditional hardware options (del-Río-Ortega et al., 2019). ***Key findings:*** Technical aspects as databases, interfaces to other IS, organizations and units are addressed in several papers. In addition, measures to guide hardware selection are mentioned.

Interaction *(C₂)*: The literature review shows that many researchers consider the interaction between different process participants (Jonnavithula et al., 2015; Koliadis et al., 2006; Legner & Wende, 2007; Merunka et al., 2009; Muehlen & Ho, 2008; Oberweis, 2010; Rittgen, 2006). They address interactions in terms of how key actors depend on each other (Jonnavithula et al., 2015; Koliadis et al., 2006; Merunka et al., 2009; Rittgen, 2006), how they communicate, and how the data flows are designed (Koliadis et al., 2006; Merunka et al., 2009). Therefore it can be helpful to visualize all possible interactions between the process participants (Merunka et al., 2009). Process participants can also be seen as actors with different roles implying several competencies, and therefore the interactions between the roles can be specified (Oberweis, 2010). Furthermore, interactions in the field of inter-organizational process models can be discussed. An important step is to clarify interactions and interdependencies between different organizations, especially if tasks need to be allocated (Legner & Wende, 2007). Moreover, a case study about BPMN usage found that only a small subset of BPMN constructs is sufficient to create business process models. To visualize interactions, participants accidentally placed certain activities between two lanes to represent ad-hoc coordination and collaboration. A specific symbol for ad-hoc interaction was missing, and instead of using an XOR connector, they decided to create their own modeling notation (Muehlen & Ho, 2008). In contrast to the interactions between the process participants, human-computer interaction is also relevant. According to Fedorowicz et al. (2005), process activities can be classified as manual, automated, or human-computer interaction. Receiving computer outputs, the need to input data manually, or interventions of operations are examples of human-computer interactions. For the visual representations, the use of separate swim lanes is proposed (Fedorowicz et al., 2005). ***Key findings:*** The literature shows that mainly interactions between different actors in a process are considered. Only one paper includes human-computer interaction.

Visualization requirements *(C_3)*: In general, several authors consider inputs and outputs to business process models in their articles (Becker et al., 2010; del-Río-Ortega et al., 2019; Fedorowicz et al., 2005; Rittgen, 2000). Since there is no domain-specific modeling language for the banking sector so far, a new business process modeling language using semantic building blocks was developed for that purpose. For this new language with respect to the visualization, the inputs are considered, defining different communication channels for process inputs, e.g., to request a document via different channels (Becker et al., 2010). In the domain of inter-organizational systems, the visualization of inputs and outputs is also discussed. According to the authors, it is helpful to include the way of input, e.g., via keyboard, and the output, e.g., using a screen. This can be done using symbols, either from a standard flowcharting notation or to create own symbols for the representation (Fedorowicz et al., 2005). Furthermore, the visualization requirements become relevant for the representation of process performance indicators. PPIs are relatable to key performance indicators (KPIs) but specifically for processes. The concept of data measures can, e.g., be used to visualize attributes of inputs and outputs (del-Río-Ortega et al., 2019). Another visualization method can be done using the so-called BORM (Business Object Related Modeling) process diagram. This method can be used for projects with the aim of knowledge visualization in general (Merunka et al., 2009). In addition, the use and application of EPC inputs and outputs are relevant as well. Although they are not included in the EPC extension, the authors identify the consideration of documents, data, and other resources as relevant for future research. This is in line with our findings with respect to the assumed research gap (Rittgen, 2000). ***Key findings:*** The findings related to the visualization requirements can be subsumed under inputs and outputs of business processes. Different visualization possibilities are discussed, and the integration of documents is considered.

Management perspective *(C_4)*: To gather insights about economic efficiency, time-related aspects can be considered. The literature supports the involvement of timestamps, durations, and waiting times in business process models (Bajaj & Ram, 1996; Becker et al., 2010; del-Río-Ortega et al., 2019; Oberweis, 2010). By measuring the duration between two time instances, the cycle times, as well as the linear times, can be calculated (del-Río-Ortega et al., 2019). Timespans and durations can be included in the business process model as a separate construct (Bajaj & Ram, 1996) or as an attribute of activities (Becker et al., 2010). If the time-related aspects are included, this can be used to analyze each activity's time demands and thus identify cost-saving potential (Becker et al., 2010). One possibility to reduce waiting times is to make better choices regarding the involved resources. This can also mean optimizing the activity assignment to human resources relying on suitable competence and skillsets (Oberweis, 2010). Furthermore, management-related concerns can be IT bottlenecks related to the system configurations. IT bottlenecks can influence the timespans and durations of activities and should be kept in mind during process modeling (Jonnavithula et al., 2015). ***Key findings:*** Timestamps, durations, and waiting times are well represented in the business process modeling literature. The ability to save costs by improving time-related aspects and reducing IT bottlenecks is discussed.

Comprehensibility and appropriateness *(C_5)*: An important factor is the comprehensibility of process models to make them more accessible for practice, especially for SMEs. A literature review focusing on the cognitive effort in comprehending process models has shown that not all process models are easy to understand. For this reason, we include this paper as relevant for the process modeling of AR processes because we have to determine what influences the intuitiveness and understandability of AR process models (Figl, 2017). To support the comprehensibility as well as the appropriateness of business process modeling languages, it can also be reasonable to investigate the discrepancy between the model and the real-world scenario. Since the gap between the process model and the actual circumstances is a well-known concern, process modeling approaches need to be proven appropriate (Jonnavithula et al., 2015). ***Key findings:*** The comprehensibility of process models and appropriateness of the modeling languages are discussed.

Innovation *(C_6)*: An appropriate way to support innovations and creative thinking is to visualize processes using storyboards. This shows an approach investigating the combination of storyboards and process models. Especially in the early stages of process modeling, the method is appropriate, and it could be supported using design thinking methods (Miron et al., 2019). ***Key findings:*** Storyboards can be used to visualize innovative processes. In addition to that, there are no further insights regarding the modeling of innovations and the transfer of the findings to AR/MR.

13.5 Discussion

The literature review results reflect that there has been no consideration of AR in business process modeling. Hence, we still need further research to cope with AR as a lever for redesigning and improving business processes. By doing so, a promising avenue for scholars emerges that is likewise relevant for practice. Since our review proves that comprehensibility and appropriateness are core aspects of business process models and the management perspective in terms of efficiency is addressed very well, we see no immediate need for action there (Badakhshan et al., 2020). To path the way for further consideration of AR in business process modeling, we propose a research agenda that builds upon shortcomings of current practice from an AR perspective and points to directions of possible solutions. We also add the until now neglected criteria Task-Technology-Embeddedness *(C_7)* and augmented reality relation *(C_8)* as these are key for developing a holistic AR perspective in BPM. The resulting twelve directions for further research are presented in Table 30.

Based on the systematic analysis, several research directions occur related to the dimensions we propose. Thus, we derive a broad range of research directions to enhance the representability of AR in business process modeling. Regarding technical requirements, the results show that technical aspects such as interfaces and databases are already broadly covered in business process modeling. However, as a technical precondition for most AR applications, network-related aspects are not mentioned in any of the papers. Especially when using AR in an industrial context, e.g., picking processes in warehouses (Stoltz et al., 2017) or repair and maintenance processes (Henderson & Feiner, 2011), a complete wireless LAN coverage in warehouses or production facilities is not always given. However, since in these contexts, the applications often require real-time access to data and systems via the network, the network infrastructure should be considered when using AR. Thus, there is a (1) *fundamental lack in representing network infrastructure*. Such a perspective is needed to cope with the technical preconditions of AR to prevent problems already

Table 30. Avenues for future research

Criterion	**Future research should...**
C_1 Technical requirements	(1) address network infrastructure as a technical precondition for most AR applications.
C_2 Interaction	(2) investigate how novel modes of interactions can be represented. (3) support decision-making on what kind of interaction is appropriate and efficient.
C_3 Visualization requirements	(4) add representations for different types of visualization in AR. (5) explore if outputs and their characteristics of AR need to be represented. (6) integrate tracking mechanisms of AR in process models to enable an encompassing process representation. (7) explore if differences regarding dimensionality in AR exist and, if so, investigate an inclusion in business process models.
C_6 Innovation	(8) evaluate storyboards to represent innovative approaches like AR. (9) identify further approaches to represent innovation in business process models.
C_7 Task-Technology-Embeddedness	(10) address the conditions that enable AR, thus depending on the mode of interaction needed (i.e., hands-free). (11) investigate representations that imply changes in the mode of interaction and media breaks.
C_8 Augmented reality relation	(12) address the specific requirements of AR to enable an encompassing perspective in BPM.

during process modeling, but even more so, other application areas, e.g., remote services, can benefit from it as well.

Some papers consider interactions but mainly focus on the visualization of interactions between actors in processes. One paper also includes the interaction between computers and humans using different swim lanes (Fedorowicz et al., 2005). Since AR requires and levers new modes of interaction like touch, voice, or gesture interactions, (2) *a specification of the interaction pattern is still missing.* Thinking about AR glasses, choosing a suitable interaction pattern, and providing several interaction alternatives becomes even more complex and important (Griffiths et al., 2000; Hornbæk & Oulasvirta, 2017; Ren et al., 2020). For this reason, we argue that (3) *future research should focus on how to visualize different interaction patterns and interaction alternatives.* An example to illustrate this could be an industrial maintenance process that does not allow all forms of interaction for work safety reasons so that only specific interaction patterns can be used for certain process steps. Overall, it would be advantageous to integrate interaction patterns directly into the process model in order to design a process that is as seamless, user-friendly, and efficient as possible (Webel et al., 2011).

Within the category visualization requirements, business process modeling can cope with several types of inputs and outputs. Although knowing the inputs and outputs of the process is essential, it is unclear which information needs to be visually depicted in the AR system. Thus, (4) *representations for types of visualization in AR need to be developed.* Depending on the modeling notation, the characteristics of the inputs and outputs are also not always specified. In addition, for AR systems, it (5) *should be examined if the emerging outputs from the AR system and their characterization need their own notation form as well.* Furthermore, none of the articles relates to tracking information on real-world objects for AR systems. Thus, another research opportunity is to (6) *identify the need for tracking information in a business process modeling system.* Future research should examine if information about the tracking in each process step is required and if technical maturity might be helpful, for example, for the future development of the AR system. Nevertheless, the literature review revealed no distinction between the visual representation of two-dimensional content and three-dimensional content. Future research should also concentrate on the (7) *differences and usefulness of including differentiation between two-dimensional and three-dimensional depictions.* These characteristics and requirements go hand in hand with the choice of hardware and the design of AR systems (Palmarini et al., 2017). If the above-mentioned points are already considered during the process modeling, the overall result can also gain in quality and usability, as well as increase efficiency. The literature review reveals that only one paper addresses the issue of modeling innovations. We included the criterion regarding innovative technologies in the analysis to be able to transfer knowledge about the modeling of new technologies and trends. As only one paper concerns the topic and proposes to use storyboards (Miron et al., 2019), it can be said that two different future research opportunities exist. On the one hand, the (8) *appropriateness of storyboards for modeling AR processes should be evaluated.* On the other hand, (9) *further approaches for the modeling of innovations need to be investigated.*

Since the Task-Technology-Embeddedness is not considered in the literature, we see great potential for future research. The question, (10) *what process steps can be supported by AR* while it is appropriate to wear an AR system, is highly relevant. In addition, AR-specific criteria concerning hands-free working as a great advantage of AR glasses should be taken into consideration (Klinker et al., 2018). Furthermore, a (11) *visualization of media breaks and changes in the mode of interaction* in the process might be helpful. This can, for example, include the change between AR glasses and reality (Osterbrink et al., 2021).

Since we found no evidence for existing approaches to model AR, VR, or MR in business processes, the assumption that there is a research gap is confirmed. Although we found two papers covering virtual environments and smart glasses, the articles focus on supporting the modeling process within a 3D environment or smart glasses (Fellmann et al., 2018; Recker & West, 2010). Therefore, we can argue that no process modeling language, notation, or approach specified for the modeling of AR processes exists. Due to the (12) *new requirements resulting, amongst other things, from increased immersion and new interaction techniques, new demands and challenges are also emerging for the modeling of AR processes.* For this reason, we consider the entire topic of AR process modeling to be relevant for future research.

Our literature review thus has some limitations. First, we did solely cover a fraction of scholarly outlets in our review. We broadened the perspective by adding several journals and conferences to the senior scholars' basket of eight, but an even broader review could lead to more insights. Nevertheless, the included outlets represent the prime venues for publications in our domain. Second, a literature review does represent the past of scientific discourse. Accordingly, some issues raised can potentially be addressed in the meantime.

13.6 Conclusion and Outlook

Within service design, we seek to explore the boundaries of novel technologies to enhance service delivery and create novel touchpoints for customers (Andreassen et al., 2016; Percival, 2016; Roto et al., 2016). Thus, to implement such novel approaches, business process modeling supports organizations in developing a systematic understanding of services, roles, and activities (Bitner et al., 2008). Nevertheless, novel technology-driven opportunities like augmented reality have requirements, characteristics, and preconditions that need to be carefully considered in service design. Therefore, the goal of our literature review was to assess the current state of representations for augmented reality in business process modeling. As AR has the potential to drastically alter processes and urge the need for process redesign, a plausible representation that copes with specific aspects of AR is needed. Thus, the results of the review show that only a fraction of aspects related to AR is already covered by business process models. There is no single paper that deals with AR specifically and how to represent it from a process perspective. Therefore, we derived twelve research directions representing a research agenda to cope with AR in service design by business process modeling (Mendling et al., 2020). These directions aim for increased adaptability of process models to ensure that emerging technologies, especially AR, can be represented to inform decision-making on the application of such technologies. By further developing these directions, we follow the goal of representing AR within business process models to enable scholars and practitioners to further investigate potential applications of AR in their routines. By integrating the technological context into business process modeling, we intend to promote a holistic view so that the technology applied and the processes are aligned, benefit from each other, and enable novel customer experiences. Thus, we contribute to the ongoing discourse on the impact of digitalization in organizations as we systematically assess process modeling regarding their applicability in innovative use cases. Additionally, extending the knowledge base on the representation of technology-driven service innovation can likewise be applied regarding the mixed reality continuum, thus even adding more value, as a result, could lead to a broader overview of potential technologies that can contribute to service design. Consequently, we expect that further research will be conducted in this area, and we seek to broaden scholarly engagement in this recent and relevant research area.

13.7 Acknowledgments

This research was partly sponsored by the German Federal Ministry for Education and Research and in the project WizARd under the reference 02K18D181. Further information can be found under: http://www.wizard.tu-dortmund.de/.

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14 Conceptualizing Interactions of Augmented Reality Solutions

Bräker, J., Hertel, J., & Semmann, M. (2022). Conceptualizing Interactions of Augmented Reality Solutions. *Proceedings of the Hawaii International Conference on System Sciences*, 712–721

Abstract

The rapid evolution of augmented reality has resulted in an ever-increasing number of applications in a wide range of industries and services. Despite this progress, there is still a lack of conceptual understanding of AR interactions and the entire solution space. To bridge this gap, we conceptualize AR solution interactions and provide a comprehensive taxonomy. To represent the state-of-the-art, we build upon an extensive literature review. The resulting taxonomy consists of seven dimensions that encompass 29 characteristics. We contribute to the understanding of AR interactions and, as a result, the applicability of AR solutions in businesses by developing the taxonomy. Likewise, the taxonomy can guide the design of AR solutions as it convincingly describes the solution space.

Keywords

New potentials of mixed reality and its business impact, literature review, mixed reality, taxonomy.

14.1 Introduction

The applicability of augmented reality (AR) for business and consumer solutions increased tremendously in recent years. A wide range of solutions applies in various industries, such as technical services (Niemöller et al., 2019), healthcare (Klinker et al., 2020a), logistics (Rauschnabel & Ro, 2016), infrastructure maintenance (Osterbrink et al., 2021), consumer goods (Hilken et al., 2017; Scholz & Duffy, 2018; Wedel et al., 2020), as well as mobile and stationary gaming (Das et al., 2017; Lintula et al., 2017). Despite the increasing application of AR in business contexts, there is still a lack of systematic guidance for designing and orchestrating interactions with AR systems. Even though AR and taxonomies are both areas of interest in IS research, there is little research to date. Although preliminary work exists in the HCI domain, there is no recent taxonomy for conceptualizing AR interactions. Back in the 1990s, Bowman (1998) developed a general framework for conceptualizing interaction techniques in immersive virtual environments, but it does not address AR and thus does not leverage AR's specific potential. Additionally, the hardware options were not as mature as they are now. Benford et al. (2005) mention several existing taxonomies for input devices, but these do not focus on AR specifically.

As the capabilities of AR increase and novel modalities emerge, the need to systematize AR interactions to foster understanding of applications and guide the design of solutions rises. A systematization of atomic AR interactions to support the design and development of new AR solutions appears highly beneficial, particularly for service design and modeling AR processes (Bräker & Semmann, 2021). Atomic interactions are, in this regard, the most granular interactions between users and AR devices. An example on the HoloLens 2 for such an atomic interaction is opening a menu by selecting a button presented on the user's palm. The focus is not on what the interaction explicitly aims for, e.g., object creation or manipulation, but much more on the activity of the interaction itself. For this reason, we address the following research question: *How can atomic interactions with AR systems be systematically classified to support service design and AR application development?*

To bridge this gap and take recent findings into account, we conducted a systematic review of literature on interactions and applications of AR to conceptualize interactions of AR solutions. As a result, we create a concise taxonomy that aids in understanding, assessing, and designing AR solutions in terms of interaction patterns. The guiding meta-characteristic for taxonomy development is *"user inter-*

action within services in the realm of AR". In this regard, we identified seven core dimensions and 29 characteristics in total.

The remainder of the paper is structured as follows: the next section presents related work and lays the core foundations regarding AR. Then we describe our overall research design, the literature review, and the development of the taxonomy. In the fourth section, we introduce the taxonomy of interactions for AR, followed by an in-depth discussion. Finally, we conclude and discuss our paper's contribution as well as potential future research directions.

14.2 Related Work

14.2.1 Taxonomy Research

Taxonomies are defined as "systems of groupings that are derived conceptually or empirically" (Nickerson et al., 2013, p. 338). Taxonomies attempt to conceptualize objects in a domain of interest to aid researchers and practitioners in their understanding. Taxonomies consist of dimensions that include mutually exclusive and collectively exhaustive characteristics, which means that every object must have one of the dimension's characteristics. However, no object can have two different characteristics in one dimension (Nickerson et al., 2013). Nickerson et al. (2013) propose a method for systematic taxonomy development widely used in the IS domain. It begins with identifying a meta-characteristic for the taxonomy, which serves as the central question. Following that, ending conditions should be defined, which can be objective or subjective. Subsequently, taxonomy development begins, following either an empirical-to-conceptual or a conceptual-to-empirical approach. Iteratively, the taxonomy develops by discovering new dimensions and characteristics until the predefined ending conditions are met.

14.2.2 Augmented Reality

AR has grown in popularity in recent years, and it is increasingly used in organizations (Gattullo et al., 2020) and the gaming industry (Elo et al., 2021; Lintula et al., 2017). However, AR is not a new phenomenon, having its beginnings in the 1960s (Sutherland, 1968). According to Milgram and Kishino (1994), AR can be positioned on a continuum between an entirely virtual world – also called virtual reality (VR) –

and reality. This continuum is called the virtuality continuum and includes various forms of mixed reality (MR) between the two extremes. In the case of AR, virtual elements augment reality, but the reality is still predominant. If virtual overlays are in focus, but parts of reality are still present, the author speaks of augmented virtuality (AV). In this paper, we only consider AR as a manifestation of MR. Azuma (1997) defines AR as the combination of real and virtual elements, whereas an AR solution allows for real-time interactions, and virtual objects are registered in three-dimensional space.

In contrast to traditional desktop interfaces, AR solutions deliver visual information in a more immersive and spatial manner (Milgram & Kishino, 1994), necessitating the development of new ways of interaction, i.e., the exchange of information between systems and users. A recent study shows that AR interaction techniques are a major topic in human-computer interaction research because AR applications' usefulness depends on the interaction with the AR user interface, including methods to let the user provide input to the systems (Kim et al., 2018). While traditional desktop interfaces typically use a keyboard and mouse as input devices to enable the user to provide information to the system, AR solutions give a wider variety of interaction options, e.g., through various input sensors like microphones, tracking cameras and gyroscopes. Based on this multitude of possibilities, it is necessary to understand interactions in AR better (Bräker & Semmann, 2021). To achieve such understanding, we propose the following research design to develop a taxonomy of AR interactions.

14.3 Research Design

To bridge the identified gap concerning a taxonomy for AR interactions, we conduct the following research: our approach consists of two phases. The first one is a thorough literature review on interactions with AR solutions in the IS and HCI communities. The identified literature serves as the foundation for taxonomy development. Following that, we create the taxonomy in six iterations.

14.3.1 Literature review

We started by conducting a structured literature review based on Webster and Watson (2002) and vom Brocke et al. (2009) to identify literature dealing with interactions in AR solutions.

We used the query *(interact* OR interface OR input) AND ("augmented reality" OR "mixed reality" OR "smart glass*")* for our keyword search. We limited our search to the title, keywords and abstract, where possible. We set no time restrictions and only looked at peer-reviewed articles. Litsonar (litsonar.com) assisted in the generation of search queries for the databases. Included databases were (1) ACM Digital Library (ACM DL), (2) AIS Electronic Library (AISeL), (3) EBSCO Business Source Complete (EBSCO), (4) IEEEXplore, (5) ProQuest, (6) ScienceDirect (SD), (7) ScholarSpace (SchS), and (8) SpringerLink. We began our search within the IS community and then broadened it to include selected HCI outlets. Regarding IS literature, we included the "Senior Scholars' Basket of IS Journals", "Business & Information Systems Engineering", "Communications of the AIS", "Information & Management", and "Journal of Information Technology Theory and Application", as well as the IS Conferences "International Conference on Information Systems", "European Conference on Information Systems", "Hawaii International Conference on System Sciences", "Americas Conference on Information Systems", "Pacific Asia Conference on Information Systems", "International Conference on Wirtschaftsinformatik", and "International Conference on Design Science Research in Information Systems and Technology". We also added the journal "AIS Transactions on Human-Computer Interaction" for more HCI literature within the IS community. Furthermore, we included the HCI outlets "ACM Transactions on Computer-Human Interaction", "IEEE Transactions on Knowledge and Data Engineering", "IEEE Transactions on Mobile Computing", "IEEE Transactions on Pattern Analysis and Machine Intelligence", "IEEE Transactions on Services Computing", "IEEE Transactions on Software Engineering", "IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)", "IEEE Transactions on Visualization and Computer Graphics", "IEEE Transactions on Computers", "IEEE Transactions on Information Theory", "IEEE Transactions on Multimedia", "IEEE Transactions on Robotics", and "IEEE Intelligent Systems".

We reviewed 309 papers in total (see Table 31). Two independent researchers carried out the literature review.

The inclusion criteria were as follows: articles should contain a focus on AR or MR solutions and we considered both the implementation of AR using HMDs, as well as mobile or projection-based AR. In addition, papers had to address interactions with the AR or MR solution. We included case studies with concrete implementations as well as more theoretical and conceptual articles dealing with interactions.

Table 31. Literature review

	Database	1^{st} round	2^{nd} round	Relevant for taxonomy
IS	AISeL	24	21	10
	EBSCO	3	2	2
	IEEEXplore (only HICSS)	6	3	3
	ProQuest	0	-	-
	SD	0	-	-
	SchS	13	11	7
	SpringerLink	21	6	2
HCI	ACM DL	18	12	9
	IEEEXplore	224	46	18
	Total	309	101	51

We sorted out 208 papers during the first round by scanning the title, keywords, and abstract. As a result, we had 101 papers for the second round of review. In the second round, we examined the papers in more detail and coded them for further taxonomy development regarding essential keywords. In doing so, we highlighted meaningful passages in the text that related to our research question and met the meta-characteristics described in the following section and recorded the keywords in an Excel spreadsheet to use as input for taxonomy development. We completed the review process with 51 papers after the second round of literature review. Twenty-four of the articles are from the IS community, and 27 are from the HCI community. We proceeded with the taxonomy development with these 51 papers.

14.3.2 Taxonomy Development

We created the taxonomy using the methodology described by Nickerson et al. (2013). Figure 37 depicts the development process over six iterations. We defined *"atomic user interaction within services in the realm of AR"* as our meta-characteristic. We are not interested in the context in which the AR solution is deployed or entire AR applications but take a much broader perspective and look at any atomic user interactions and their technical constraints. Nickerson et al. (2013) provided objective and subjective ending conditions, which we both used. As objective ending conditions, we applied that we examined a representative sample of the literature and that no dimensions or characteristics were added, merged, or split in the previous iteration. In addition, we made sure that at least one object was classified for each characteristic. We considered another essential point that the dimensions, characteristics, and cells are unique and not duplicated. Subjective ending conditions include attributes such as conciseness, robustness, comprehensiveness, extensibility, and explainability. More concretely, this means that the number of dimensions is within a reasonable range and is neither overwhelming nor too small to be meaningful. In this context, five to nine dimensions are considered an adequate guideline to meet the end condition. Regarding robustness, we examined whether the dimensions and characteristics allow for sufficient differentiation. The comprehensibility criterion states that all objects should be classifiable using the taxonomy. We investigated the latter two factors and explainability by repeatedly applying examples to our taxonomy. Extensibility is given when new dimensions and features are easy to add so that the taxonomy is always up to date. We verified this by considering other focal points and evaluating extensibility with this view.

We followed a conceptual-to-empirical iteration before the first iteration because Nickerson et al. recommend this approach when “little data are available[,] but the researcher has [a] significant understanding of the domain” (Nickerson et al., 2013, p. 345). Following this approach, we conceptualized the *hardware*, *input modalities*, and *output modalities* dimensions from the researchers’ expertise. In the subsequent iterations, we used the empirical-to-conceptual approach to validate our assumptions.

As data, we used the results of our literature review, and in this way, we identified the objects we aim to classify with our taxonomy. We did this by documenting single characteristics in an Excel sheet and discussed the characteristics with the independent researchers after each iteration. In this way, we could cluster and assess the characteristics onto the dimensions and afterward combine or split characteristics and dimensions if needed. We chose a random sample of eight IS papers for the first iteration, validated our initial dimensions *hardware*, *input modalities*, and *output modalities*, and added two new dimensions: *interactivity relation* and *sequence of interactions*. For the second iteration, we added eight more IS papers and were able to add the dimension *interaction implementation* and several new characteristics to existing dimensions. We included the last eight IS papers in the third iteration, added the dimension *users per device*, and added new characteristics to two existing dimensions. We decided to continue the process with HCI literature because we have not yet met our ending conditions. We added nine papers from the ACM DL database in the fourth iteration. As a result, we discovered a new characteristic. In the fifth iteration, we examined eight HCI papers from IEEEXplore and added one characteristic. In the sixth and final iteration, we analyzed the remaining set of ten IEEEXplore papers and met the objective and subjective ending conditions described above after this iteration. Thus, all of our ending conditions were fulfilled, and the taxonomy development was completed.

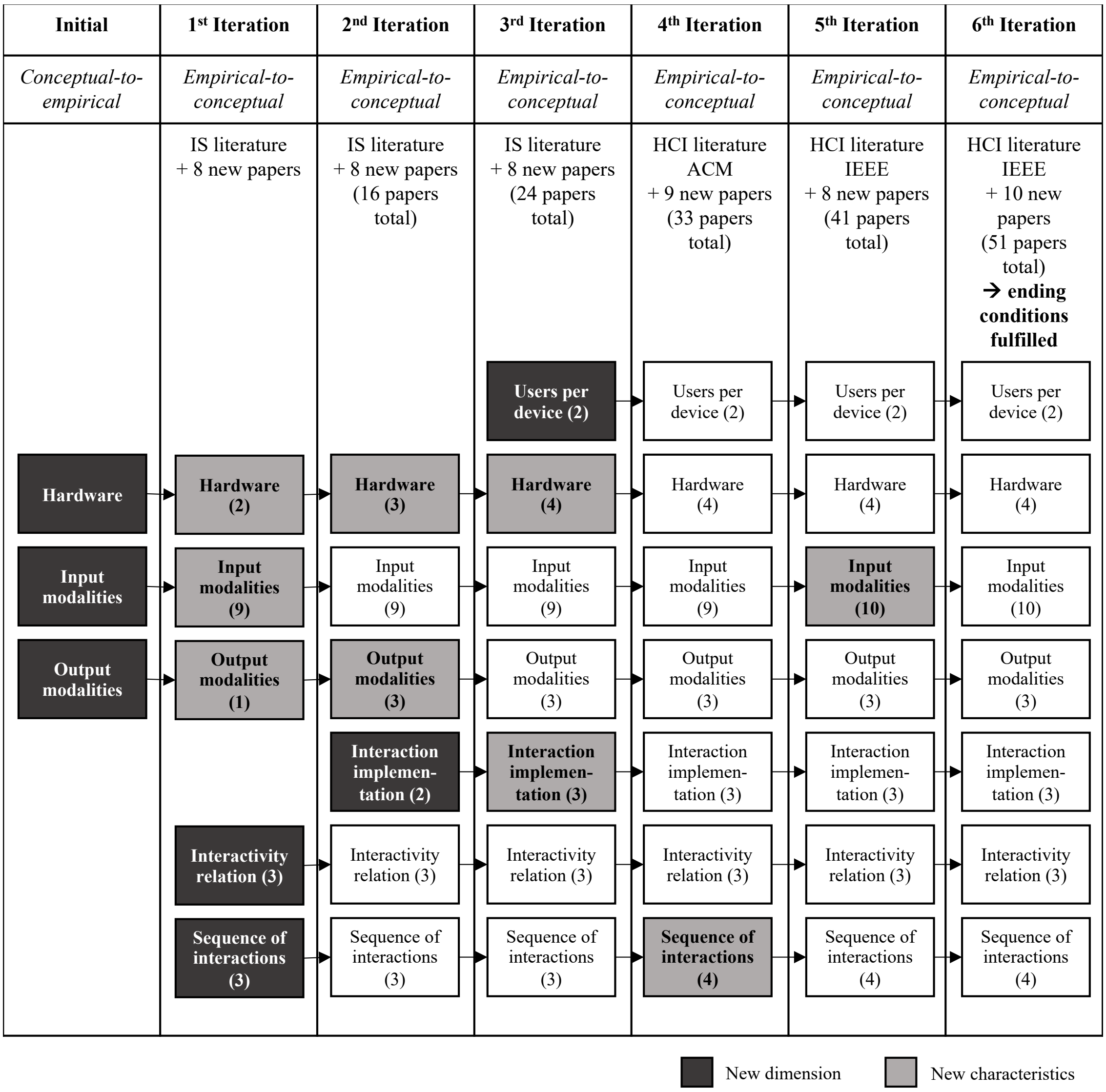

Figure 37. Development of taxonomy dimensions and characteristics (adapted from Remane et al., 2016)

14.4 Taxonomy of Interactions for Augmented Reality

Our taxonomy is composed of 29 characteristics distributed across seven dimensions (see Table 32). While the characteristics are collectively exhaustive, we deviate from Nickerson et al. (2013) by not requiring mutual exclusiveness to be fulfilled everywhere. This is due to the multimodality of AR solutions, which may include multiple input and output modalities simultaneously. In the following, we describe each of the seven dimensions and the subsumed characteristics in more detail.

D_1 Users per device: AR solutions can be used by a single user or multiple users concurrently. According to our analysis, the vast majority of the articles – 49 out of 51 – describe ***single-user*** settings. We classified the solution as ***multi-user*** if it involves more than one user simultaneously, as shown in the cases of Benford et al. (2016) and Enyedy et al. (2017). Both articles describe a multi-user setting in which several users share a virtual and physical space. One device per user is used in the first case, but they share the same virtual and physical space. Multiple users are present in the same space in the latter case, but only one device is used for all of them.

D_2 Hardware: The implemented hardware significantly impacts how the user interacts with the AR solution. Four major characteristics have been identified: ***mobile AR*** (Abowd & Mynatt, 2000; Benford et al., 2005; Gattullo et al., 2020; Gutiérrez et al., 2019; Henderson & Feiner, 2011; Holopainen et al., 2018; Lin et al., 2017; Lintula et al., 2017; Prilla et al., 2019; Riar et al., 2021; Si-Mohammed et al., 2020; Sommerauer, 2021; Tarafdar et al., 2020), such as smartphone or tablets, and ***HMDs***, including monocular (Laramee & Ware, 2002; Lin et al., 2017; Prilla et al., 2019) and binocular (Benford et al., 2005; Biocca et al., 2007; Biocca et al., 2006; Broll et al., 2005; Dudley et al., 2018; Ferrari et al., 2020; Gattullo et al., 2020; Gutiérrez et al., 2019; Hix et al., 2004; Holopainen et al., 2018; Jang et al., 2015; Kotranza et al., 2012; Laramee & Ware, 2002; S. Lee & Hua, 2011; Lin et al., 2017; Mättig & Kretschmer, 2019; Mcgill et al., 2020; Prilla et al., 2019; Rehring et al., 2019; R. Reuter et al., 2019; Riar et al., 2021; Shang & Wu, 2022; Si-Mohammed et al., 2020; Sommerauer, 2021; Williams et al., 2020; Xiao et al., 2018; Y. Yang et al., 2021), are the most common hardware options. ***Projection-based AR*** (Enyedy et al., 2017; Gattullo et al., 2020; Koike et al., 2001) and ***desktop AR*** (Gattullo et al., 2020; Riar et al., 2021; Salvador-Herranz et al., 2013) both use a static non-mobile environment, with the former using projectors for augmentation and the latter describing a static desktop setting. The hardware also influences whether hands-free interaction is possible. Accordingly, HMDs, for example, are likely to support hands-free interaction patterns.

Table 32. Taxonomy of augmented reality interactions

Dimensions	Characteristics									
D_1 Users per device	Single-user					Multi-user				
D_2 Hardware	Mobile AR		HMDs			Projection-based AR		Desktop AR		
D_3 Input modalities	Voice	Touch	Gestures	Free body movement	Gaze	Sensor	Eye-tracking	Video/ image	BCI	Generic input device
D_4 Output modalities	Haptic feedback			Visual feedback			Auditory feedback			
D_5 Interaction implementation	Virtual object selection			Physical object selection			Virtual object manipulation			
D_6 Interactivity relation	Digital objects			Physical objects			People			
D_7 Sequence of interactions	Frequency		Duration			Variety		Concurrency		

D_3 Input modalities: Because of the possibility of multimodality, the characteristics of the input modalities are not mutually exclusive. Multimodality is defined as an interaction that can include multiple input modalities at the same time, such as voice and gestures. The analysis reveals that there are numerous input opportunities. The most common are voice, touch, and gestures. ***Voice input*** (Abowd & Mynatt, 2000; Benford et al., 2005; Berkemeier et al., 2019; Broll et al., 2005; Dudley et al., 2018; Gutiérrez et al., 2019; Klinker et al., 2019; Luo et al., 2020; Mahfoud et al., 2018; Prilla et al., 2019; Rehring et al., 2019; Sesay & Steffen, 2020; Shang & Wu, 2022; J. Vogel & Thomas, 2019; Williams et al., 2020; Xiao et al., 2018) can be command-based or natural language processing (NLP) (Klinker et al., 2019). ***Touch interaction*** (Dudley et al., 2018; Hobert & Schumann, 2017; Klinker et al., 2019; Koike et al., 2001; Luo et al., 2020; Mcgill et al., 2020; R. Reuter et al., 2019; Sesay & Steffen, 2020; J. Vogel & Thomas, 2019; Xiao et al., 2018) can include both near and far touch. Near touch in this context refers to directly touching the interaction trigger, whereas far touch refers to a mapping of the touch interaction, i.e., ray-casting on a distant object (Klinker et al., 2019). Near touch interaction can take the form of giving input via a virtual keyboard while wearing an HMD (Dudley et al., 2018) or simply touching buttons (Hobert & Schumann, 2017; J. Vogel & Thomas, 2019). Mcgill et al. (2020) provide another example of near touch interaction. The authors describe an AR solution in which 3D content is attached and mapped onto the body, in this case around the user's wrist. ***Gestures*** (Abowd & Mynatt, 2000; Benford et al., 2005; Berkemeier et al., 2019; Broll et al., 2005; Erat et al., 2018; Gutiérrez et al., 2019; Henderson & Feiner, 2011; Hong & Brooks, 2020; Jang et al., 2015; Klinker et al., 2019; Koike et al., 2001; Lin et al., 2017; Luo et al., 2020; Mahfoud et al., 2018; Prilla et al., 2019; Rehring et al., 2019; R. Reuter et al., 2019; Sesay & Steffen, 2020; J. Vogel & Thomas, 2019; Williams et al., 2020; Xiao et al., 2018; Y. Yang et al., 2021) are the most commonly used AR input modality and include gestures using fingers, hands, arms or the entire body. They are widely used regardless of hardware, but tracking mechanisms are required to detect the gestures. ***Free body movement*** (Benford et al., 2005; Enyedy et al., 2017; Mahfoud et al., 2018) in the environment, such as the user's position, can be used as input as an alternative to gestures. In some cases, such as the HoloLens 1 cursor, the line of ***gaze*** (Benford et al., 2005; Berkemeier et al., 2019; Mahfoud et al., 2018; Mcgill et al., 2020; Prilla et al., 2019; Xiao et al., 2018) also serves as an input. Aside from active user inputs, ***sensors*** (Benford et al., 2016; Benford et al., 2005; Berkemeier et al., 2019; Hobert & Schumann, 2017; Koike et al., 2001; Luo et al., 2020; Prilla et al., 2019; J. Vogel & Thomas, 2019) can provide autonomous input. Internal or external sensors can be used. Some examples are infrared cameras, acceleration sensors and gyroscopes, other telemetry sensors, GPS, Bluetooth, or RFID. Gyroscopes, for example, are also used to detect and record head movement and position. With the help of GPS, it is possible to track the user's location. Sensor combinations are also possible in this case. Furthermore, tracking ***eye movement and blinks*** (Berkemeier et al., 2019; Klinker et al., 2019; Mcgill et al., 2020; Prilla et al., 2019) can be used as inputs. Inputs can also be ***video or image*** data (Benford et al., 2005; Berkemeier et al., 2019; Hobert & Schumann, 2017; Klinker et al., 2019; Koike et al., 2001; Kotranza et al., 2012; Lin et al., 2017; Prilla et al., 2019; J. Vogel & Thomas, 2019). Cameras are used to take photos or videos for further analysis. QR code or barcode readers are common, particularly in industrial settings. The ***brain-computer interface (BCI)*** (Si-Mohammed et al., 2020) is an emerging input technology in which brain activities are measured and used as inputs. In addition, ***generic input devices*** (Benford et al., 2005; Berkemeier et al., 2019; Dudley et al., 2018; Enyedy et al., 2017; Erat et al., 2018; Henderson & Feiner, 2011; Klinker et al., 2019; S. Lee & Hua, 2011; Mahfoud et al., 2018; Mättig & Kretschmer, 2019; Mcgill et al., 2020; Prilla et al., 2019; Salvador-Herranz et al., 2013; Xiao et al., 2018; Y. Yang et al., 2021) are mentioned, which allow for other types of user input. Scanning gloves, handheld clickers, foot pedals, and traditional input devices are examples of these. External tracking hardware, such as cameras for tracking hand localization, is also described.

In general, the inputs mentioned above can be used as predictive features. Thus, it is possible to predict what a user will do next, for example, by analyzing eye movements. Therefore particular objects may come into focus and become more likely for a subsequent interaction. As previously stated, input modalities do not need to be mutually exclusive because multiple inputs can be addressed simultaneously. Furthermore, specific sequences of input modalities occur frequently together. For example, as with HoloLens 1, gaze-then-gesture can be used in combination (Dudley et al., 2018).

D_4 Output modalities: This dimension defines an interaction's output, which can be haptic, visual, auditory, or a combination of these. ***Haptic feedback*** (Henderson & Feiner, 2011; Mättig & Kretschmer, 2019; Tarafdar et al., 2020) can be active or passive and can be provided by an additional haptic glove. The most described characteristic is ***visual feedback*** (Berkemeier et al., 2019; Biocca et al., 2007; Biocca et al., 2006; Erat et al., 2018; Ferrari et al., 2020; Gattullo et al., 2020; Gutiérrez et al., 2019; Henderson & Feiner, 2011; Hix et al., 2004; Hobert & Schumann, 2017; Holopainen et al., 2018; Hong & Brooks, 2020; Kalkofen et al., 2009; Koike et al., 2001; Kotranza et al., 2012; Lintula et al., 2017; Luo et al., 2020; Madsen et al., 2016; Prilla et al., 2019; Riar et al., 2021; Sommerauer, 2021; Sommerauer & Müller, 2018; J. Vogel & Thomas, 2019; Xiao et al., 2018; Y. Yang et al., 2021), which includes any form of visual presented information as an output from an interaction. The final output characteristic is ***auditory feedback*** (Biocca et al., 2007; Biocca et al., 2006; Hobert & Schumann, 2017; Sommerauer & Müller, 2018), which refers to audio feedback from the interaction. Output modalities, like input modalities, are not mutually exclusive and can be combined.

D_5 Interaction implementation: Interaction can be divided into three main task purposes, independent of the information the user aims to interact with. The goal of an interaction can be ***virtual object selection*** (Benford et al., 2005; Berkemeier et al., 2019; Biocca et al., 2007; Biocca et al., 2006; Broll et al., 2005; Ferrari et al., 2020; Gutiérrez et al., 2019; Henderson & Feiner, 2011; Hix et al., 2004; Hobert & Schumann, 2017; Holopainen et al., 2018; Hong & Brooks, 2020; Kalkofen et al., 2009; Laramee & Ware, 2002; S. Lee & Hua, 2011; Lintula et al., 2017; Luo et al., 2020; Prilla et al., 2019; Riar et al., 2021; Sommerauer, 2021; J. Vogel & Thomas, 2019; Williams et al., 2020; Xiao et al., 2018). Object selection is mostly always the first step in a sequence of interactions. Because AR combines virtuality and reality, the interaction can also include ***physical object selection*** (Biocca et al., 2007; Biocca et al., 2006; Xiao et al., 2018). Following selection, ***virtual object manipulation*** (Benford et al., 2005; Enyedy et al., 2017; Ferrari et al., 2020;

Henderson & Feiner, 2011; Hong & Brooks, 2020; Kalkofen et al., 2009; Koike et al., 2001; S. Lee & Hua, 2011; Lin et al., 2017; R. Reuter et al., 2019; Sommerauer, 2021; Steffen et al., 2019; Williams et al., 2020; Xiao et al., 2018) is common, which can be, for example, in the form of picking, dropping, dragging, rotating, or zooming.

D_6 Interactivity relation: The dimension interactivity relation classifies interaction as digital, physical, or human. This dimension is independent of the specific use case scenario and the information. We define ***digital objects*** (Elo et al., 2021; Erat et al., 2018; Riar et al., 2021; Salvador-Herranz et al., 2013; Sesay & Steffen, 2020; Steffen et al., 2019; Tarafdar et al., 2020) as only virtual objects in AR that the user can interact with. Additionally, this can include smart objects and IoT data. Interactions can also occur with ***physical objects*** (Benford et al., 1998; Benford et al., 2005; Broll et al., 2005; Enyedy et al., 2017; Erat et al., 2018; Gattullo et al., 2020; Gutiérrez et al., 2019; Henderson & Feiner, 2011; Koike et al., 2001; Kotranza et al., 2012; Madsen et al., 2016; Sesay & Steffen, 2020; Sommerauer, 2021; Sommerauer & Müller, 2018; Tarafdar et al., 2020; Yannier et al., 2016). I.e., the users interact with their immediate physical surroundings, and the AR solution serves as a mediator between the user and the real world. Tangibles are one example of this. Despite the interaction with objects, face-to-face interactions with other ***people*** (Enyedy et al., 2017; Rehring et al., 2019; Sesay & Steffen, 2020; Sommerauer, 2021), such as co-workers, are possible when using an AR solution. This can be face-to-face interaction in reality, as AR allows for the simultaneous perception of reality and virtuality, or virtual interactions with other people, such as video calls.

D_7 Sequence of interactions: This dimension describes how a sequence of multiple interactions can be designed. This sequence may include various input modalities and interaction implementations. Interactions can be classified according to their ***frequency*** (Tarafdar et al., 2020), ***duration*** (Benford et al., 1998; Benford et al., 2005; Tarafdar et al., 2020) or speed, variety (Tarafdar et al., 2020), and ***concurrency*** (Benford et al., 2005).

14.5 Discussion

The paper's goal was to create a taxonomy to aid scholars and practitioners in developing a shared understanding of AR interactions. We are convinced that when designing new AR applications, the choice of interactions is not trivial. With the help of this taxonomy, users can achieve guidance in terms of the variety of interaction patterns and consider all possibilities during new design and development. We have shown a wide range of dimensions and characteristics. Our taxonomy is independent of application domains because it focuses on individual atomic interactions rather than AR solutions and their context. This also means that we do not focus on the purpose of the interaction, such as collaboration, documentation, or process support, because these tasks can also be mapped on single interactions and are not unique in their interaction patterns. When it came to input modalities, we discovered ten characteristics in particular. This large number of modalities reflects the technological advancement and the increasing applicability of hardware. Touch interfaces and precise tracking technologies, for example, are now state-of-the-art but were not so easily accessible a decade ago. As a result, the complexity of input modalities increases further because the dimension does not meet the criterion of mutual exclusiveness proposed by Nickerson et al. (2013). The reason for dropping this criterion is that while AR solutions can use a single input modality to fulfill a task, most AR solutions use multiple input modalities to enhance the perception and usefulness of the augmentation. Consequently, the combination of modalities is becoming more common in recent papers as technological capabilities improve. This means that it is not necessary to choose only one input modality for service design but that a combination is indeed possible and reasonable. The same effect is visible in output modalities, which are also combined in AR solutions.

Following the technological advancement, it is apparent that the hardware dimension defines features such as the possibility of hands-free interaction. Consequently, understanding the use case of an AR solution is crucial for selecting appropriate hardware.

Surprisingly, collaboration within AR is only scarcely addressed by research. Only three papers deal with interactions with co-workers, and two emphasize the ability to collaborate locally. This limited collaboration is also mirrored in *D_1 Users per device*, with only two papers proposing interactions for multiple users per AR device. This demonstrates that, until now, there has been a focus on single-user settings for AR solutions. Osterbrink et al. (2021) have shown, for example, that collaboration with co-workers is a necessary requirement for AR applications in safety-critical environments. Another noteworthy aspect is *D_7 sequence of interactions*, which is only covered by three papers, none of which address every characteristic. Thus, one reason for this is that core HCI literature, in particular, is more focused on specific facets of interactions, and therefore dealing with a fine-grained interaction is plausible. This reliance on single interactions in IS literature is surprising and opens up a broad field of research opportunities.

14.6 Conclusion

In this paper, we systematically created a taxonomy to conceptualize the interactions of AR solutions. The provided taxonomy has seven dimensions and 29 characteristics, and it serves as a tool for researchers and practitioners by supporting a systematic analysis of interactions in AR solutions. To the best of our knowledge, this is the first attempt in IS to systematize this domain. Despite analytical support, the taxonomy can guide the design of AR solutions because the solution space is described comprehensively. As a result, practitioners can use it to determine whether an AR solution is feasible for the business's needs.

Despite the taxonomy's thorough development, the paper has some limitations. Firstly, regarding the breadths of the literature review: we decided to concentrate on a wide range of IS literature and solely add core HCI journals. A broader range of HCI literature could have expanded the taxonomy's foundation. Still, as we met the ending conditions proposed by Nickerson et al. (2013), we are convinced that the resulting taxonomy is exhaustive.

The taxonomy reveals potentials for future research. Because the literature is primarily focused on single interactions, researchers may revisit the issue of multimodality and investigate best practices and advantageous combinations for input and output modalities and patterns. This may, for example, be manifested by introducing archetypes of interaction patterns. Moreover, the collaborative aspect of AR is frequently understudied in literature, resulting in unrealized potentials for AR. For these reasons, we want to encourage researchers to investigate this field further.

14.7 Acknowledgments

This research was partly sponsored by the German Federal Ministry for Education and Research and in the project WizARd under the reference 02K18D181. Further information can be found under: http://www.wizard.tu-dortmund.de/.

14.8 References

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15 A Taxonomy of Interaction Techniques for Immersive Augmented Reality based on an Iterative Literature Review

Hertel, J., Karaosmanoglu, S., Schmidt, S., Bräker, J., Semmann, M., & Steinicke, F. (2021). A Taxonomy of Interaction Techniques for Immersive Augmented Reality based on an Iterative Literature Review. *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality*, 431–440. https://doi.org/10.1109/ISMAR52148.2021.00060

Abstract

Developers of interactive systems have a variety of interaction techniques to choose from, each with individual strengths and limitations in terms of the considered task, context, and users. While there are taxonomies for desktop, mobile, and virtual reality applications, augmented reality (AR) taxonomies have not been established yet. However, recent advances in immersive AR technology (i.e., head-worn or projection-based AR), such as the emergence of untethered headsets with integrated gesture and speech sensors, have enabled the inclusion of additional input modalities and, therefore, novel multimodal interaction methods have been introduced. To provide an overview of interaction techniques for current immersive AR systems, we conducted a literature review of publications between 2016 and 2021. Based on 44 relevant papers, we developed a comprehensive taxonomy focusing on two identified dimensions – *task* and *modality.* We further present an adaptation of an iterative taxonomy development method to the field of human-computer interaction. Finally, we discuss observed trends and implications for future work.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction techniques—, Human-centered computing—Interaction design theory, concepts and paradigms—

15.1 Introduction

The research fields of augmented reality (AR) and virtual reality (VR) have their origins more than 50 years ago in the 1960s (Sutherland, 1968). Besides the AR/VR display technologies themselves, various techniques, which allow users to interact with these systems, were pro- posed and investigated ever since. Previous work has established the systematization of interfaces and interaction techniques with a focus on VR. For instance, in 1999, Bowman and Hodges (1999) formalized interaction techniques for immersive virtual environments (VEs) in the form of a taxonomy. They identified three universal tasks – (i) viewport motion control, (ii) selection, and (iii) manipulation, which they decomposed into fine-grained subtasks. For each of these subtasks, they identified several existing interaction techniques that could be used to accomplish them. The resulting tree-like taxonomy presented a broad overview of existing interaction techniques and was also used as a basis for evaluating interaction techniques (Bowman & Hodges, 1999). While this taxonomy was focused on immersive VEs only, in 2004, Bowman et al. (2004) collected 3D user interfaces that included both VR and AR. In their book, they suggest design guidelines for the development of AR and VR interaction techniques.

Since these early approaches to systematically guide interaction design, *immersive AR* has experienced enormous technical advancements. In this context, we define *immersive AR* as technology, which allows viewing AR content in an immersive way (e.g., via head-worn displays or projection-based AR) without external displays as used in mobile or hand-held systems. The recent launch of self-contained untethered head-mounted displays (HMDs), such as the Microsoft HoloLens in 2016 (Microsoft, n.d.), paved the way to let consumers observe virtual content in an unobtrusive manner. Due to the integration of multisensory input systems, including voice recognition, head tracking, hand tracking, and even eye tracking (e.g., on the HoloLens 2), developers and users have access to various interaction possibilities. However, the lack of standardization in immersive AR interaction techniques as well as the variety of options often complicates the design process and might confuse AR developers and researchers.

In the last years, researchers reviewed, analyzed, and structured various aspects of the field of AR. For instance, there are reviews focusing on uses, advantages, and trends of AR in specific application fields like education (Akçayır & Akçayır, 2017; Garzón et al., 2019), medicine (Eckert et al., 2019; Munzer et al., 2019), or maintenance (Egger & Masood, 2020; Fernández del Amo et al., 2018). Further, taxonomies about subtopics of AR research like visualization (Zollmann et al., 2021) and context awareness (Grubert et al., 2017) were developed. In 2018, Muhammad Nizam et al. (2018) reviewed interaction techniques in AR, focusing on multimodal interaction. Expanding the existing body of research, we aimed to analyze interaction techniques in immersive AR systems. We did not focus on specific kinds of techniques but performed an explorative approach examining common characteristics among techniques to develop a comprehensive taxonomy. While in the field of human-computer interaction (HCI) the concept of interaction can be understood as a reciprocal exchange between a user and a system, we only focus on actions a user performs actively. Hence, we considered techniques that allow a user to provide any kind of input to an immersive AR system and did not consider aspects like visualization and feedback.

Our work aims to capture the current state of research of immersive AR interaction techniques, extract common characteristics among these techniques, and develop a taxonomy that sorts and groups them accordingly. The taxonomy is intended to provide an overview, a common ground for discussion as well as an aid to identify research gaps, emerging trends, and related interaction techniques to evaluate new ones. For this purpose, we considered research papers published within the last five years since 2016. In the year 2016 – sometimes referred to as the “year of AR” (Boyajian, 2016) – several AR milestones have been achieved such as the launch of Microsoft HoloLens or Pokémon Go (Niantic and Nintendo and The Pokémon Company, n.d.).

In this paper, we aim to answer the following research questions:

- **RQ1:** *Which immersive AR interaction techniques are investigated in the current literature?*
- **RQ2:** *Which characteristics can be found among these techniques and how can these be systematized?*

To answer these research questions, we conducted a literature review on the Association for Computing Machinery (ACM) (“ACM Guide to Computing Literature,” n.d.) and Institute of Electrical and Electronics Engineers (IEEE) (“Institute of Electrical and Electronics Engineers,” n.d.) databases. We derived a taxonomy of emerging immersive AR interaction techniques based on 44 research publications, that were identified in an iterative process (Nickerson et al., 2013). In summary, our contributions are as follows:

Table 33. Data sources, queries, dates, numbers and publication dates of results

Data Source	Query	Number of Papers
ACM *Search Date: April 23, 2021*	`"interact* AND ("augmented reality" OR "ar" OR "mixed reality" OR "mr")"` Only Abstract and Title	725
IEEE *Search Date: April 23, 2021*	`"interact* AND ("augmented reality" OR "ar" OR "mixed reality" OR "mr")"` Only Abstract and Title	1540

- application and adaptation of a taxonomy creation methodology to the field of HCI,
- presentation of a taxonomy of emerging immersive AR interaction techniques focused on the task and modality features,
- report and discussion of the implications of these techniques based on the literature review.

The remainder of this paper is structured as follows. Section 15.2 introduces the methodology of the iterative literature review. Section 15.3 introduces the resulting taxonomy, supported by examples that were considered during the literature review. Section 15.4 discusses the findings and limitations of our approach. Section 15.5 concludes the paper and gives an outlook on future work.

15.2 Methodology

In this work, we aimed to capture the current state of research of immersive AR interaction techniques and categorize them in a comprehensible form. We decided to develop a taxonomy, which is “a system of groupings that are derived conceptually or empirically” (Nickerson et al., 2013). Structured procedures to develop taxonomies are commonly used in other fields of research, like biology or information systems (IS) (Nickerson et al., 2013). We introduce and adapt an established taxonomy definition and development approach from the IS field to the field of HCI. The approach was developed by Nickerson et al. (2013) in 2013 and is commonly used in IS research since then (Land et al., 2013; P. Vogel et al., 2020). Nickerson et al. define a taxonomy as a set of dimensions, where each dimension consists of characteristics. The characteristics are mutually exclusive – no object can have multiple characteristics in a dimension – and collectively exhaustive – each object must have one characteristic in each dimension. We extended this definition by subcategories, so that categories can be split up if needed to reflect a more fine-grained characterization. Further, we noticed that forcing interaction techniques to be mutually exclusive could conceal valuable insights. Thus, we did not adopt the mutual exclusivity restriction to depict, for example, multimodality.

To develop such a taxonomy, Nickerson et al. designed an iterative approach, which allows researchers to include a subset of objects in each iteration until pre-defined ending conditions are met. In each iteration, the current taxonomy is refined based on newly emerged characteristics.

15.2.1 Meta-characteristics

The initial step in the taxonomy development process is the definition of meta-characteristics. In general, they are conceptually induced based on the researcher's knowledge and should reflect the intended purpose of the taxonomy. As meta-characteristics, we chose *people, activities, context,* and *technologies*, the four dimensions of the PACT framework developed by Benyon (2013). The framework's premise is that people use technology to undertake activities in contexts, and thus these dimensions should be considered when designing interactive systems. Here, *people* include physical, psychological, and social differences between users. For *context*, aspects like physical and social environments should be analyzed. Regarding *activities*, Benyon considers the overall purpose of the activity as most important. *Technology* includes, for example, the input and output of a system. By analyzing articles with regard to these meta-characteristics, we expect to find characteristics of interaction techniques that are valuable for researchers and designers.

15.2.2 Ending Conditions

We also defined ending conditions before the actual iterative process started. They are both objective and subjective and determine when the taxonomy development process should terminate. We used the ending conditions proposed by Nickerson et al. which include objective ones (e.g., the taxonomy was not modified in the last iteration, the taxonomy is valid in regard to the definition of a taxonomy) and subjective ones (the taxonomy should be concise, robust, comprehensive, extendable, and explanatory).

15.2.3 Data Acquisition

The following steps of our taxonomy development process aimed at capturing the current state of research by extracting immersive AR interaction techniques from research articles. To obtain an initial set of articles, we followed the core steps of the PRISMA-P protocol (Shamseer et al., 2015). The PRISMA protocol of our study can be found in the supplementary materials.

The PRISMA flowchart (Figure 38) shows all steps we followed for the literature review: identification of sources (N = 2265), removal of duplicates and ACM articles that did not include our search terms (N = 2100), identification of venues depending on their number of papers (VR ("IEEE Virtual Reality Conference (VR)," n.d.), CHI ("ACM Conference on Human Factors in Computing (CHI)," n.d.), TVCG ("IEEE Transactions on Visualization and Computer Graphics (TVCG)," n.d.), ISMAR ("IEEE International Symposium on Mixed and Augmented Reality (ISMAR)," n.d.), UIST ("ACM Symposium on User Interface Software and Technology (UIST)," n.d.), IROS ("IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)," n.d.)), iterative screening step for identified records (N = 283), full-text screening step for eligibility (N = 74). As a result of these steps, a total number of 44 papers were integrated into our taxonomy.

We performed a search using the digital libraries of IEEE and ACM, but only included venues with a CORE2020 rank ("CORE Rankings Portal," n.d.) of "good" or higher (A*, A, or B). We chose to use these databases as they cover the best known and most relevant HCI conferences in the field related to 3D interaction techniques. The goal was to capture recent research interaction techniques with a focus on immersive AR. An initial informal analysis revealed that terms like "interaction technique" or synonyms are often not mentioned directly. Thus, we included a more general term in our search query: "interact*". Since "immersive AR" is not an established term yet, we searched for AR and MR in general and filtered for immersive AR during the subsequent screening step. We restricted our search to the document title and abstract since terms such as AR and MR often appear in conference titles and keywords. Table 33 shows the resulting search query. We included peer-reviewed research articles, excluding posters, published since 2016. The search was conducted on April 23, 2021.

The initial search resulted in 2265 research articles (ACM = 725, IEEE = 1540) from which we removed 22 duplicates based on title and year. The ACM website automatically included articles where the venue title matched our search query but the article title did not. We excluded these articles (N = 143). The remaining 2100 articles were grouped by venue and the venues were sorted by the number of articles in descending order. By this means, research papers were divided into subsets to include them iteration-wise, with one venue per iteration. In total, we performed 6 empirical-to-conceptual iterations, resulting in the inclusion of 283 articles from 6 venues. The remaining 1817 articles were not screened.

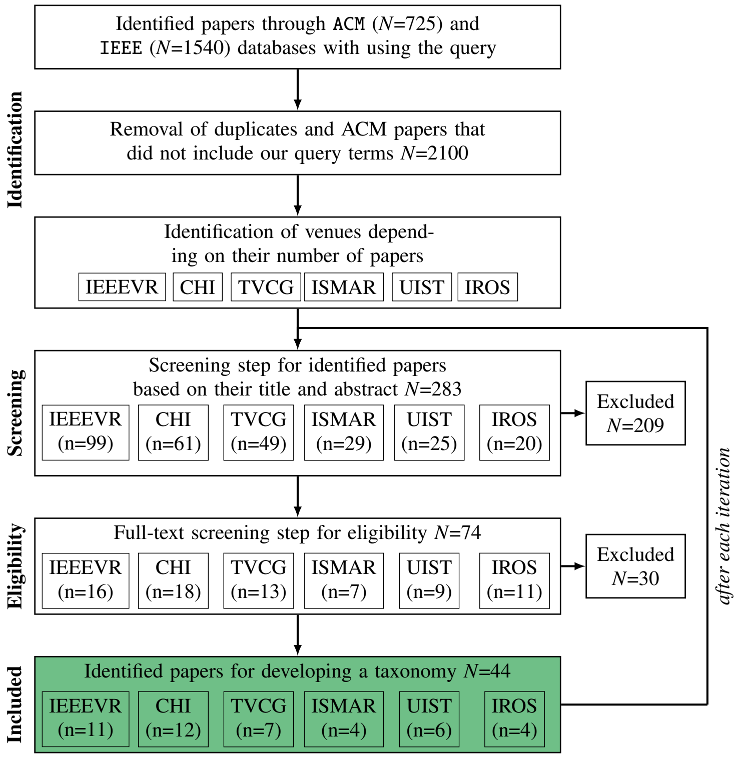

Figure 38. PRISMA flowchart, which illustrates our literature review process for creating a taxonomy with an iterative approach (Nickerson et al., 2013)

15.2.4 Iterative Development Process

For each iteration, the researchers choose whether to follow an *empirical-to-conceptual* or a *conceptual-to-empirical* approach. In the former, new subsets of objects are included and common characteristics among them are identified. Then, these characteristics are grouped into dimensions and the taxonomy is created or revised. In the latter, characteristics and dimensions are conceptualized based on existing work or the researchers' knowledge. Then, objects for these characteristics and dimensions are examined and the taxonomy is created or revised.

Empirical-to-conceptual Iterations

In each empirical-to-conceptual iteration, we performed a literature review of the corresponding subset of research articles as follows.

Screening In total, we screened the titles and abstracts of 283 papers and excluded articles ($N = 209$) which did not match the following inclusion criteria:

- Papers should either present or evaluate one or more interaction techniques. We excluded papers with a focus on an application or experiment, where the used interaction technique was mentioned but not described in detail.
- Interaction techniques should clearly be intended for immersive AR applications. We excluded papers about interaction techniques for general or VR settings, where the authors only mention the possibility to adapt the interaction technique to AR. We also excluded interaction techniques for hand-held AR systems. We included interaction techniques that were clearly designed for AR applications but implemented or evaluated in VR settings.
- We excluded literature reviews such as meta-analyses.

Three researchers were involved in this step, two of them having a background in computer science and AR, and one of them having a cognitive systems background. Each third of the data was screened by two researchers, the third one acted as a tie-breaker. Since this step requires rigorous consensus between the coders, we conducted Cohen's Kappa test to calculate inter-rater reliability between the three researchers (Gamer et al., 2012). The findings indicated high agreement between lead and second (97.9%; $\kappa = 0.956$, $z = 9.37$, $p < .0001$), lead and third (94.7%; $\kappa = 0.846$, $z = 8.46$, $p < .0001$), and second and third (95.6%; $\kappa = 0.887$, $z = 8.52$, $p < .0001$) researchers. In this step, we excluded 209 papers based on our inclusion criteria: duplicates ($N = 7$), AR is not the main focus ($N = 6$), non-immersive AR ($N = 26$), interaction techniques are not the main focus ($N = 143$), literature review ($N = 1$), and no publication ($N = 18$).

Full-text Eligibility In this step, we considered the full text of the remaining papers ($N = 74$) for eligibility and used keyword coding as described below:

- **Keyword coding:** We searched keywords with regard to the meta-characteristics (PACT (Benyon, 2013)), for example, *multi-user*, *selection task*, *gestures*, *HoloLens* (more examples can be seen in the supplementary material).

We used keyword coding to facilitate the taxonomy development in the next step. This step was done by the same three researchers and the same division as in the previous step.

Taxonomy Development This step consists of determining the characteristics and dimensions of the taxonomy by deriving them from included papers. We considered 44 papers that resulted from the full-text eligibility step.

- **Characteristics and dimension identification:** Each keyword identified in the last step was transferred onto a digital sticky note on the digital whiteboard platform Miro ("Miro," n.d.). In a group discussion with three researchers, these sticky notes were grouped into characteristics and dimensions by moving them around. Only characteristics and dimensions that seemed relevant to the researchers were created while keeping the purpose of the taxonomy and the main constraint (every object must have one characteristic in each dimension) in mind.
- **Tagging:** Based on the derived characteristics and dimensions, the first and third authors tagged all interaction techniques of the current batch. Subsequently, all previous interaction techniques were retagged, since the taxonomy changed iteratively. Further, the nuances from these assignments were discussed after each iteration with a group of three researchers. This step verified that the current taxonomy is valid and the main constraint is fulfilled.

We note that we included at least two researchers (analysis triangulation) for each step of our literature review to ensure reliability and reduce potential errors (Buscemi et al., 2006; McDonald et al., 2019).

Conceptual-to-Empirical Iteration

After the third iteration of our literature review, we noticed that some identified papers use terms interchangeably, for instance, for describing gestures and tangibles. Also, taxonomy development generally requires an in-depth engagement with previous literature in order to be valid, concise, and consistent. Hence, we decided to use the conceptual-to-empirical approach after the third iteration.

We identified 8 papers to refine our taxonomy. These were Bowman and Hodges's (1999) taxonomy on 3D VR interaction techniques and tasks, Quek et al. (2002)'s prior work on gestures and speech, Shaer and Hornecker's (2010) paper on tangible user interfaces, Besançon et al.'s (2019) work on touch/tangible spatial 3D selection tasks, Karpov and Yusupov's (2018) work on multimodal interfaces, Buxton's (1983) work on input devices, Muhammad Nizam et al.'s (2018) review of multimodal interaction techniques, and Augstein and Neumayr's (2019) taxonomy of interaction modalities and devices from a human-centered perspective.

In this step, the first three authors read the above articles in detail and hold a discussion to clearly define the characteristics and dimensions of the current taxonomy at that stage. As a result, we renamed, merged, or split some characteristics and dimensions. We applied these changes to all previously considered papers. Afterwards, we continued with an empirical-to-conceptual iteration.

15.3 Derived Taxonomy: Immersive AR Interaction Techniques

Our review aimed to develop a taxonomy of immersive AR interaction techniques. As described in Section 15.2, a taxonomy is a set of dimensions, where each dimension consists of characteristics. Since the taxonomy has to be collectively exhaustive, all dimensions are required to be applicable to every interaction technique and to contain at least one characteristic suitable for each interaction technique. By analyzing the empirically derived set of interaction techniques with a focus on PACT as meta-characteristics, we finally identified two dimensions matching these constraints: *task* and *modality*. Both dimensions' characteristics can be interpreted as *categories* comprising a set of similar tasks and modalities, respectively. In the remainder of this paper, the terms characteristic and category will be used interchangeably.

To add further details, we separated these into sub-characteristics where appropriate. Figure 39 shows the resulting taxonomy. To reflect the concept of multimodality, we chose to apply a mutual exclusivity restriction only to the task dimension: each interaction technique has exactly one task, but one or more modalities. Table 34 shows the frequency of each task-modality combination in both, uni-modal and multimodal interaction techniques. This table acts as an overview and guideline by presenting which modalities were commonly used to perform certain tasks.

15.3.1 Tasks

Similar to Bowman and Hodges (1999), we identified several granular tasks. Each of them can either be used stand-alone or combined with other tasks to create more complex, high-level functionalities. Below, we will provide a brief definition of each task and present exemplary interaction techniques examined in our literature review.

Creation

The task category creation includes actions a user can perform in order to let virtual objects appear visually. We identified three subcategories based on what kind of object is created and how much user input is needed. An *activation* is performed when the user does not define the geometry or visual appearance of the object. That includes, for example, an existing digital object that is not rendered until a user performs an activation to let it visually appear (Lu et al., 2020), labels that are superimposed on objects (Huynh et al., 2019), or details on demand in the context of data visualization (Mahmood et al., 2019). Furthermore, an activation can generate a new virtual object. Here, properties like the object's position, rotation, and scale may be predefined in the application (e.g., Ens et al., 2021; Williams et al., 2020), set through previous actions (e.g., copying an existing object (Mahmood et al., 2019)), or are implicitly given by the user while performing the activation, for example, via the user's current head orientation or hand position (Liu & Shen, 2020; Quintero et al., 2018). In contrast, the other subcategories contain tasks that require the user to incrementally define the appearance of the created object, either by modifying textures (*2D drawing* (Arora et al., 2018; Roo & Hachet, 2017; Y. Zhang et al., 2019)) or by modifying the object's geometry (*3D modeling* (Arora et al., 2018; Peng et al., 2018)).

All subcategories of creation can also include the deletion of objects. However, we did not include the deletion as a separate task, since all of the reviewed deletion interaction techniques use the same modality as their activation counterparts.

Selection

To interact with virtual objects, various interaction techniques require the user to identify an object through a selection. We identified selection as the most common task as it was included in 32 out of 44 papers. A selection can be applied as a single task that triggers a function linked to the selected object, for example, when interacting with a button on a user interface (UI) (e.g., Li et al., 2019; Peng et al., 2018) or highlighting a part of the virtual scene (e.g., Mahmood et al., 2019). Moreover, a selection can precede tasks like geometric manipulation by determining the object to which the following operations should be applied (e.g., Whitlock et al., 2018). The release of a selected object can be considered as a separate task (Bowman & Hodges, 1999). However, based on the literature review we examined that a release is typically performed indirectly by reverting or releasing the selection activity, like stopping a gesture or releasing a button (e.g. Kang et al., 2020; J. H. Lee et al., 2018). Besides, a release can not be performed standalone, as it has to be preceded by a selection. Thus, our taxonomy does not consider release explicitly.

We identified two subcategories based on the arrangement of objects that can be selected: *2D selection* and *3D selection*. For 2D selection, either a single or multiple virtual objects are placed on a planar surface like a real or virtual wall or an abstract plane (Kytö et al., 2018). A common example is a UI menu, consisting of multiple virtual buttons arranged in a 2D grid structure (Kang et al., 2020; Li et al., 2019; Peng et al., 2018). In contrast, if selectable objects are spatially arranged, like virtual furniture placed in a room (Kang et al., 2020), a 3D selection is needed. The sub-categories differ regarding the complexity of the required interaction technique. Some of the reviewed interaction techniques used for 2D took advantage of the planar arrangement to increase precision or overall usability. For instance, a 2D menu can be displayed on the user's own arm to provide passive haptic feedback when touching buttons (Y. Zhang et al., 2019) or on the floor to be selectable via foot to prevent arm fatigue (Xu et al., 2019).

For 3D selection, we observed different kinds of methods, mainly used depending on the distance between the user and the objects. Near objects were often selected directly by letting the user's hand or a hand-held device collide with the virtual object, like grabbing or touching it (Hochreiter et al., 2018; Kang et al., 2020). In contrast, distant objects were often selected via *pointing*, a method to select via ray-cast, starting either from the user's head or eyes (gaze) (Kang et al., 2020), or hand (laser-pointer metaphore) (Whitlock et al., 2018). Both methods typically require the user to perform a confirmation to finally select the indicated object.

Alternatively to the selection of distinct objects, a 2D area or 3D range can be selected. Such techniques are deployed for high-level use cases such as selecting a region inside a 3D data visualization for subsequent filtering operations (Englmeier et al., 2020), or defining a viewport (Piumsomboon et al., 2019).

Geometric Manipulation

Based on the results of our literature review, geometric manipulation is a commonly used group of tasks (N = 74). It comprises the manipulation of an object's position (*translation*), its orientation (*rotation*), and its size (*scale*). While translation and rotation are rigid transformations and can also be applied to physical objects, the possibility to scale objects is an inherent feature of virtual environments.

In our literature review, we observed that interaction techniques often combine different geometric manipulations. We identified two variants of combinations: an interaction technique can either support multiple manipulations simultaneously or sequentially. For instance, Gao et al. (2022) evaluated a 6-degrees of freedom (DOF) manipulation technique that allows a user to simultaneously rotate and translate a virtual object by mapping the position and orientation of a handheld controller to the object (Gao et al., 2022). Chaconas and Höllerer (2018) evaluated different two-handed gestures to rotate and scale objects. In their experiment, they included techniques that allow the user to simultaneously rotate and scale an object with a single hand movement as well as techniques where the user defines which manipulation they want to perform at the beginning of the gesture — either based on the hand's starting position or by the first detected moving direction after starting the gesture (Chaconas & Höllerer, 2018). However, since we consider an interaction technique as a combination of exactly one task and one or more modalities, such combinations are not reflected in our taxonomy.

Interaction techniques can also limit the supported DOF of single manipulations, which can be used to prevent undesired behavior. For example, we reviewed interaction techniques to move furniture by limiting translations to the floor plane (Kang et al., 2020), and to set a clock's hand by restricting the rotation to one axis (Z. Zhang et al., 2019). In contrast, unlimited interaction techniques were typically applied to abstract geometric shapes like cubes (Krichenbauer et al., 2018) or tetrahedrons (Gao et al., 2022).

Geometric manipulations are not limited to 3D objects. Especially translation can also be applied to interact with UI elements, for example, by scrolling or swiping through 2D content, or by moving slider handles (Z. Zhang et al., 2019; Q. Zhou et al., 2020). Further, interaction techniques can extend the action provided by the user by automatically applying manipulations, as J. H. Lee et al. (2018) presented. Their approach enables a user to translate, rotate, and scale 2D windows. When releasing the window, it is projected (translated) to a surface while simultaneously being scaled, keeping the apparent size for the user unchanged (J. H. Lee et al., 2018).

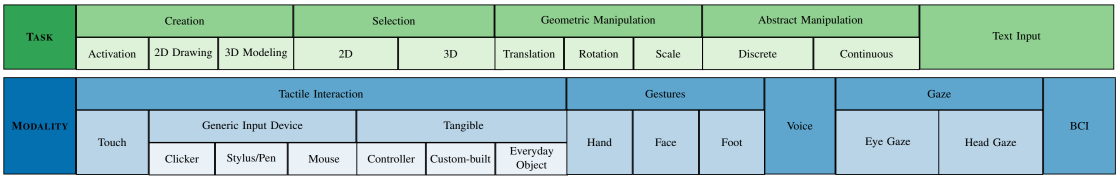

Figure 39. Our derived taxonomy to categorize immersive AR interaction techniques. We examined two dimensions - task and modality. Both dimensions contain a set of characteristics. For the task dimension, the characteristics are mutually exclusive.

Abstract manipulation

While geometric manipulations interact with virtual objects rendered in AR, abstract manipulations cover all user commands which are not directly related to visualized objects. Based on the literature review, common use cases for abstract manipulations are actions to change the internal system state, for example, commands to load content (Gupta et al., 2020) or to switch between different modes (Normand & McGuffin, 2018; Quintero et al., 2018), and actions to interact with physically existing objects like internet of things (IoT) devices (Masai et al., 2020; Sun et al., 2019) while the AR system is used to supplement the user's view with feedback or further information.

We identified two subcategories that differ regarding the provided input data type. A *discrete* command directly triggers a fixed function (e.g., switch to menu mode (Normand & McGuffin, 2018), turn on a lamp (Sun et al., 2019)). In contrast, for *continuous* control, an ongoing function is applied as long as the user performs the corresponding action, like gradually raising the volume of a speaker (Sun et al., 2019).

Text input

While text input is a common task for traditional desktop interfaces, our literature review only included two papers presenting corresponding techniques (Li et al., 2019; Zhu & Grossman, 2020). Theoretically, text input techniques could be broken down to fundamental tasks presented in this taxonomy. For instance, a virtual keyboard could be considered as a 2D selection technique, where the user selects multiple buttons successively. However, such a classification would strongly depend on the modality and type of visualization used. Instead, we included text input as a characteristic to our taxonomy that covers all kinds of techniques that enable a user to enter characters, words, or sentences.

15.3.2 Modalities

Here, we will introduce the modalities that were identified during our iterative literature review. For each modality, we will provide a brief definition as well as some insights into the observed variants using the example of selected research papers.

Tactile interaction

Since AR allows to superimpose virtual content onto the real-world surroundings of a user, physical objects can be naturally involved in the interaction. Related analytical reviews use varying terms for such interaction techniques, as for instance *contact interaction* (Karpov & Yusupov, 2018) or *physical controls* (Mine, 1995). To not confuse our definition with the partially different characteristics of those related concepts, we introduce a new category of *tactile interaction* into our taxonomy, including the subcategories *touch, generic input devices,* and *tangibles.*

Touch For interaction techniques that require the user to contact a surface with their bare hands, we introduced the modality of touch. We identified various kinds of surfaces acting as touch recipients. Commonly known, even besides the field of AR research, are touch screen devices like smartphones (Jeong et al., 2020; Normand & McGuffin, 2018). Besides, the deployment of various sensors allows developers to turn passive surfaces into touchable, interactive surfaces, like parts of the user's physical environment (e.g., a table (Jansen et al., 2020)) or even the user's own skin (Y. Zhang et al., 2019). Most of the interaction techniques we reviewed used single touch events as inputs for 2D selection tasks ($N = 6$), however, continuous movements along the surface were also used, for example, for 2D drawing (Y. Zhang et al., 2019) or translation (Normand & McGuffin, 2018; Q. Zhou et al., 2020).

Generic input devices As a key differentiator between generic input devices and tangibles, we consider the form of multiplexing as suggested by Fitzmaurice (1996). According to the author's definition, all physical input devices can be classified to be either time- or space-multiplexed. Time-multiplexing denotes a dynamic assignment of functions over time and therefore allows the usage of one generic input device for a diverse set of tasks. This characterization applies to all traditional GUI input devices, such as mice and keyboards, as well as to controllers that are delivered with modern VR/AR HMDs.

The reviewed input controllers featured a differing number of DOF, including 2-DOF traditional mice and styli, 3-DOF controllers with positional tracking, 3-DOF controllers with orientational tracking, and 6-DOF controllers with a combination of both tracking types. In addition, devices with discrete input, such as the button of the HoloLens clicker, were used. While we observed such input devices in comparatively many papers, they were mostly used in multimodal input techniques or as baseline conditions for comparing input via other modalities.

Tangibles In contrast to time-multiplexed generic input devices, tangible user interfaces are space-multiplexed, meaning they involve spatially distributed objects with dedicated functions. Due to the spatial nature of such UIs, different tasks can be performed simultaneously, which can be considered as an advantage over the strictly sequential task execution in time-multiplexed UIs.

Strictly following the original definition, tangible UIs have to offer multiple input devices, each with a permanently assigned function. For creating our taxonomy, we loosen these requirements by allowing UIs with (i) single-input devices that are reasonably extendable to space-multiplexed multi-device systems, and (ii) input devices that fulfill the same task for extended periods of time but not necessarily for their entire lifespan. These adaptations are meant to take account of the prototypic nature of many research projects (e.g., Cordeil et al., 2020; Ssin et al., 2019) and the trend towards reusable everyday tangible objects (e.g., Gupta et al., 2020; Q. Zhou et al., 2020), respectively.

Input devices that do not conform with the extended definition of tangibles are classified as generic input devices, even if stated otherwise in the respective paper (e.g., Englmeier et al., 2020; Krichenbauer et al., 2018). By this means, we aim to establish a consistent and transparent methodology for building our taxonomy.

For tangibles, we observed a variety of different custom-built devices ($N = 6$) as well as an emerging trend towards using everyday physical objects ($N = 7$) to interact with the AR environment. By coupling a virtual object and a tangible, the object can be naturally viewed from different angles, hence implementing an intuitive form of rotation and translation (e.g., Bach et al., 2018; Gupta et al., 2020). Furthermore, tangibles were used for the creation, selection, and abstract manipulation of AR content (see Table 34). Besides these basic tasks, 2 papers that utilized everyday physical objects took advantage of the object's natural affordances, for example, using a physical album to browse through photos (Gupta et al., 2020). In contrast, 5 papers introduced an artificial mapping between the tangible and its function, such as using a smartphone as a bat (Eichhorn et al., 2019) or a marker to cycle through playing cards (Q. Zhou et al., 2020).

Table 34. From each reviewed article, we extracted one or more presented interaction techniques. This table shows the frequencies of task-modality combinations examined in these interaction techniques. For each cell, the left and right values indicate the occurrences in unimodal and multimodal interaction techniques, respectively. Hence, the total number of task-modality combinations is higher than the number of interaction techniques. In total, we reviewed 173 interaction techniques: 137 were unimodal, 35 were bimodal, and one included three modalities, resulting in 137 occurrences in unimodal techniques and 72 occurrences in multimodal techniques.

<table>
<tr><th colspan="2" rowspan="2">Modality
Task</th><th colspan="3">Tactile Interaction</th><th colspan="3">Gestures</th><th rowspan="2">Voice</th><th colspan="2">Gaze</th><th rowspan="2">BCI</th><th rowspan="2">Total</th></tr>
<tr><th>Touch</th><th>Generic Input Device</th><th>Tangible</th><th>Hand</th><th>Face</th><th>Foot</th><th>Eye Gaze</th><th>Head Gaze</th></tr>
<tr><td rowspan="3">Creation</td><td>Activation</td><td>- | -</td><td>1 | -</td><td>5 | -</td><td>3 | 1</td><td>- | -</td><td>- | -</td><td>2 | 3</td><td>1 | -</td><td>- | 2</td><td>- | -</td><td>12 | 6</td></tr>
<tr><td>2D drawing</td><td>1 | -</td><td>1 | -</td><td>1 | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>3 | -</td></tr>
<tr><td>3D modeling</td><td>- | -</td><td>1 | 1</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>1 | 1</td></tr>
<tr><td rowspan="2">Selection</td><td>2D</td><td>6 | -</td><td>3 | 4</td><td>2 | -</td><td>6 | 5</td><td>- | -</td><td>1 | -</td><td>- | -</td><td>1 | 3</td><td>2 | 7</td><td>- | -</td><td>21 | 19</td></tr>
<tr><td>3D</td><td>1 | 2</td><td>6 | 3</td><td>4 | 4</td><td>6 | 7</td><td>- | -</td><td>- | -</td><td>1 | 5</td><td>1 | -</td><td>1 | 5</td><td>1 | -</td><td>21 | 26</td></tr>
<tr><td rowspan="3">Geometric Manipulation</td><td>Translation</td><td>3 | -</td><td>6 | -</td><td>7 | -</td><td>12 | 2</td><td>- | -</td><td>- | -</td><td>2 | 3</td><td>- | -</td><td>- | 1</td><td>- | -</td><td>30 | 6</td></tr>
<tr><td>Rotation</td><td>1 | -</td><td>6 | -</td><td>9 | -</td><td>5 | 3</td><td>- | -</td><td>- | -</td><td>1 | 3</td><td>- | -</td><td>- | 2</td><td>- | -</td><td>22 | 8</td></tr>
<tr><td>Scale</td><td>1 | -</td><td>4 | -</td><td>1 | -</td><td>5 | 3</td><td>- | -</td><td>- | -</td><td>1 | 2</td><td>- | -</td><td>- | 1</td><td>- | -</td><td>12 | 6</td></tr>
<tr><td rowspan="2">Abstract Manipulation</td><td>Discrete</td><td>1 | -</td><td>- | -</td><td>3 | -</td><td>1 | -</td><td>1 | -</td><td>- | -</td><td>2 | 0</td><td>- | -</td><td>1 | -</td><td>- | -</td><td>9 | -</td></tr>
<tr><td>Continuous</td><td>- | -</td><td>- | -</td><td>1 | -</td><td>2 | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>1 | -</td><td>- | -</td><td>4 | -</td></tr>
<tr><td colspan="2">Text Input</td><td>1 | -</td><td>1 | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>- | -</td><td>2 | -</td></tr>
<tr><td colspan="2">Total</td><td>15 | 2</td><td>29 | 8</td><td>33 | 4</td><td>40 | 21</td><td>1 | -</td><td>1 | -</td><td>9 | 16</td><td>5 | 18</td><td>3 | 3</td><td>1 | -</td><td>137 | 72</td></tr>
</table>

Gestures

Gestures are commonly considered as a form of nonverbal communication, in which body movements convey a message to interlocutors (Kendon, 2004). While some definitions focus on movements that are performed using the hands only (e.g., Quek et al., 2002), others do not limit the definition to the upper limbs but also include feet and facial gestures. In the reviewed papers, we found instances of all mentioned body parts and therefore use the latter, more broad definition of gestures in our taxonomy. Further, we only categorized interaction techniques to be primarily gesture-based when they are uninstrumented and, in the case of hand gestures, performed in midair. In contrast, techniques using additional input devices or touch input are classified as tactile interactions, as described in Sect. 3.2.1.

In the reviewed literature, hand gestures are the most frequently investigated modality for all selection and manipulation tasks (see Table 34). Authors reason their choice with the interaction being natural and intuitive (Kang et al., 2020; J. H. Lee et al., 2018), allowing for direct manipulation of virtual objects that are within arm's reach (Brasier et al., 2020; Williams et al., 2020), without the need of additional user instrumentation (Satriadi et al., 2019; Xu et al., 2019). Interactions with distant targets can also leverage hand gestures by complementing them with another modality such as gaze (Whitlock et al., 2018) or by visually extending the arm (Feuchtner & Müller, 2017). Depending on the focused tasks, we found a preference towards unimanual gestures (selection, translation) or bimanual gestures (rotation, scale). For selection, users either performed a predefined hand sign, such as the air tap, or a pointing movement. In the literature, such gestures are also referred to as *semaphoric* or *deictic* gestures, respectively (Quek et al., 2002). In contrast, in *manipulative* gestures, hand movements are directly controlling an object's properties, such as the pose or scale. Since the correlation between the task and the definitions of semaphoric, deictic, and manipulative gestures is very strong, we decided to not include them as subcategories of hand gestures in our taxonomy.

In contrast to the variety of reviewed papers investigating hand gestures, only one paper each was considering foot gestures (Xu et al., 2019) or facial gestures (Masai et al., 2020). In the foot-based interaction technique (Xu et al., 2019), users can select options of a floor-projected, circular menu using directional motion. The authors report a lower overall workload and higher usability than for a reference condition using hand gestures. However, user feedback suggests that foot-based gestures are particularly useful for indoor scenarios, when actions are performed in front of familiar people, such as family members or colleagues. In comparison, interaction via facial gestures (Masai et al., 2020) was designed to be particularly subtle and, therefore, could yield a higher social acceptance in public settings.

Voice

Besides the non-verbal interaction methods described before, we identified human speech as another modality in our taxonomy. Voice commands were particularly used for simple tasks, such as choosing from a limited set of discrete modes (Quintero et al., 2018) or for activation and deletion of a virtual object (Mahmood et al., 2019; Williams et al., 2020; Yue et al., 2017).

For more complex tasks, such as selecting from a pool of virtual targets, voice was paired with gaze or pointing gestures and only used as a confirmation (Krupke et al., 2018; Whitlock et al., 2018). Whitlock et al. (2018) even went a step further by suggesting a multimodal interaction technique for transforming virtual objects. In the presented study, users were able to select an object via gaze before initiating a movement or rotation using commands such as "Move up/down/left/right". Another voice stop command was necessary to terminate the transformation. However, when compared to hand gestures as well as controller input, voice interaction was shown to be less accurate, slower, and the least enjoyable condition. Another disadvantage of voice commands was illustrated in a Wizard of Oz study by Williams et al. (2020). Participants of their study were asked to manipulate a displayed virtual cube using speech, however, without predetermining a correct command. An analysis of the collected responses showed that there was much disagreement on the most appropriate utterances, showing that voice interfaces have to be learned to a certain extent.

Gaze

While gaze could be considered as a deictic gesture in the broader sense (Quek et al., 2002), we observed a high number of explicit mentions in the literature and thus introduced a separate category in our taxonomy.

23 of the relevant interaction techniques were considering inter- action via head gaze, while only 6 described an eye gaze technique. One reason for this imbalance could be the advantage of head-based input of being a "more affordable surrogate" (Esteves et al., 2017) of eye gaze. While the paper's authors found that most study

participants tended to use the eyes rather than head movements to track objects, they also measured an improved accuracy of head gaze when participants were explicitly asked to follow the targets with their heads.

Only four papers used gaze in a unimodal setting (Brasier et al., 2020; Esteves et al., 2017; Huynh et al., 2019; Mahmood et al., 2019), primarily because an additional mechanism is required to not only hover over a scene object but for triggering a selection. This can be either done by using time-based methods, such as dwell (Brasier et al., 2020) or smooth pursuit (Esteves et al., 2017), or by adding a second modality. In our literature review, we found combinations of gaze with hand gestures (Chaconas & Höllerer, 2018; Kang et al., 2020; Kytö et al., 2018; Liu & Shen, 2020; Mahmood et al., 2019; Whitlock et al., 2018; Xu et al., 2019), generic input devices (Kytö et al., 2018), and voice (Krupke et al., 2018; Quintero et al., 2018; Whitlock et al., 2018).

BCI

Brain-computer interfaces (BCI) convert measured activity of the central nervous system to control commands of an external device (He et al., 2020). The mapping of neural signals to a meaningful output is challenging since each natural task that is controlled by the brain usually requires the involvement of multiple cerebral regions.

This complexity is also reflected in the fact that only one of our reviewed papers considered this modality for the use in AR interfaces (Si-Mohammed et al., 2020). In the paper, the authors present an operational prototype for mobile robot control using the combination of an EEG headset for input and the HoloLens for augmented output. The EEG signals are scanned for specific patterns that are associated with visual stimulation at certain frequencies. By assigning different frequencies to multiple visual targets, researchers are able to discriminate which target the user is focusing, therefore supporting a 3D selection task.

15.4 Discussion

Below, we will reflect on the results of the literature review as well as the methodology itself.

15.4.1 Reflection on Empirical Research

Real-world interactions One principal difference between AR and VR is the role of the user's real environment. While VR aims at a full replacement of all sensory information provided by the real world, AR still allows users to directly involve their physical surroundings. This feature of AR particularly manifested in the excessive use of techniques involving tactile interaction – a modality that was not considered in the well-known taxonomy on 3D UIs by Bowman et al. (2004). 54 of the overall 173 interaction techniques that were identified in our literature review were based on touch or tangibles. Authors praised the intuitive, comfortable, and accurate use of tactile interactions in general (e.g., Englmeier et al., 2020; Min et al., 2019; Y. Zhang et al., 2019; Q. Zhou et al., 2020) as well as the potential of collaborative use of tangibles in particular (e.g., Cordeil et al., 2020; Ens et al., 2021; Gupta et al., 2020).

Besides physical objects being part of the input mechanism, we also observed a range of tasks that were directly aiming at manipulating the real environment of the user, for example, in the context of smart home systems. AR interactions were used to control inherent properties of real-world objects, such as the brightness of a lamp (Sun et al., 2019), height of a desk (Feuchtner & Müller, 2017), or volume of a speaker (Y. Zhang et al., 2019). To represent these AR-specific tasks, we introduced the category of *abstract manipulations* in our taxonomy.

Multimodality 36 of the 173 identified interaction techniques involved at least two different modalities. As can be seen in Figure 40, hand gestures were paired with all different modalities except BCI. Furthermore, head gaze and voice were particularly used in multimodal settings (cf. last row of Table 34). On their own, they have limited power to support complex, fine-grained tasks such as geometric manipulations. However, in combination with other modalities, they act as a natural support for pointing or confirmation actions – two subtasks that are involved in almost every identified interaction. Besides the simultaneous use in pointing-confirmation tasks, multiple modalities can also be used sequentially. For example, voice commands can specify whether a following hand gesture should be interpreted as a rotation or scaling operation (Mahmood et al., 2019).

Mobile optical see-through AR In the literature review, we intentionally focused on the period of 2016 to 2021, thus starting with the year of the Microsoft

HoloLens launch. This milestone is also reflected in the reviewed literature, to the effect that 29 papers were using an optical-see through (OST) display while only 9 papers draw on video-see through (VST) technology. With 3 mentions, projection-based systems were the least used output technology in the considered research papers (the remaining 3 papers were using VR to simulate AR). Through further technological improvements, this prevalence of OST displays may be even strengthened as some authors mentioned the currently inferior field of view and render quality as the main reasons to decide in favor of a VST device (Peng et al., 2018).

Another aspect of modern self-contained devices is their suitability for mobile applications since they do not have to be tethered to a powerful workstation. As such, involvement of the current environment of the user is especially preferable, to eliminate the necessity for dedicated input devices (Masai et al., 2020; Q. Zhou et al., 2020).

Subtle interaction Besides affecting the technical aspects of interaction techniques, advancements in AR technology also allow developers to have a stronger focus on user experience. We observed attempts to replace expansive movements with more subtle alternatives to increase perceived comfort in public or other social settings. Examples include discreet finger and facial gestures (Brasier et al., 2020; Masai et al., 2020; Y. Zhang et al., 2019) as well as eye gaze (Huynh et al., 2019; Lu et al., 2020). While the easier trackable alternatives, such as hand gestures and head gaze, were still prevalent in the reviewed literature, it can be speculated that we will experience a gradual shift towards the subtle variants with improving technology such as integrated eye trackers.

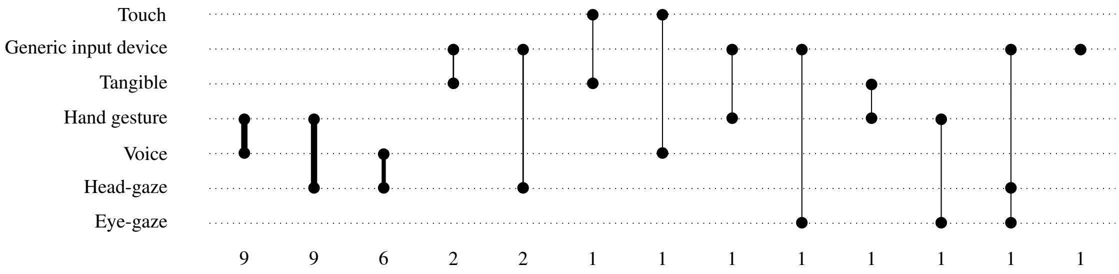

Figure 40. Observed combinations of multiple modalities, each represented by a dot, with the absolute numbers of occurrences (references can be found in the supplementary materials). The last dot represents an interaction technique combining mouse and stylus.

Brain-computer interfaces In the literature review, we encountered one paper using neural signals to select 3D virtual objects in an AR environment (Si-Mohammed et al., 2020). Considering current developments in BCI research, such as the emergence of noninvasive systems (He et al., 2020) and open-source platforms ("OpenBCI Documentation," n.d.), it is reasonable to assume that BCIs become more widespread beyond clinical usage and that more complex AR tasks will be performed based on neural signals.

Application fields Throughout the literature review, we came across a variety of application fields, which the authors envisioned for their developed interaction techniques. The problem statement that was addressed most frequently in the reviewed literature was the interactive visualization of (abstract) data (e.g, Bach et al., 2018; Cordeil et al., 2020; Ens et al., 2021; Mahmood et al., 2019). Authors suggested combining the spatial view of 3D data with the precision of tangible devices to focus on different aspects. Another trend was the usage in smart homes (e.g., Esteves et al., 2017; Feuchtner and Müller, 2017; Masai et al., 2020; Sun et al., 2019), which is strongly related to the support of real-world interactions as stated earlier in this section. Finally, we would like to mention interactions with robots (Kytö et al., 2018; Quintero et al., 2018; Si-Mohammed et al., 2020; Z. Zhang et al., 2019) and drones (Liu & Shen, 2020) that were facilitated by using AR technology to preview future actions of the robot or to provide a direct interface to the system's current state. In summary, we observed a strong connection between the suggested interaction techniques and physical tasks, either in the form of directly controlling properties of the user's real surroundings or by using tactile interactions for working with abstract data.

15.4.2 Reflection on the Taxonomy Development Method

In this work, we applied Nickerson et al.'s (2013) iterative methodology, which is widely used in the IS literature, to create a valid and extendable taxonomy. This methodology offers many advantages. For example, a novice researcher can easily use this method and obtain comprehensive information about the literature by following the steps we mentioned above (e.g., the empirical-to-conceptual approach). Due to its iterative nature, it offers a time-efficient solution. Therefore, researchers can get easily familiar with the literature in each iteration. Finally, it provides a valid result: a taxonomy. Even if some of the articles could have been missed in the literature review, the taxonomy itself still serves its purpose and can easily be extended by future work.

Despite Nickerson et al.'s (2013) method being our basis for generating a taxonomy, we encountered aspects that are not applicable to our case: (i) limitation of subcategory creation and (ii) mutual exclusivity. We observed that many modalities differ fundamentally and should be categorized in detail (e.g., stylus/pen and clicker) to create a useful taxonomy, leading us to extend the original methodology by subcategories. Moreover, we noticed that several modalities are used as parts of the same interaction technique in the literature (e.g., voice and gestures). Hence, we chose not to use the mutual exclusivity feature of this method to avoid restricting the use of multimodality.

We also note that taxonomies within the field of HCI are often presented without a thorough description of the applied development method. To support transparency, we reported our methodology in detail and, therefore, hope to provide guidance for future reviews.

15.4.3 Limitations

This work considered 44 articles from the 2016-2021 time frame. Although we kept our search term broad, used an iterative approach, and covered traditional techniques (e.g., the baseline condition of several articles), this may be considered a limitation.

Due to the broadness of our search terms, we limited the included venues by focusing on ACM and IEEE and restricting the scope using the CORE rank. While this ensures that only high-quality venues were included, it does not guarantee the inclusion of all relevant sources.

Regarding our query, we observed many articles mentioning "interact*" in their abstracts but focusing on either feedback or visualization in their full paper. It is likely that some papers did not use this term and, therefore, were not considered in our review. During the process, we noticed that "input" could be used as one of the key terms, e.g., to specifically capture text input articles. Although this category is part of our taxonomy, we speculate that frequencies might be higher when including the term "input" in the query.

At least two researchers were involved in each step (Buscemi et al., 2006; McDonald et al., 2019) and the inter-rater reliability was high, yet the researchers could introduce bias because of their perspectives and backgrounds. Following the recommendations of qualitative research practices (Berger, 2015), we reported the backgrounds of the three main researchers in Sect. 2.4.1.

15.5 Conclusion

In this paper, we introduced a taxonomy for interaction techniques for immersive AR technologies based on an iterative literature review including 44 research papers from the period of 2016 to 2021. Our taxonomy is based on emerging and immersive AR interaction techniques and focused on two identified dimensions – task and modality. In the process of taxonomy formulation, we put emphasis on the identification of distinctive characteristics for each category, in order to create consistent terms and according definitions. This holistic view on AR interaction techniques is of particular value since we observed partially conflicting definitions of concepts in previous reviews that only focused on specific sub-areas of AR interaction, such as gestures or tangibles.

Our taxonomy can provide important guidelines for the development of future AR interaction techniques. It could serve as a basis for (i) developers to determine common uni- and multimodal methods to perform specific tasks in AR, and (ii) researchers to identify research gaps and, accordingly, potential for future investigations.

15.6 Acknowledgments

The authors acknowledge the support of the German Research Foundation, European Union's Horizon 2020, the German Federal Ministry of Education and Research, and the Federal Ministry for Economic Affairs and Energy.

15.7 Supplementary Materials

PRISMA-P Protocol

Table 35. The PRISMA protocol (PRISMA-P) is prepared based on Shamseer et al. (2015)

Checklist Items	Item No.	Note
Administrative Information		
Title:		
Identification	1a	A Taxonomy of Interaction Techniques for Immersive Augmented Reality based on an Iterative Literature Review
Update	1b	No update.
Registration	2	Not pre-registered.
Authors:		
Contact	3a	Blinded for review.
Contributions	3b	Blinded for review.
Amendments:	4	n/a
Support:		
Sources	5a	Blinded for review.
Sponsor	5b	None
Role of sponsor or funder	5c	Blinded for review.
Introduction		
Rationale	6	The research field of augmented reality (AR) encompasses various application fields, hardware, technologies and uses cases. In particular with the advancements in hardware systems (e.g., untethered head-mounted displays) with built-in tracking capabilities and integration of multi-modal input sensors, new categories of interaction techniques emerged. Currently there are taxonomies focusing on interaction in 3D environments in general (including VR) or interaction techniques for specific tasks (e.g. menus), as well as research papers giving overviews over several interaction techniques. By developing a taxonomy based on a literature review, this work aims to provide a structured overview of the current state of research in the field of immersive AR interaction techniques.

Objectives	7	The goal of the review is to provide an overview of the field of currently explored immersive AR interaction techniques without constraining to a particular subset or characteristic. The goal is to get an overview of the current state of research, extract common characteristics among interaction techniques and develop a taxonomy that sorts and groups the techniques accordingly. The taxonomy will be able to be used as a overview, a common ground for discussion, an aid to identify research gaps and emerging trends, and to find related interaction techniques to evaluate new ones.
Methods		
Eligibility criteria	8	Papers were considered when their language was English. Screening inclusion criteria for the title and abstract were as follows: (1) papers either presenting or evaluating interaction techniques with a focus on immersive AR (either HMD or projection-based). (2) Interaction techniques should clearly be intended for immersive AR applications. We excluded papers about interaction techniques for general or VR settings, where the authors only mention the possibility to adapt the interaction technique in AR. (3) We excluded literature reviews and other kinds of meta analysis.
Information sources	9	IEEE and ACM databases, but only conferences and journals with a CORE ranking of A*, A, or B will be considered.
Search strategy	10	We considered research articles focusing on interaction techniques, published since 2016 and containing the search terms in the title or abstract. The specific search term were defined by the three leading authors jointly. To develop the taxonomy, we followed an iterative approach Nickerson et al., 2013, in which empirical-to-conceptual and conceptual-to-empirical iterations are performed until predefined ending conditions are met. Which of both approaches are used in a next iteration, were decided for each iteration separately after finishing the previous one. In the first empirical-to-conceptual iteration, we started by considering the research articles from one venue, and added venues in later iterations. The order of venues to add was determined by the number of results found by using the search query.
Study records:		

Data management	11a	We manually downloaded the papers from the digital data bases of ACM and IEEE. We used python scripts to detect and remove duplicates (depending on their year and title) and further removed the ACM articles, which did not include our search terms. We used Dovetail for screening, keyword extraction and tagging phases. We further used Miro for sorting keywords and finding characteristics and dimensions.
Selection process	11b	Screening: the records were divided onto 3 researchers (2 researchers for each third of the data, 1 researchers as tie-breaker). Keyword extracting: same 2 researchers for the same thirds of data as in the screening process. Dimensions and characteristics identification (taxonomy development): group discussion between 3 researchers.
Data collection process	11c	Screening and tagging: assigning custom tags in Dovetail. Keyword extracting: custom text fields in Dovetail. Taxonomy development: creating one sticky note for each keyword and grouping them by moving them around on the whiteboard.
Data items	12	Title, doi, year, source. Further relevant variables, i.e. characteristics, will emerge during the taxonomy development process.
Outcomes and prioritization	13	Papers do not have to include any kind of evaluation and outcomes will not matter.
Risk of bias in individual studies	14	Disagreements resolved by a third researcher (tie-braker) and discussion meetings were hold after each iteration between three researchers.
Data synthesis	15a	We analyzed the papers according to the following conceptually deduced meta-characteristics: people, activities, context, technology (PACT framework)
	15b	Report of quantities of objects per characteristics.
	15c	Qualitative synthesis to assign taxonomy characteristics to the interaction techniques.
	15d	n/a
Meta-bias(es)	16	n/a
Confidence in cumulative evidence	17	n/a

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Shamseer, L., Moher, D., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., & Stewart, L. A. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: Elaboration and explanation. *BMJ: British Medical Journal*, *349*. https://doi.org/10.1136/bmj.g7647

Keyword Coding

We analyzed the papers focusing on the PACT framework (people, activities, context, technologies) as meta-characteristics. In the following, we will provide some examples of keywords we created for each meta-characteristic.

People

- Dyadic interaction
- Non-expert users
- Multi-player
- Designers
- Collaborative

Activities

- Rotation
- 3D model viewer
- Data visualization
- Setting of waypoints
- Hand gestures

Context

- Indoor
- Public space
- Eye-free interaction
- Precise
- High mobility

Technologies

- HoloLens
- Magic Leap
- Handheld controllers
- Pupil Labs eye tracker
- Robotic arm

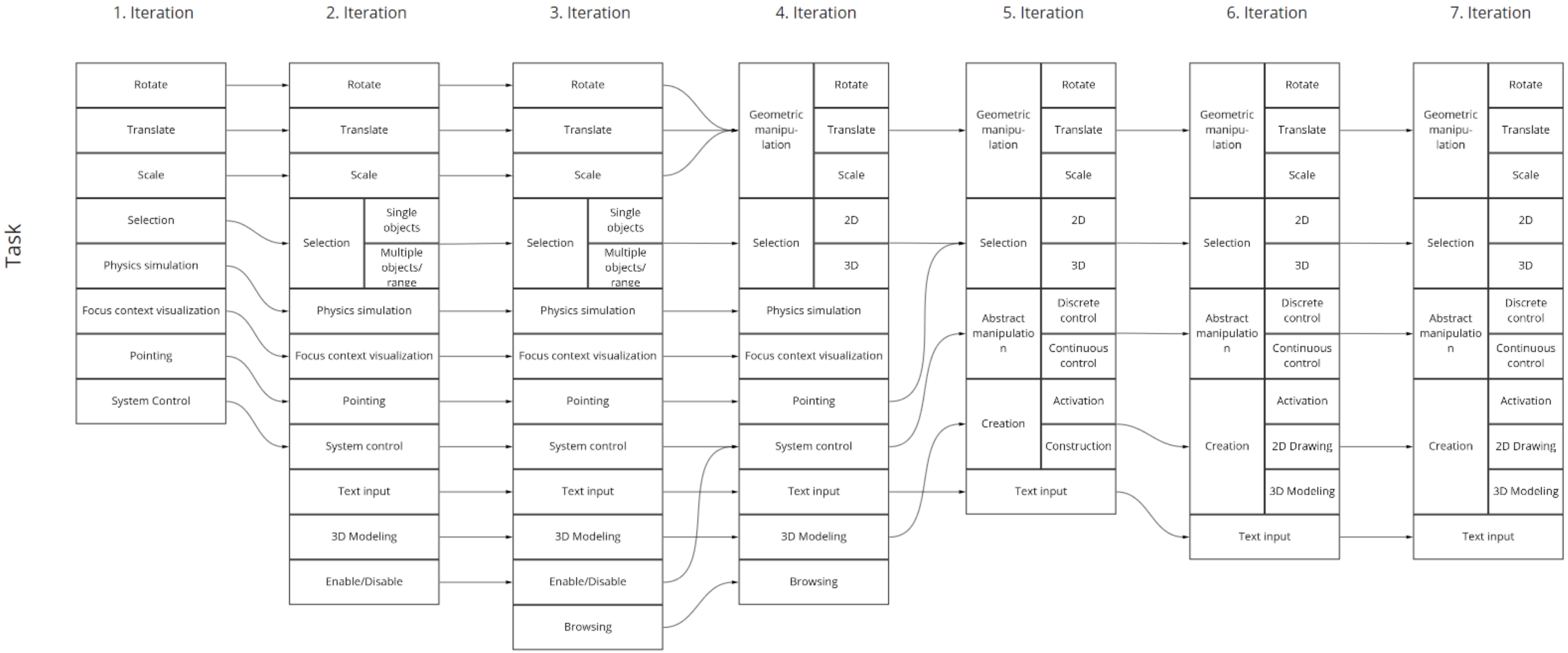

Figure 41. Iterative taxonomy development process that was performed. In each iteration, new characteristics were (i) added if new tasks occurred, (ii) merged if similarities were observed, (iii) renamed if more descriptive terms appeared, and (iv) removed if they were not distinctive anymore. Since the taxonomy did not change in iteration 7, our ending conditions were fulfilled and we terminated the process.

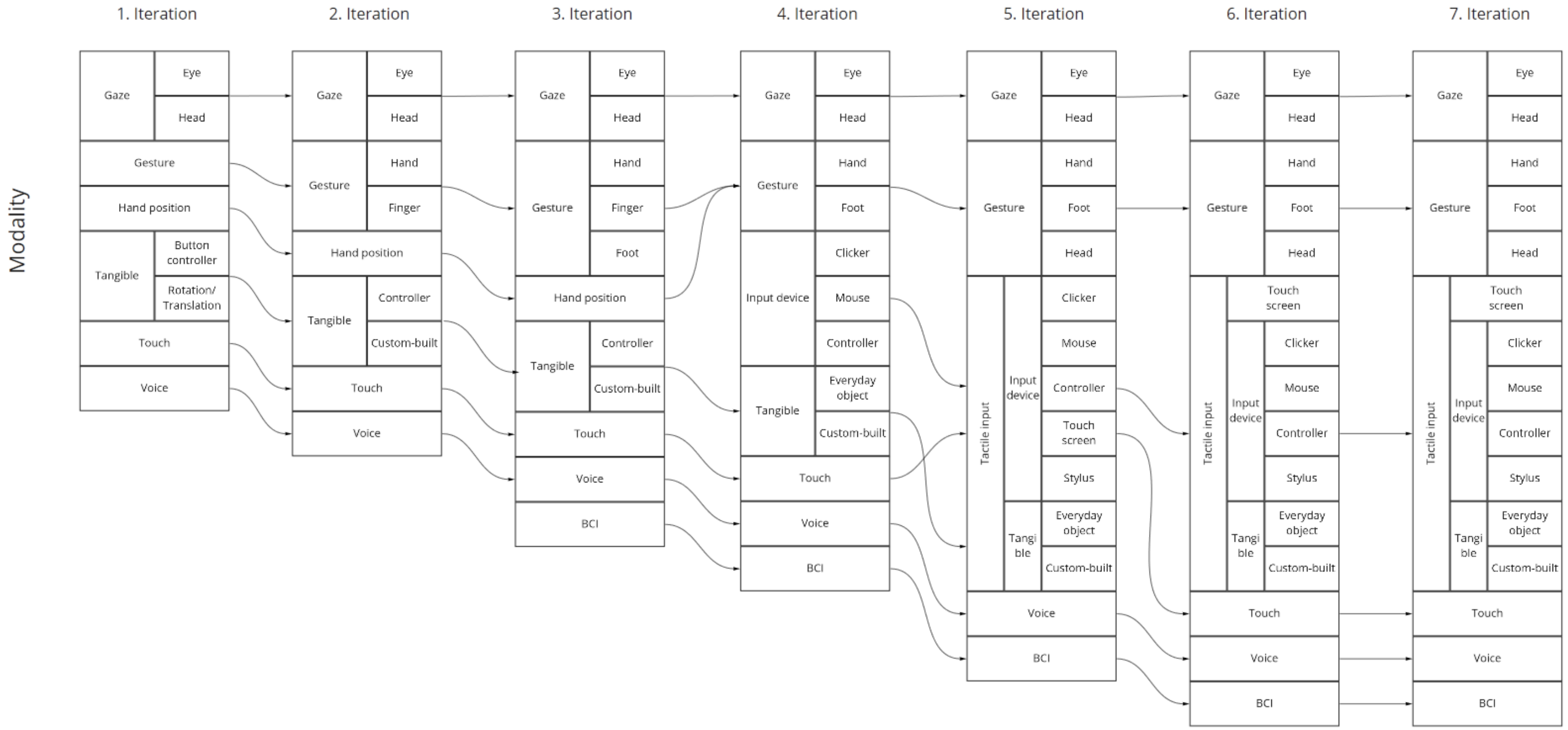

Figure 42. Iterative taxonomy development process that was performed. In each iteration, new characteristics were (i) added if new modalities occurred, (ii) merged if similarities were observed, (iii) renamed if more descriptive terms appeared, and (iv) removed if they were not distinctive anymore. Since the taxonomy did not change in iteration 7, our ending conditions were fulfilled and we terminated the process.

Table 36. Frequencies of task-modality combinations observed during the literature review. For each cell, the left and right values indicate the occurrences in unimodal and multimodal interaction techniques, respectively. This is an extension to Table 2 from the paper as references to the respective research papers are added.

		Tactile Interaction			Gestures			Voice	Gaze		BCI	
		Touch	Generic Input Device	Tangible	Hand	Foot	Head		Head Gaze	Eye Gaze		
Creation	Activation	0 | 0	1 | 0 [68]	5 | 0 [54,58,73,76,90]	3 | 1 [69,84,86]	0 | 0	0 | 0	2 | 3 [71,77,64,68]	0 | 2 [71,77]	1 | 0 [49]	0 | 0	12 | 6
	2D Drawing	1 | 0 [87]	1 | 0 [47]	1 | 0 [78]	0 | 0	0 | 0	0 | 0	0 | 0	0 | 0	0 | 0	0 | 0	3 | 0
	3D Modeling	0 | 0	1 | 1 [47,75]	0 | 0	0 | 0	0 | 0	0 | 0	0 | 0	0 | 0	0 | 0	0 | 0	1 | 1
Selection	2D	6 | 0 [61,62,74,87,89,90]	3 | 4 [47,53,66,75]	2 | 0 [54,81]	6 | 5 [49,61,63,66,68,71,74,85]	1 | 0 [85]	0 | 0	0 | 0	2 | 7 [49,55,63,66,71,85]	1 | 3 [55,66]	0 | 0	21 | 19
	3D	1 | 2 [58,59,90]	6 | 3 [48,51,59,64,67,78,83]	4 | 4 [48,51,76,89,90]	6 | 7 [51,59,63,65,67,69,83,84,86,88,90]	0 | 0	0 | 0	1 | 5 [58,65,83,84]	1 | 5 [63,65,69,71,83]	1 | 0 [60]	1 | 0 [80]	21 | 26
Geometric Manipilation	Translation	3 | 0 [74,87,89]	6 | 0 [53,57,64,67,83,89]	7 | 0 [48,52,54,58,62,73,78]	12 | 2 [63,67,68,69,71,74,77,79,83,84,86,88,90]	0 | 0	0 | 0	2 | 3 [71,83,84,86]	0 | 1 [83]	0 | 0	0 | 0	30 | 6
	Rotation	1 | 0 [90]	6 | 0 [53,57,64,67,83]	9 | 0 [48,52,54,58,62,73,78,81,90]	5 | 3 [50,67,71,83,84,88]	0 | 0	0 | 0	1 | 3 [71,83,84]	0 | 2 [50,83]	0 | 0	0 | 0	22 | 8
	Scale	1 | 0 [74]	4 | 0 [53,64,67]	1 | 0 [81]	5 | 3 [50,67,71,74,79,84]	0 | 0	0 | 0	1 | 2 [71,84]	0 | 1 [50]	0 | 0	0 | 0	12 | 6
Abstract Manipulation	Discrete Control	1 | 0 [74]	0 | 0	3 | 0 [58,73,74]	1 | 0 [82]	0 | 0	1 | 0 [72]	2 | 0 [58,77]	1 | 0 [55]	0 | 0	0 | 0	9 | 0
	Continuous Control	0 | 0	0 | 0	1 | 0 [54]	2 | 0 [56,82]	0 | 0	0 | 0	0 | 0	1 | 0 [55]	0 | 0	0 | 0	4 | 0
Text Input		1 | 0 [90]	1 | 0 [68]	0 | 0	0 | 0	0 | 0	0 | 0	0 | 0	0 | 0	0 | 0	0 | 0	2 | 0
		15 | 2	29 | 8	33 | 4	40 | 21	1 | 0	1 | 0	9 | 16	5 | 18	3 | 3	1 | 0	137 | 72

Table 37. Frequencies of task-modality combinations observed during the literature review, with a focus on multimodal interaction techniques. This table extends Figure 3 from the paper by including references to the respective research papers.

		Hand Gesture + Voice	Hand Gesture + Head-Gaze	Voice + Head-Gaze	Generic Input Device + Tangible	Generic Input Device + Head-Gaze	Touch + Tangible	Touch + Voice	Generic Input Device + Hand Gesture	Generic Input Device + Eye Gaze	Tangible + Hand Gesture	Hand Gesture + Eye-Gaze	Generic Input Device + Head-Gaze + Eye-Gaze	Generic Input Device Mouse + Stylus	
Creation	**Activation**	1 [84]	0	2 [77,71]	0	0	0	0	0	0	0	0	0	0	3
	2D Drawing	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3D Modeling	0	0	0	0	0	0	0	0	0	0	0	0	1 [47]	1
Selection	**2D**	0	4 [66,85,71,63]	0	0	2 2x [66]	0	0	0	1 [66]	0	1 [66]	1 [66]	0	9
	3D	2 [65,84]	3 [69,83,63]	2 [65,83]	2 [48,51]	0	1 [90]	1 [58]	1 [59]	0	1 [51]	0	0	0	13
Geometric Manipilation	**Translation**	2 [71,84]	0	1 [83]	0	0	0	0	0	0	0	0	0	0	3
	Rotation	2 [71,84]	1 [50]	1 [83]	0	0	0	0	0	0	0	0	0	0	4
	Scale	2 [71,84]	1 [50]	0	0	0	0	0	0	0	0	0	0	0	3
Abstract Manipulation	**Discrete Control**	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Continuous Control	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Text Input		0	0	0	0	0	0	0	0	0	0	0	0	0	0
		9	9	6	2	2	1	1	1	1	1	1	1	1	36

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16 Empowering Users to Create Augmented Reality-Based Solutions – Deriving Design Principles for No-Code AR Authoring Tools

Bräker, J., Hertel, J., & Semmann, M. (2023b). Empowering Users to Create Augmented Reality-Based Solutions – Deriving Design Principles for No-Code AR Authoring Tools. *Proceedings of the International Conference on Information Systems*

Abstract

Grounded on an experimental study with 18 participants, we derive 15 design principles for no-code AR authoring tools in an organizational setting. The study consists of two distinct treatments that aim to augment lightweight processes with AR. The outcomes are two interactive tutorials utilizing AR instructions. Following the no-code approach, the participants were empowered to create relevant AR content using a reduced interface and no need for advanced configurations or coding. The study thus combines two research streams with the aim of better understanding mechanisms for AR use in a professional context. As prior work has shown, despite the potential benefits, the adoption of AR authoring tools is limited because ramping up AR to productive use is heavily dependent on consulting and custom software solutions. Our novel approach bears the potential to broaden application domains and empower professionals to apply AR.

Keywords

User study, mixed reality, thinking aloud, digital innovation, IT adoption.

16.1 Introduction

As the pace of innovation cycles increases, organizations face the challenge of utilizing novel approaches to realize underlying benefits (Wehking et al., 2021). Likewise, users need to cope with all such ever-changing environments, and a need for adaptation arises. This area of tension results in failed innovation projects, abandoned proof of concepts or increased reluctance of employees. A lever to overcome these issues is seen in no-code and low-code platforms because they aim to empower users to design and apply innovative solutions within their workplace (Atkins, 2020; Bock & Frank, 2021). User-driven innovations are core characteristics of such platforms (Elshan et al., 2023). By providing a simplified interface and pre-built components, no- and low-code platforms allow users with no or little programming experience to create individual solutions. This reduces the reliance on IT departments and allows for faster implementation of ideas (Bock & Frank, 2021). An innovative technology that faces challenges in its dissemination in organizational contexts is augmented reality (AR). Especially for instructions and process support, AR offers a wide range of potential applications (Bräker, Osterbrink, et al., 2023; Hertel et al., 2022). However, adoption in business contexts remains scarce. Developments using game engines like Unity are challenging for inexperienced, non-technical designers. Professional AR authoring tools find low acceptance since they require a certain level of programming knowledge and much practice. AR authoring tools aim to create AR applications without programming experience. For example, organizations can discover whether AR adoption would be beneficial without enormous hurdles and financial investments. Existing AR authoring tools require less programming experience but are no less training-intensive and complex in their usage (Hönemann et al., 2022; Nebeling & Speicher, 2018). Therefore, we seek to understand the underlying design principles of no-code AR authoring tools to make them more accessible. Accordingly, we address the following research question:

RQ: How can no-code AR authoring tools be designed to enhance accessibility for users?

We approach this problem with an experimental user study with 18 participants that aims to design AR instructions for two exemplary processes. The no-code AR authoring tool enables users to define processes and attach AR elements to instruction steps. The outcomes are AR-based process descriptions that could be used for training purposes or to ensure a standardized process flow. Based on the study results, we derive 15 design principles in eight dimensions that guide the development of AR authoring tools that are accessible to users and do not need expert knowledge. To the best of our knowledge, this is the first study that combines AR authoring and no-code platforms to derive design knowledge for the future design of such platforms. In this way, we contribute to the understanding of no-code AR authoring tools in a theoretical way and to the concrete design knowledge at a practical level.

The remainder is structured as follows: The next section covers related work on AR and no-code/low-code platforms. After that, we present the research design with particular regard to the data collection, data analysis and derivation of the design principles. We then present our results in depth and discuss these while mirroring the state of the art. We conclude the paper with an outlook.

16.2 Related Work

Mixed reality technologies range from entirely virtual to real environments with varying degrees of virtual and real characteristics. Augmented reality (AR) extends reality with computer-generated elements, whereas virtual reality (VR) is fully immersive (Milgram & Kishino, 1994). The merging of the virtual and real world, real-time interaction, and the registration of virtual content in three-dimensional space are the characteristics of AR (Azuma, 1997).

The ability to enhance reality with virtual elements holds enormous potential for application in organizational settings. AR has been proven to assist in manufacturing, maintenance, and inspection processes such as assembly tasks (Kohn & Harborth, 2018) or general mechanical engineering tasks (Kammler et al., 2019). Besides, AR is used to assist safety-critical services (Bräker, Osterbrink, et al., 2023; Osterbrink et al., 2021), education (Mohammadhossein et al., 2022), and healthcare (Klinker et al., 2020a). However, previous research shows that the development of AR applications remains challenging (Ashtari et al., 2020). Especially small and medium enterprises (SMEs) struggle to realize these potentials (Cranmer et al., 2021; Masood & Egger, 2019). The reasons for this are manifold. Limited financial resources and little experience may make it difficult to invest in AR technologies. Other challenges include the complexity of identifying and selecting potential processes and the lack of guidance in process modeling (Bräker & Semmann, 2021, 2022, 2023b).

AR authoring tools for enterprises aim to create AR applications without intensive knowledge of software development. They focus on a low-code or no-code manner for creating AR content. AR content creation is multifaceted and includes, for example, placing virtual content in 3D space, creating visualizations and models, and including interactions. The authoring can be done using various hardware devices but is often desktop-based. Low-code development platforms are seen as innovation drivers because they make technologies accessible to new target groups (Elshan et al., 2023). This makes AR more accessible for SMEs, and proof of concepts can be implemented more quickly. However, existing AR authoring tools on the market require long training periods, and licenses are expensive. They come with numerous challenges and limitations. As a result, they are often operated by authoring experts. They do not cover encompassing design space. Additionally, AR authoring tools often come with a unique toolchain that makes users dependent, or they end up with a patchwork of tools (Hönemann et al., 2022; Nebeling & Speicher, 2018). An analysis across 26 AR authoring tools by Dengel et al. (2022) supports this impression. Most tools on the market require programming skills, while half of the 26 tools are not freely accessible or do not provide enough interactivity.

16.3 Research Design

We follow the research design shown in Figure 43 to generate knowledge about the design of AR authoring tools. The starting point for our study is an AR authoring tool developed as part of a research project. With its as-is solution state, the authoring tool aims to allow users to create customized AR instruction apps. We tested the AR authoring tool in a user study in order to be able to make statements about requirements and design principles as well as the usability and usefulness of the current prototype version. Users had to create AR instructions for two different processes. We combined qualitative and quantitative methods, thus following a mixed-method approach (Venkatesh et al., 2016). With established questionnaires, we measured usability, user experience, and workload. We analyzed the questionnaires with inferential statistics. We followed the think-aloud approach, which allowed us to make qualitative statements about the AR authoring tool. We recorded the screen and spoken words to document the think-aloud process. We coded the think-aloud recordings and the open questions from the questionnaires. From the codes, we derived requirements, from which we finally derived the design principles.

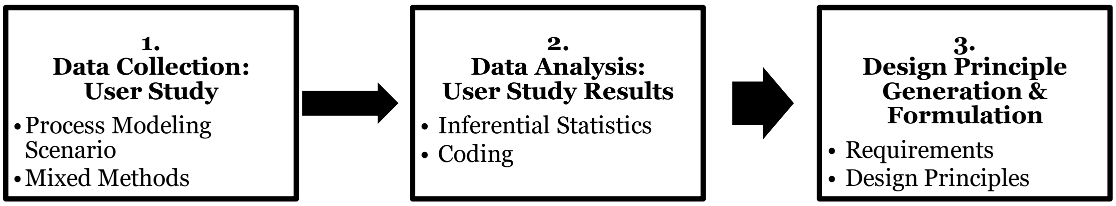


Figure 43. Research design

16.3.1 User Study

We conducted a user study during which participants interacted with the prototypical AR authoring tool to create in situ AR instructions. The goal of the application is to be deployed in organizations to facilitate the usage of AR by providing a no-code alternative for creating AR instructions. This study aims to get insights into how an AR authoring tool needs to be designed. By evaluating the status quo of the AR authoring tool, we aim to investigate whether the prototype is already a suitable alternative to programming AR instructions from scratch or whether there is improvement potential. Participants of the study were computer science students and members of the department. Most of them had programming experience. Thus, it allows them to assess their preference and the estimated effort of using the prototype compared to programming a similar app.

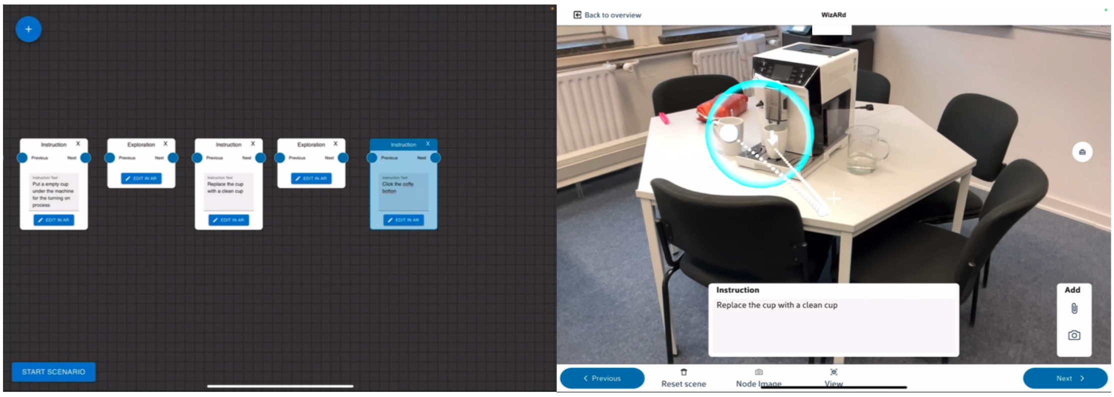
Besides, we focused on assessing the usability, user experience, induced workload, and other subjective opinions, thoughts, and ideas about the prototype. These metrics might be influenced by the AR authoring tool's design. We aimed to assess if the prototype was intuitive to use, to what extent it matched the participants' expectations and mental models, and which difficulties occurred when used by untrained users. By doing so, we aim to elicit specific information about usage behavior that we can use to derive design knowledge for the design of such AR authoring tools. To avoid influencing and priming the study participants, we did not provide tutorials or explicit instructions on using the app beforehand. Instead, participants freely explored the prototype while their thoughts were captured using the think-aloud protocol.

Prototypical AR Authoring App

As part of previous research, a mobile application was developed that allows users to create instructions for AR processes in a no-code manner (Konopka et al., 2022).

In contrast to traditional AR authoring tools, which are complex and require much training, this tool aims to create AR instructions without training or programming skills. The tool is characterized by the fact that the instructions can be created directly in AR based on the "what you see is what you get" (WYSIWYG) principle. The instruction can be created and viewed on the same device, for example, using a tablet computer.

The app has three main screens: (1) A node editor to model the process (see Figure 44, left). Thereby, one node represents one process step. (2) An AR editor, in which the instruction AR content for the process steps can be created and edited directly in AR (see Figure 44, right). (3) An AR scenario preview, in which the user can view the result, i.e., the AR instructions. The node editor can be used to create different node types. The info node creates a 2D canvas with a title and a textual description. The exploration node allows displaying different points of interest (POIs) in AR. Two AR elements can be added to the AR exploration scene. The first is a simple marker with a location icon, and the second is a tether with the same marker at the end. For each of the POIs, a textual description can be added. The third node, the instruction node, aims to create process steps for instructions. This node has an instruction text for the scene, and a wider choice of AR elements is available. Arrows, two different tethers, sticky nodes, and a halo, i.e., a transparent circle, can be placed in the AR scene. The different nodes can be connected in the node editor screen to create the process flow. The AR scenario preview screen shows the resulting outcome – the AR instruction app. The user can view the created instructions step by step and check how the result will look.


Instruction Text
Put a empty cup under the machine for the turning on process

Instruction Text
Replace the cup with a clean cup

Instruction Text
Click the coffe botton

Instruction
Replace the cup with a clean cup

Figure 44. AR authoring tool, populated node editor (left) and AR editor with several AR elements in the scene (right)

Task

To investigate the suitability of the prototype for different use cases, we included two scenarios in this experiment for which participants were asked to create AR instructions using the AR authoring app:

Scenario 1 – Coffee machine. This scenario included creating AR instructions for typical steps to prepare a coffee machine, like filling in coffee beans and water, placing a cup, plugging in the power plug and pressing a button to make a coffee. Here, the coffee machine was the only point of interest. All required items (coffee beans, water, cup) were placed on a table beside the coffee machine. The table was placed in the middle of the room to allow participants to move around it freely. For instance, to see the power plug, participants had to walk around the machine to see its back side.

Scenario 2 – Seminar room. In contrast to the first scenario, participants had to move around a room to create AR instructions while points of interest were placed around them. Participants were asked to create instructions on how to prepare a university's room for a seminar, including steps like connecting a notebook to a projector, turning on the projector on a wall-mounted interface, closing windows and writing the current date on a blackboard.

We aimed to let participants freely convert a process into instructions without explicitly providing the division into single steps. This way, we mimicked a situation of implicit knowledge, e.g., an expert knowing how to perform a process without it being written in a handbook, freely explaining it to a new worker. Thus, we decided not to provide the process text-based since such a presentation would inherently structure the process into distinct steps. Instead, we recorded videos to demonstrate the processes. For these videos, we filmed a person performing the processes, i.e., preparing the coffee machine and preparing the seminar room as described above. This way, participants had to convert the process into distinct steps and these steps into an instruction by themselves. For instance, they had to decide if "closing windows" could be one step or if they created a single step for each window that must be closed. The videos did not include auditory or textual descriptions of the process but simply showed its execution in one take. Based on these videos, participants were asked to create AR instructions for the shown process, i.e., use the app like a professional in an organization would use it to create an instruction for a process. We explicitly stressed that they should not recreate the process (e.g., not making a coffee) but instead create instructions for the process using the prototype's features.

Procedure

Before starting the study, participants signed an informed consent form and were asked to fill out a questionnaire about demographics, their experience with AR and their experience as developers. Then, they read a short informational text about AR and the prototypical AR authoring tool. To familiarize themselves with the prototype, they were handed a tablet with the prototype running. They were asked to explore the application freely. We particularly encouraged them to stand up and explore the spatial functionality of the prototype. The participants were allowed to finish this exploration as soon as they felt ready but were given a maximum of 15 minutes. After the exploration, they started with the first scenario. The order in which participants completed the two scenarios was counterbalanced to avoid any learning or fatigue effects coupled with a specific scenario. Thus, half of the participants started with the coffee machine scenario and the other half with the seminar room scenario. For each scenario, the participant first watched the video demonstrating the process. Participants were allowed to watch the video as often as they wanted before creating the instructions. They were also allowed to watch it again during the instruction creation process. They could freely slide through the video with a standard video player interface. After watching the video, they were again handed the tablet with the prototype running and an empty scenario and were asked to create instructions for the given process. For each process, a maximum of 30 minutes was given. Depending on whether the participant quickly finished the conditions or used the maximum time, the study took about 60 to 90 minutes.

Measurements

After each scenario, they were asked to complete an unweighted NASA Task Load Index (NASA TLX) questionnaire (Hart, 1986; Hart & Staveland, 1988). After completing the second scenario, they were also asked to fill out the System Usability Scale (SUS), a 10-item scale to measure usability (Lewis, 2018), the short version of the User Experience Questionnaire (UEQ), an 8-item scale to assess the pragmatic and hedonic quality of a product (Schrepp, 2015; Schrepp et al., 2017). Pragmatic quality describes how far users can reach their goals with the product. Hedonic quality focuses on aspects like novelty and fun while using the product. During the exploration mode and both conditions (scenarios), participants were asked to follow the think-aloud protocol (van Someren et al., 1994), i.e., speaking out loud their thoughts while interacting with the prototype. Their voice was recorded using the tablet's built-in microphone. We also stored screen recordings to analyze the usage of the AR authoring prototype. Additionally, the completion time per condition was logged.

Participants

The study was completed by 18 participants (7 female, 10 male, 1 preferred not to tell). The participants' age ranged from 20 to 35 years (M = 26.3, SD = 4.7). The participants were students (N = 16) or staff members (N = 2) from a university's computer science department. When asked how often they use AR applications, most (N = 11) reported that they have used AR a few times, 5 participants have never used AR, and 2 participants use AR at least monthly. On a scale from 1 (unexperienced) to 5 (expert), they rated their experience with different types of AR as follows: mobile AR (M = 2.8, SD = 0.8), head-mounted displays (HMDs) (M = 1.8, SD = 1.1), spatial AR (M = 1.3, SD = 0.6). One participant has used AR for instruction or guidance before, 5 for design or planning, 5 for games, 2 for education and one for social media. We also assessed the participants' developer experience on a scale from 1 (unexperienced) to 5 (professional) as a developer in general (M = 2.5, SD = 1.2), as an AR developer (M = 1.2, SD = 0.5) and as a game engine developer (e.g., Unity) (M = 1.7, SD = 1.0).

16.3.2 Data Analysis

We collected data from 18 participants, who each performed two conditions (scenarios). In the following, we describe how we analyzed all collected data, i.e., completion times, questionnaire results and think-aloud recordings.

Completion Time

We investigated whether the time participants needed to create the instructions differed between the first and second conditions they completed to investigate if they got faster in creating instructions over time. In the following, times are reported in minutes. Due to technical issues, some time values were not stored successfully, which led to the exclusion of the data of 4 participants from the completion time analysis. For the remaining 14 participants, all the time groups were normally distributed. We performed a paired-sample t-test and found a significant difference between the first condition (M =21.5, SD = 5.14) and the second condition (M = 14.99, SD = 5.34) at the 5% significance level (t(13) = 2.97, $p < 0.05$), indicating a higher completion time for the first condition than for the second one.

Usability, User Experience and Workload

To investigate the prototype's usability, we used the SUS. Following the calculation method proposed by Brooke (1996), the application was rated with a mean usability score of M = 40.4 (SD = 17.0) on a scale from 0 to 100, indicating below-average usability (Lewis, 2018). The user experience was measured using the short version of the UEQ. Transformed to a scale from -3 to 3, we measured a pragmatic quality of 0.25, a hedonic quality of 1.0, and an overall user experience of 0.625. These values indicate a neutral pragmatic quality, a positive hedonic quality, and a neutral overall user experience.

After each condition, we measured the perceived workload with the unweighted NASA TLX. Figure 45 (left) shows the results, grouped by scenario. In order to investigate if the workload differs between both evaluated scenarios (i.e., coffee machine and seminar room), a paired-sample t-test was conducted. Values were log 10 transformed before the resulting residuals were confirmed to follow a normal distribution using the Shapiro-Wilk test. We found no significant difference between the coffee machine scenario (M = 36.21, SD = 19.62) and the seminar room scenario (M = 35.08, SD = 16.22) at the 5% significance level. To get a deeper insight, we investigated differences per dimension. The data did not follow a normal distribution for multiple dimensions and could not be transformed to be normally distributed with standard transformations. Hence, two-sided Wilcoxon signed-ranks tests were performed for each dimension. We found a significantly higher mental demand in the coffee machine scenario than in the seminar room scenario (Z = 96, $p < 0.05$). For the other dimensions, we did not find a significant difference.

We also investigated possible learning and fatigue effects by comparing the workload of the first condition a participant completed to the second one. The grouped workload values can be seen in Figure 45 (right). Again, a paired-sample t-test was conducted, and values were log 10 transformed before the resulting residuals were confirmed to follow a normal distribution using the Shapiro-Wilk test. We found a

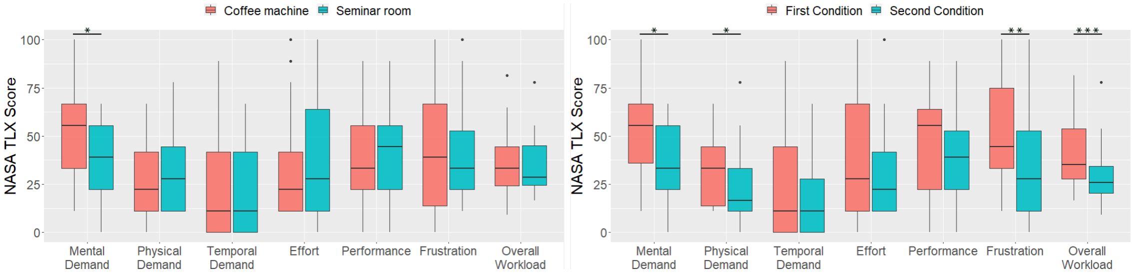


Figure 45. Measured workload grouped by scenario (left) and condition number (right) Asterisks depict significant differences (* < 0.05, ** < 0.01, *** < 0.001)

significant difference between the first condition (M = 40.74, SD = 17.35) and the second condition (M = 30.56, SD = 17.12) at the 5% significance level (t(17) = 4.66, $p < 0.001$). The results suggest that the overall workload was higher in the first condition than in the second one. Again, we performed dimension-wise comparisons. The data did not follow a normal distribution for multiple dimensions and could not be transformed with standard transformations to be normally distributed. Hence, two-sided Wilcoxon signed-ranks tests were performed for each dimension. We found a significantly higher mental demand (Z = 115, $p < 0.05$), higher physical demand (Z = 65.6, $p < 0.05$), and higher frustration (Z = 112, $p < 0.01$) for the first condition than for the second one. For the other dimensions, we did not find a significant difference.

Participants' Subjective Feedback and Preference Estimation

Figure 46 shows the answers to the further questions that do not stem from a standardized questionnaire regarding the participants' opinions about the app's difficulty, complexity, and suitability. Each question was asked on a 5-point semantic differential scale. In the questionnaire used in the study, some questions had different positive-negative directions (e.g., difficulty was rated from 1 – easy to 5 – difficult). For a clearer presentation, we inverted some scales to reach a universal direction (i.e., a higher value indicating a more positive response). For each question, participants could optionally add a comment. We performed a one-sided Wilcoxon signed-ranks test against the neutral value of 3 for each question. For difficulty, we found a significant effect (Z = 73.5, $p < 0.05$) indicating a trend toward "easy" (M = 3.56, SD = 0.99). Participants significantly preferred an AR app when asked about their preference for using an AR authoring tool compared to a desktop interface (M = 4.33, SD = 0.69; Z = 136, $p < 0.001$). According to the comments, participants appreciate the in situ / WYSIWYG aspect (N = 6) and suggest combining AR and desktop (N=3). In contrast, the desktop could be used for more precise positioning or labeling. Participants significantly perceived mobile AR as suitable (M = 3.94, 0.88; Z = 100, $p < 0.01$). Three Participants mentioned the usage of an HMD, whereas one participant discussed concerns regarding cybersickness. They also proposed using a smaller device (N= 4) like a smartphone to reduce fatigue while holding the device and facilitate the text input. They also discussed the advantage of the tablet's large screen compared to smaller devices. Regarding a preference for using such a no-code authoring app instead of programming an app to show similar instructions, participants preferred the app (M = 4.67, SD = 0.49; Z = 171, $p < 0.001$). One participant described their preference as context-dependent and would only prefer the app for a static environment and a linear task. When comparing the time they would use for creating instructions either with the app or by programming, we observed a trend towards a longer expected time for programming (M = 4.61, SD = 0.98; Z = 160, $p < 0.001$). We also asked the participants to estimate the time they would expect to spend programming an app that shows similar instructions to the ones they authored in the study, given the example of the Unity engine for programming. We did not provide any time unit to avoid bias but let them freely describe their time estimation. The answers covered some hours, days, weeks, and even months. The smallest estimations were “2 hours”, “probably several hours of concentrated works”, “probably a day or so [...]”, and “36 hours”, the remaining answers clearly exceed a range of hours and days. Participants rated the app's complexity as balanced, as the answers did not significantly indicate a rate of “too complex”, or “too basic” (M = 3.06, SD = 0.94; Z = 25, p = 0.8). Five participants suggested one or more additional features like logic gates (N = 1), an overview of all AR elements (N = 1), rotatable objects (N = 1), adding videos (N = 1), and blending out nodes (N = 1), and one participant suggested to limit the range of functionalities. We did not find a significant effect regarding the participants' opinion of whether they would be more suitable for small or large areas (M = 2.61, SD = 0.98; Z = 12, p = 0.1). Some participants reason their opinion for larger environments with tracking inaccuracies and argue that these issues would matter less in larger environments (N = 3).

Analysis of the Think Aloud Recordings

For the analysis of the think-aloud recordings, we were interested in the users' thoughts they spoke out loudly on the one hand and the usage behavior, i.e., what they do with the app and how they use it, on the other hand. Because of technical problems, we could not properly analyze the videos from three of the 18 participants. We excluded them from the analysis. We transcribed all video recordings of the remaining 15 participants. We enriched the transcripts with descriptions of the user behavior.

We coded the transcripts with two independent researchers following the grounded theory open coding method (Strauss & Corbin, 1994). This resulted in 144 different initial atomic codes. We then clustered these codes thematically into concepts and merged duplicates. This results in 140 concepts that describe challenges, problems, and suggestions for improvement. We derived 47 requirements for the AR authoring tool from the codes and concepts describing challenges, problems, and suggestions[1]. We have generated and formulated 15 design principles for AR authoring apps based on these requirements.

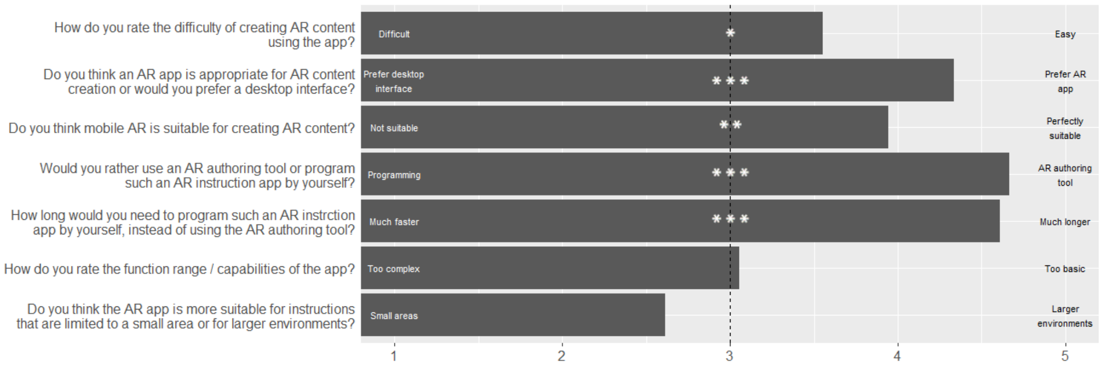


Figure 46. Mean values of the participants' answers on estimations and preference evaluations Asterisks depict values significantly different from the neutral value of 3 (* < 0.05, ** < 0.01, *** < 0.001)

16.3.3 Design Principle Generation and Formulation

Design principles are "prescriptive statements that indicate how to do something to achieve a goal" (Gregor et al., 2020, p. 1622). They can focus on user activity, i.e., what users should be able to do with an artifact, focus on the artifact with its features, or both. Design principles are formulated in a standardized syntax. We follow the schema by Gregor et al. (2020):

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[1] All codes, concepts, requirements and resulting design principles are available at (Bräker, Hertel, & Semmann, 2023a): http://doi.org/10.25592/uhhfdm.13222

"DP Name: For Implementer I to achieve or allow for Aim A for User U in Context C, employ Mechanisms M1, M2, ... Mn involving Enactors E1, E2, ... En because of Rationale R."

Design principles can be generated from newly designed artifacts (Purao et al., 2020). They can be inspired by what worked in the artifact and what did not work as expected. This can be evaluated, e.g., by conducting a user study. Our data basis for generating the design principles consisted of design requirements derived from the think-aloud recordings. We validated and enriched the design requirements with statements from the questionnaires. In the questionnaire, we asked the users for additional opinions, estimations and preferences. These are related to difficulties in using the app, the suitability of a tablet as hardware, the functional scope of the app and how likely they are to use it. The answers from the questionnaires go in line with the requirements from the think-aloud data. We aggregated the requirements by grouping similar goals. As Möller et al. (2020) proposed, we mapped the design requirements to design principles. Based on this, we formulated the design principles. Thus, every design requirement is mirrored in at least one design principle. According to the definition, the design principles describe what and how something must be done to achieve these goals. The resulting design principles are described in more detail in the following section.

16.4 Result – Design Principles for AR Authoring Tools

Our result is 15 design principles for AR authoring tools that emerged from the user study. These principles serve as a guideline for developing AR authoring applications. Table 35 shows the design principles. Each design principle has a title and a description, according to (Gregor et al., 2020). The design principles can be grouped into eight dimensions. These are principles for an ergonomic app usage (DP1), consideration of expectation management (DP2), guiding principles for improving understanding of the app (DP3 and DP4), basic interaction design principles (DP5-DP7), principles to support process modeling (DP8), principles for enabling comprehensive information coding in the AR app (DP9-DP11), principles for positioning AR elements (DP 12 and DP13), and for tracking the 3D environment (DP14 and DP15). In the following, we describe each design principle in more detail. We give insights and examples from our user study.

Table 38. Design principles for AR authoring tools

	Title	Design Principle
Ergonomics	**DP1:** Consider hardware requirements and limitations	For users to achieve a seamless and ergonomically comfortable experience using the app with a tablet, app design must avoid *(1)* holding the tablet in their hands continuously for too long while *(2)* not putting the tablet down too often because physical exhaustion due to the weight of the hardware and media breaks should be avoided.
Expectation Management	**DP2:** Manage and shape expectations for app use and outcomes in the beginning	To ensure that users do not develop false expectations and are satisfied with their outcomes, ensure expectation management in regard to *(1)* goals, tasks, and time required for app use, and *(2)* the possible outcome in the beginning because otherwise users will be disappointed and doubt their abilities.
Guidance	**DP3:** Limit free exploration to guide familiarization with the app	To allow users to use the app with little prior knowledge, employ mechanisms that provide users with guidance and assistance while leaving room for free and creative exploration because users struggle to understand the app without any guidance.
	DP4: Provide tutorials, tooltips, workflow patterns, and best practices	To allow users to acquire basic knowledge about the app, learn from existing knowledge, and get help when they encounter difficulties, employ *(1)* appropriate tutorials, *(2)* tooltips as help mechanisms, *(3)* example workflow patterns, and *(4)* best practices, because otherwise users will feel helpless, frustrated, and doubt their abilities.

Basic Interactions	**DP5:** Consider traditional interaction design and usability patterns	For the app to achieve usability, employ *(1)* traditional interaction design and usability patterns like feedback, different input mechanisms, assistance, and transparency, and *(2)* expect users to make mistakes or change their minds and therefore employ an undo and redo feature because otherwise low usability and user experience with the app leads to frustration and discomfort.
	DP6: Don't let users do unnecessary tasks that can be automated	To allow users to have a seamless experience with the app, employ mechanisms that automate unnecessary tasks because the user does not know they need to do the task, or it annoys them to do it repeatedly.
	DP7: Empower power users	To allow experienced users to use the app efficiently and effectively, employ mechanisms that empower them to quickly complete their goals because otherwise, the app seems inconvenient.
Process Modeling	**DP8:** Enable the modeling of complex processes	To enable users to model their processes as realistically as possible, enable them to *(1)* construct more complex processes with branches and conditions and not only linear processes and *(2)* combine different node types because otherwise, not all processes can be modeled correctly.
Extensive Information Encoding	**DP9:** Enable textual descriptions to enrich AR elements	To allow users to deliver comprehensive information, employ mechanisms to create additional textual descriptions for scenes, AR elements, and nodes because, in some cases, simple geometric AR elements are not expressive enough.
	DP10: Provide a variety of AR elements and style options	To allow users to deliver information in a diverse way, provide a variety of AR elements to choose from and allow individual styling options in terms of color, size, and rotation because the distinction by geometric shapes alone is not expressive enough.

	DP11: Allow adding, editing, and enriching the scene with photos and videos	To allow users to deliver information in the form of real-world snapshots, employ a mechanism for adding photos and videos and enriching/editing them because photos and videos are a simple option to capture a current state or target state of real-world objects.
AR Element Positioning	**DP12:** Facilitate the spatial perception of AR elements	To support users in the precise positioning of AR elements, employ mechanisms that *(1)* give feedback on surface detection and *(2)* support distance estimation because the placement of AR elements requires a clear idea of the spatial position of the element.
	DP13: Support precise positioning of AR elements	To allow users to create spatially accurate AR instructions, employ an interface that enables precise placement of AR elements because the position of AR elements mainly encodes instruction information and is an essential feature of the app.
Tracking	**DP14:** Tracking accuracy is essential	For users to achieve a sense of reliability, employ accurate and reliable tracking mechanisms because with unstable tracking, users will become frustrated, and the usefulness of instructions cannot be guaranteed.
	DP15: Implement object tracking	For users to achieve a feeling of blending real and virtual contents, employ mechanisms to track dynamic real-world objects because then AR elements can be attached to moving real-world objects.

DP1: Consider hardware requirements and limitations. For users to achieve a seamless and ergonomically comfortable experience using the app with a tablet, app design must avoid *(1)* holding the tablet in their hands continuously for too long while *(2)* not putting the tablet down too often because physical exhaustion due to the weight of the hardware and media breaks should be avoided.

Hardware choice influences the design of the app thoroughly. Using a tablet for AR applications requires the users to hold the tablet in their hands for a long time, which was reported as heavy and exhausting. Especially when the AR elements are placed in the 3D environment, the users must hold the tablet straight up in front of them to view the environment through the camera. Doing tasks requiring both hands is not possible. Doing one-handed tasks, e.g., taking a photo and showing something with the other hand simultaneously, is possible but causes quicker exhaustion. Some participants tended to put down the tablet to model the process or type longer texts. However, they also described these media breaks, i.e., putting the tablet down and lifting it again, as exhausting and annoying. Thus, the app design must avoid holding the tablet for extended periods, while on the other hand, laying it down in between should be minimized to prevent media breaks.

DP2: Manage and shape expectations for app use and outcomes in the beginning. To ensure that users do not develop false expectations and are satisfied with their outcomes, ensure expectation management in regard to *(1)* goals, tasks, and time required for app use, and *(2)* the possible outcome in the beginning because otherwise users will be disappointed and doubt their abilities.

Expectation management regarding the app and the outcome can prevent users from being frustrated. It is essential to clarify the AR authoring app's capabilities and limitations, the expected time required to create AR instructions, and the expected level of prior knowledge. Our results show that participants needed much more time than expected, which frustrated them. Also, regarding the outcome – i.e., the AR instruction app the users create, not all users were satisfied with their results because they had higher expectations. They did not see an example outcome before and had no example comparison. Managing and shaping these expectations might help users be more satisfied with their performance and abilities. One participant said that the created result would not be helpful for other people because it did not look like an AR app.

DP3: Limit free exploration to guide familiarization with the app. To allow users to use the app with little prior knowledge, employ mechanisms that provide guidance and assistance while leaving room for free and creative exploration because users struggle to understand the app without any guidance.

Finding the sweet spot of guidance with room for free and creative exploration must be explored. Without guidance, participants quickly felt lost during app use - especially those with low prior knowledge. On the other hand, with too much guidance, users might feel restricted in accomplishing their goals. For example, predefined templates for recurrent tasks may guide and assist the users in app usage.

DP4: Provide tutorials, tooltips, workflow patterns, and best practices. To allow users to acquire basic knowledge about the app, learn from existing knowledge, and get help when they encounter difficulties, employ *(1)* appropriate tutorials, *(2)* tooltips as help mechanisms, *(3)* example workflow patterns, and *(4)* best practices, otherwise users will feel helpless, frustrated, and doubt their abilities.

Our results show that users require tutorials and help functions in the app. Participants asked for initial tutorials describing the app's general functions and concepts. The app's concepts did not directly match their mental model. Not understanding the different screens (concept node editor, concept AR editor, concept scenario preview) and the navigation between them, participants reported feeling lost and not knowing how to start. An approach to overcome these challenges could be an introductory tutorial in the form of a video or text. Further, participants asked for help because they struggled with specific features. Not all buttons and functions are self-explanatory. It is not apparent how the different types of nodes work and which functionalities they come with. Some also struggled to find the toolbox to select different AR elements and how to interact with them. The differences between node images, media and the photo button were also unclear and took some time to explore and understand. Especially new concepts like the selection cursor or the hand-moving button might need special attention because users are unfamiliar with these concepts from other apps. Helping functions could be implemented using helping buttons that open overlays with short explanations.

Although participants struggled initially, they experienced a learning effect. The longer they used the app, the faster and more confident they were in handling the app. This is underlined by the fact that they needed less time for the second task of the study. The orientation phase, in the beginning, could be shortened by providing appropriate helping mechanisms.

To encourage users even more, workflow patterns and best practices could be supportive. Example patterns could suggest how to navigate and use the app efficiently. For example, some participants tried to improve the workflow by modeling the process in the node editor as a first step. Then, they edited the scenes in the AR editor sequentially, and last, they viewed the results in the AR scenario preview. In contrast, most participants added one node in the node editor and then edited this node in AR. Afterward, they returned to the node editor and added the next node. In between, they checked how their outcome looked in the AR scenario preview. This approach took longer because they had to jump back and forth between the different screens more often. Best practices could, for example, show which node combinations are useful for which tasks. Some participants added info nodes at the beginning and end to give basic information. In between, they used instruction nodes for the different tasks. Best practices could also describe which AR elements can be combined well. For example, tether elements were often used to navigate the way to a spot in the real world. The tether can be followed by other AR elements showing the task step at this place. Additionally, some attached an image of the end state to show what the result should look like. Another pattern we observed is to combine visual elements with textual descriptions in every scene.

DP5: Consider traditional interaction design and usability patterns. For the app to achieve usability, employ *(1)* traditional interaction design and usability patterns like feedback, different input mechanisms, assistance, and transparency, and *(2)* expect users to make mistakes or change their minds and therefore employ an undo and redo feature because otherwise low usability and user experience with the app leads to frustration and discomfort.

Use established interaction design and usability patterns to guarantee the general usefulness of the app. Provide feedback about what happens, e.g., if a scene or image is saved. Let users know when a new AR element or node is added and provide different input mechanisms. Because the tablet gets heavy to hold after some time and typing longer texts on a tablet screen is complicated, one participant said that they wished to have speech-to-text functionalities to be more efficient. This goes in line with DP1, which deals with hardware limitations. Assist whenever possible, e.g., enable hyphenation, spell check and auto-resize in text fields. Make transparent how mechanisms work. Explain why different functions are disabled and what is needed to activate them. For example, participants were confused about why the AR scenario preview button was disabled initially. They did not know that the preview only works when nodes are in the node editor.

Consider that users will make mistakes or change their minds. To ensure users feel safe using the app, provide functions to undo and redo steps. During the study, participants accidentally deleted nodes in the node editor and could not undo the deletion. They said this frustrated them because they had to add the node with all AR elements in the scene again. Further, participants asked for mechanisms that ask for confirmation before making major changes like deleting a node. Participants suggested having a prompt message asking for confirmation if they wanted to delete the complete node.

DP6: Don't let users do unnecessary tasks that can be automated. To allow users to have a seamless experience with the app, employ mechanisms that automate unnecessary tasks because the user does not know they need to do the task, or it annoys them to do it repeatedly.

Our results show that participants struggled with doing repetitive tasks. Especially when the tasks could be automated, it annoyed them. For example, when they created a new node, they had to connect it with the previous node. Some participants did not know they had to connect the nodes, which influenced the workflow. When the nodes are not connected, the AR scenario preview, for example, only shows one node because the sequence of steps is not defined. Even if the participants understood that they had to connect the nodes, they were annoyed by these repetitive tasks. Automating these steps could support the flow and user experience. Another example is the spawning of nodes in the node editor screen. In the prototype for the study, a new node always spawned at the same position. Every time participants added a new node, they had to scroll to the starting position to move the node to the end of their process chain. This task annoyed them because they sometimes did not see that the node was already created, and the scrolling took time. It is one of the most mentioned problems in the study. Automating these tasks could prevent users from not knowing that they must do this and running into further problems. Besides, it ensures a more seamless and effective experience with the app.

DP7: Empower power users. To allow experienced users to use the app efficiently and effectively, employ mechanisms that empower them to quickly complete their goals because otherwise, the app seems inconvenient.

The participants who got familiar with the app tried to optimize their workflow. In the study, we observed that participants acted more structured and goal-driven during the second task. One participant asked for a feature that allows them to place several AR elements of the same type in a row. It was inconvenient that they had to click the toolbox button and select the AR element repeatedly. For example, by enabling a power-placing mode for experienced users, they can be supported to work more efficiently. This design principle aligns with DP6, which aims to automate unnecessary steps.

DP8: Enable the modeling of complex processes. To enable users to model their processes as realistically as possible, enable them to *(1)* construct more complex processes with branches and conditions and not only linear processes and *(2)* combine different node types because otherwise, not all processes can be modeled correctly.

Most processes amenable to being assisted with an AR instruction app are linear (Bräker & Semmann, 2021). Although the tasks for the study were also linear processes, participants said they missed the opportunity to create more complex ones. They asked for functionality to add branches, conditions, and logical gates. Adding this option empowers users to model all kinds of processes. It gives more freedom to create processes as realistically as possible.

DP9: Enable textual descriptions to enrich AR elements. To allow users to deliver comprehensive information, employ mechanisms to create additional textual descriptions for scenes, AR elements, and nodes because, in some cases, simple geometric AR elements are not expressive enough.

Textual information allows users to give specific instructions and contextual information. Geometric AR elements are mainly used to give instructions, but often, they are not expressive enough to be intuitive without text. In AR scenes, participants applied textual instructions frequently to instruct and describe the task that had to be accomplished, e.g., "press power button to turn on coffee machine". Participants liked to add textual information to AR elements to give details about them. Following the previous example, the user would add an AR element to the power button and attach the description "power button" to the AR element. A short scene description would be added in the node editor, e.g., "turn on coffee machine". While the first two provide textual information to the end-user of the AR instruction app, the latter one serves as an orientation for the user of the AR authoring app. During the study, the prototype only allowed adding textual information to AR elements and scene descriptions of certain node types. Participants criticized this and explicitly wished to have the option everywhere.

DP10: Provide a variety of AR elements and style options. To allow users to deliver information in a diverse way, provide a variety of AR elements to choose from and allow individual styling options in terms of color, size, and rotation because the distinction by geometric shapes alone is not expressive enough.

Geometric AR elements are essential for AR authoring apps. They, e.g., aim to highlight specific areas or objects of interest in the real world and guide the way with tethers. In the AR authoring app, they are only distinct by geometrical shape. Styling options like color, size, and rotation of the AR elements are not customizable. Certain AR elements were only available in one node type but not in another. Our results show that participants did not want to be restricted in their selection range of AR elements. They wanted to customize the styling of elements according to their purpose. For example, a larger element could mean that it is more relevant. Color coding could indicate that red AR elements visualize warnings. Additionally, the styling might be influenced by the surroundings. In the study, participants placed a red POI element onto a red surface. Because neither the size nor the color of the AR element was customizable, the AR element was not visible.

DP11: Allow adding, editing, and enriching the scene with photos and videos. To allow users to deliver information in the form of real-world snapshots, employ a mechanism for adding photos and videos and enriching/editing them because photos and videos are a simple option to capture a current state or target state of real-world objects.

Images or videos can depict details about real-world objects' current or target state. During the study, participants could use different ways to add images. They could make a screenshot via the node image button and use it as an attached preview photo. Further, they could attach photos from the tablet's media library to a scene or take a photo directly. Users are required to have the possibility to add annotations and drawings to these images. Further, the AR elements were always visible in the scene. Participants wanted to decide if the AR elements should be shown because they sometimes occluded important real-world objects they wanted to capture. Overall, the photos were always attached to one scene. Participants missed the option to attach photos only to a specific AR element to depict a snapshot of an object's current or target state in the real world. They could not add videos during the study, which would enrich the information.

DP12: Facilitate the spatial perception of AR elements. To support users in the precise positioning of AR elements, employ mechanisms that *(1)* give feedback on surface detection and *(2)* support distance estimation because the placement of AR elements requires a clear idea of the spatial position of the element.

All participants had issues with spatial perception in AR. To position AR elements precisely, the users must understand how the tablet camera perceives the world. A visualization of the surface detection mechanism helps the user to have an idea of the spatial perception of the tablet's camera. For the study, surfaces were overlaid with orange-colored polygons. In this way, participants received feedback about the tablet's surface detection accuracy. Additionally, users can be supported in distance estimation, e.g., using visual cues. One participant mentioned that it was beneficial that objects get larger when they are closer. Without any facilitation, it is challenging for users to estimate depths correctly.

DP13: Support precise positioning of AR elements. To allow users to create spatially accurate AR instructions, employ an interface that enables precise placement of AR elements because the position of AR elements mainly encodes instruction information and is an essential feature of the app.

One of the users' biggest struggles during the study was the precise positioning of AR elements. Participants had to adjust the position of AR elements because the positioning was not working as precisely as expected. Participants mentioned that this frustrated them, and it took them longer to reset the scene or reposition the elements. The positioning was especially challenging when they aimed to place an AR element further away or on transparent or mirrored surfaces. This relates to DP12 because surface detection is unstable for transparent/mirroring surfaces, and distance estimation is challenging.

The positioning interface in the study was a static cursor in the center of the tablet screen. The cursor itself cannot be moved. The user must move the tablet to position objects so the cursor points at the aimed place. Then, the user must tap on the screen to place the AR element. To move the AR element, the user must select it again with the cursor and then press and hold the hand-moving button to reposition it. This interface was neither intuitive nor very precise to control. Participants also had issues selecting small AR elements because they were hard to target. Therefore, the need arises to provide an interface that enables precise positioning. Some participants mentioned that they would prefer to adjust the position by moving AR elements along the x-, y-, or z-axis in 3D space. This could be implemented by giving numeric values or having slides to move the AR elements per axis. Another participant mentioned listing all AR elements in the scene would be helpful. With this list, the selection and manipulation of AR elements might also be possible and more accessible than with the cursor.

DP14: Tracking accuracy is essential. For users to achieve a sense of reliability, employ accurate and reliable tracking mechanisms because with unstable tracking, users will become frustrated, and the usefulness of instructions cannot be guaranteed.

Tracking instability was a major issue during the study. All participants experienced problems in tracking accuracy and reliability. Almost everyone mentioned that they were frustrated that their positioned AR elements suddenly were not in the correct place anymore, making the app unusable. Especially when they finished creating the AR instruction app and started the AR scenario preview, the tracking became unstable. It took a long time to reposition the AR elements again to be satisfied with the outcome. This drastically influenced the usability in a negative way. Participants adapted their behavior if the tracking was unstable. Instead of placing AR arrow elements, they tended to choose circles that highlight a larger area, and therefore, tracking inaccuracy is not that restrictive. Therefore, tracking accuracy is essential for the app to function.

DP15: Implement object tracking. For users to achieve a feeling of blending real and virtual contents, employ mechanisms to track dynamic real-world objects because then AR elements can be attached to moving real-world objects.

The AR authoring app for the study implemented world tracking. This means that the surrounding is tracked, as well as static real objects that stay in the same place. However, dynamic objects that are not always in the same place in the environment are not trackable. In the study, for example, the coffee beans were not placed in a defined place. For this reason, moving the coffee beans would make the tracking invalid. Participants said that they also want to track dynamic objects and that this should be possible as an essential app feature.

16.5 Discussion

In alignment with previous research, our results show that AR authoring tools are not yet fully mature (Hönemann et al., 2022). Our proposed design principles contribute to the understanding and concrete design knowledge of no-code AR authoring tools. The results of our user study reveal that the usability of the AR authoring tool is below average (SUS score of M = 40.4). This is also reflected in the design principles DP5-DP7. Furthermore, tracking problems occurred frequently in the study (DP14), which frustrated the users and could also be an explanation for the low usability score.

The results of the UEQ reveal that the hedonic quality was positively evaluated. Hedonic quality measures non-task-oriented aspects like innovativeness and originality, which are addressed with the AR authoring app. Our results show that users would prefer the AR authoring app over a desktop application. Furthermore, users would prefer the no-code solution over programming and rate the creation of AR instructions with the AR authoring app as faster. This may seem contradictory to the users' statements that users took longer than expected to complete the tasks in the study. However, all study participants estimated the time required for programming to be significantly longer than the average duration during the study. Thus, this is an indication that no-code authoring has the potential to create AR instructions without programming effort and long training periods. This is consistent with the advantages mentioned in previous research (Elshan et al., 2023).

There was no significant difference in workload between the “coffee machine” scenario and the “seminar room” scenario. Thus, we did not find any indication that the app is better suited for one particular scenario. A lower workload and a shorter completion time were observed in the second condition. This suggests that a learning effect occurs over time, as reflected in DP4. The learning time could be shortened with tutorials and help since the users do not start from scratch.

As described in the meta principle Basic Interactions, we encountered several usability issues. For instance, participants criticized the lack of an undo function and transparency about the application’s workflow and current state (DP5). More advanced users wished for shortcuts to work more efficiently (DP7), and in general, users were frustrated by the need to perform repetitive tasks, such as manually connecting nodes (DP6). We noticed a strong overlap with usability heuristics, a concept from interaction design research that describes rules of thumb to ensure good usability. The most popular heuristics are the ten heuristics from Jakob Nielsen (Molich & Nielsen, 1990; Nielsen, 2005). For instance, the heuristic “User control and freedom” proposes that users should always be able to leave an unwanted system state and undo previous actions, which participants of this study also mentioned. The participants’ request to use more efficient ways to spawn multiple AR elements for more experienced users resembles Nielsen’s heuristic “Flexibility and efficiency of use”, which suggests implementing different interactions for users with different experience levels to ensure easy and efficient use. The possibility for users to miss the connection of nodes and, thus, accidentally not create a connected graph should be avoided according to the heuristic “Error prevention”. Furthermore, Nielson also suggests adding “Help and documentation”, which we also derived as a design principle (DP4). Overall, considering this strong overlap of the derived design principles and Nielsen’s usability heuristic, we assume that these heuristics also apply to AR authoring tools and should be considered when designing further applications. For instance, these heuristics can be used to perform a heuristic evaluation, a usability analysis in which 3-5 usability experts analyze an application based on heuristics to search for usability problems systematically (Nielsen & Molich, 1990).

Tracking problems were the most common issue in the study. The prototype does not use a marker to initialize tracking but relies on ARKit’s world tracking feature. Our results show that world tracking, in our case, was too unstable. These inconsistencies frustrated users tremendously and, in the worst case, made the AR instruction unusable. DP14 emphasizes the importance of implementing accurate tracking mechanisms.

The design principles DP9-DP11 focus on the multifaceted enabling of information encoding. This includes both the variety of elements and their design options. This aligns with Nebeling and Speicher (2018) since they also mention that users are missing encompassing and diverse design options in AR authoring tools. These findings suggest that our distinction between exploration and instruction nodes may be obsolete. It is contrary to the users' demand to have multiple options for information encoding. In a further iteration of the prototype, only two node types could be provided: A 2D node – analogous to the info node – and a 3D node that combines the features of the exploration and instruction node. Nevertheless, the business use and the consideration of role concepts could raise the need for more differentiated nodes.

A recent study found that most AR processes are linear (Bräker & Semmann, 2021). Our results nevertheless show that users aim to model more complex processes and need more flexibility in process modeling (DP8). During our study, we observed this need, especially for optional process steps. Thus, further mechanisms for this issue could be explored in the future.

16.6 Conclusion

Within our study, we investigated how to design a no-code AR authoring tool that allows users a lightweight and seamless way to augment processes without requiring any programming skills. We derived design principles that cover a broad range of relevant facets and should guide future design and development of AR authoring tools. We contribute to understanding no-code tools in the context of AR authoring. From a methodological point of view, our study is an example of a mixed-method approach in which quantitative surveys enrich and validate qualitative data. Furthermore, this approach is user-centric and aims to empower users to identify and explore the potential of AR in an accessible and convenient way.

Despite the relatively large size of the sample and the systematic analysis, the study has some limitations. First, a broader and more diverse sample would enhance the validity of the results. Specifically, the perspective of practitioners with little or no programming experience would be interesting. This issue can be overcome with future research that aims for real-world application of the AR authoring tool and, likewise, real-world processes. Second, several issues raised by the participants deal with distinct a priori design decisions in the authoring tool itself. Further refinement and maturation should help in this regard.

Additional research avenues build on the outcome of the participants' treatments. We plan to do another study that evaluates the appropriateness of the process guidance designed in this study. Doing so enables us to understand better if, to what extent, and how AR is beneficial in such scenarios.

16.7 Acknowledgments

This research was partly sponsored by the German Federal Ministry for Education and Research and in the project WizARd under the reference 02K18D181. Further information can be found at: http://www.wizard.tu-dortmund.de/.

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17 Is There More Than Pokémon Go? – Exploring the State of Research on Causal Modeling in the Field of Augmented Reality

Bräker, J., & Semmann, M. (2023a). Is There More Than Pokémon Go? – Exploring the State of Research on Causal Modeling in the Field of Augmented Reality. *Proceedings of the Hawaii International Conference on System Sciences*

Abstract

The paper explores how scholars apply causal modeling to gain an understanding of augmented reality as innovative technology and its potential for application. To do so, we conducted a structured literature review and applied a graph database-driven approach to analyze how scholars research augmented reality. Such an approach enables in-depth analysis of the body of knowledge that is not accessible in traditional ways of exploring literature. The results help to understand where we as a community stand and how directions for future research can help reshape the understanding of augmented reality and its application.

Keywords

Augmented reality, conceptual model, structural equation modeling, SEM, literature review.

17.1 Introduction

The rise of augmented reality (AR) as a technology that bears the potential to impact everyday life is also mirrored in the scientific discourse. We have come far from early prototypes of AR head-mounted displays (HMDs) (Sutherland, 1968) to more recent developments toward mobile AR and AR glasses applied in several use cases. In consumer environments, mobile AR applications such as Pokémon Go have become popular in recent years, leading to research addressing health implications (Laato et al., 2020) or motivations that drive the use of Pokémon Go (Ernst & Ernst, 2015). In organizational contexts, research concentrates, for example, on AR use in technical services (Niemöller et al., 2019), infrastructure services (Osterbrink et al., 2021), logistics (Rauschnabel & Ro, 2016), and healthcare (Klinker et al., 2020a). Other research systematizes interactions within AR (Bräker, Hertel, & Semmann, 2022; Hertel et al., 2021). Conceptualizations that seek to explore a multitude of aspects related to AR, its use and applicability, and niche aspects like privacy (Rauschnabel et al., 2018) can also be found. Such conceptualizations seek to specify real-world phenomena (Weber, 2021) while bridging the gap between theory and measurement of phenomena as it is focal in information systems (Burton-Jones & Lee, 2017). Based on this perspective, we seek to broaden our understanding of how conceptual research on AR is done and if there are directions future research should address. However, until now, there seems to be a lack of AR-specific constructs that help shape its application. Consequently, we answer the following research questions within this paper: *(1) What constructs are applied to model causalities regarding AR? (2) Which theoretical perspectives guide research on AR?*

To answer these research questions, we structure the remainder of the paper as follows: first, we introduce related work by laying out the foundations of augmented reality. Then, we present the methodology based on a structured literature review combined with a graph database-driven approach (Song, Watson, & Zhao, 2021; Song, Watson, Zhao, & Kelley, 2021). We present our results on current research on causal AR models and discuss them in detail afterward. Our results show that research on causal AR models is broad and studied by various communities. However, there is a focus on mobile AR, primarily consumer-oriented applications. Theoretical models of technology acceptance are overrepresented, although they are not the only theoretical lens. The paper concludes with a summary and opportunities for future research.

17.2 Foundations of Augmented Reality

Although research on AR dates back to the 1960s (Sutherland, 1968), the awareness of AR in the consumer environment increased in the last few years. The famous mobile application Pokémon Go, released in 2016, made AR accessible to almost everyone (Chapple, 2022). AR is part of the virtuality continuum (Milgram & Kishino, 1994) that describes different nuances of virtuality – from complete reality with no virtual aspects to complete virtuality in an immersive virtual reality (VR). AR is located between these two extremes, as it augments reality with virtual computer-generated objects. A commonly used definition accents three main characteristics of AR (Azuma, 1997). First, real and virtual objects are combined. This means that reality is still present but extended or overlaid with virtual objects. Second, the user can interact with the AR system in real time. And third, the virtual elements have a registered position in the three-dimensional reality, which makes them feel more like real objects.

The implementation of AR is possible using different hardware approaches (Bimber & Raskar, 2006). First and foremost are HMDs or AR glasses. AR glasses allow the user to either look through a transparent display (optical see-through) that blends holograms to reality or enrich video-generated images streamed on the glasses (video see-through). Because AR glasses such as the Microsoft HoloLens 2 are still quite expensive and rare, a more inexpensive and accessible way is mobile AR. Hand-held displays like smartphones or tablets can use the integrated camera to capture reality and overlay it with virtual objects. An example of mobile AR is the mobile game Pokémon Go. Apart from head-attached or hand-held devices, AR can be implemented with projectors, called spatial or projection-based AR. This way, virtual content can be directly projected onto real objects.

17.3 Methodology

In the following, we present the paper's methodology, which consists of three steps (see Figure 47). We began with a systematic literature review (vom Brocke et al., 2009; Webster & Watson, 2002). Subsequently, we followed the causal model analysis approach to literature reviewing by Song, Watson, Zhao, and Kelley (2021), coding relevant publications using Cypher language and performing query-based knowledge extraction and synthesis in Neo4j (neo4j.com).

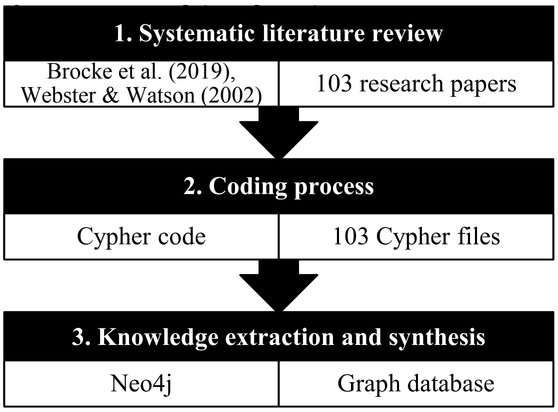

Figure 47. Research process

17.3.1 Literature Review

To assess the current state of research, we conducted a structured literature review following Webster and Watson (2002) and vom Brocke et al. (2009). We were interested in papers focusing on AR technologies and involving structural equation modeling (SEM) or causal modeling. Our query for the keyword search combines these two domains: *("causal model*" OR SEM OR "structural equation model*") AND ("augmented reality" OR "smart glass*").* Because we wanted to paint the big picture, we did not limit our search and searched within full text. We did not set time restrictions or publication filters. When possible, we filtered for peer-reviewed articles in English. We searched the databases ACM Digital Library (ACM DL), (2) AIS Electronic Library (AISeL), (3) EBSCO Business Source Complete (EBSCO), (4) IEEEXplore, (5) ProQuest ABI/INFORM (ProQuest), (6) ScienceDirect (SD), and (7) ScholarSpace (SchS). The tool Litsonar (litsonar.com) helped generate the database queries.

Table 39. Literature review

Database	**Initial results**	**1st round**	**2nd round**	**3rd round/ relevant**
ACM DL	181	7	7	1
AISeL	83	35	19	10
IEEEXplore	9	8	7	3
ProQuest	44	29	25	22
SD	786	184	79	47
SchS	24	2	0	0
Total	**1149**	**286**	**157**	**103**

The results of the literature review are shown in Table 39. Our search query initially yielded 1149 papers. We scanned the literature with two independent researchers, and in the first round, we made sure that AR was addressed in the paper and that an SEM or causal model was included. After the first round, 286 papers were potentially interesting for further processing. In the second round, we looked more closely at these 286 papers and sorted out any publications that used AR only as an example in the introduction or discussion but had no relevance to the SEM or causal model. Thus, after the second round, we had 157 papers that contained an SEM or causal model with an AR reference. In a third round, we read the papers in detail and kept only papers whose models had a direct AR focus. We sorted out papers in which AR was only a part of the model or if the results were just applicable to AR. In doing so, we ended up with 103 relevant papers for the further research process.

17.3.2 Coding Process

The second step in our research design is coding relevant literature from the literature review. Following the argumentation of Song, Watson, Zhao, and Kelley (2021), the existing knowledge is fragmented and difficult to synthesize and analyze manually. The causal model analysis approach provides a guideline for this by coding the core knowledge of the articles in the form of a graph and storing it in a database. This simplifies knowledge analysis and synthesis using database queries and allows for a more focused representation of data, which makes this approach an advantage over previous approaches to literature review.

The database represents a paper as a graph with nodes (circles) and relationships (arrows) between these nodes. We slightly adapted the original approach to our needs and added two new constructs – technology and topic – in addition to the constructs publication, element, theory, and author, as proposed in the original approach (see Figure 48). We defined a node type for each of the six constructs and further specified seven distinct types of relationships. In Cypher language, the node types are specified as labels. Each publication node can relate to one or more author, theory, topic, technology, or element nodes. For simplicity, we omit the proposed definition node as we do not consider it relevant to the big picture. We do not implement the model node because we assume that each publication has only one relevant SEM or causal model. If a publication describes more than one model, we refer to the final or revised model with only significant hypotheses. Consequently, the relationships in our graph differ from the original framework. Since we eliminated the model node, the elements are directly depicted by the publication nodes, and the publication applies a theory. The nodes and relationships can have different attributes, e.g., within each publication node, the Digital Object Identifier (DOI), citation, and a universally unique identifier (UUID) are stored.

The Codasaurus tool (https://t-rex-graph.org) developed by Song, Watson, Zhao, and Kelley (2021) assists researchers in the coding process. Codasaurus is an R application with a graphical user interface that automatically generates Cypher code files for a graph. Using Codasaurus, we generated a Cypher code template that we customized as described above and created a Cypher code file for each of the 103 publications by inserting the information into the template. We normalized some inputs by aligning author names (e.g., different abbreviations of middle names), theory names, and element names – e.g., matching plural and singular if it did not change the meaning. These Cypher code files can be imported to Neo4j, which is a graph database, in the next step.

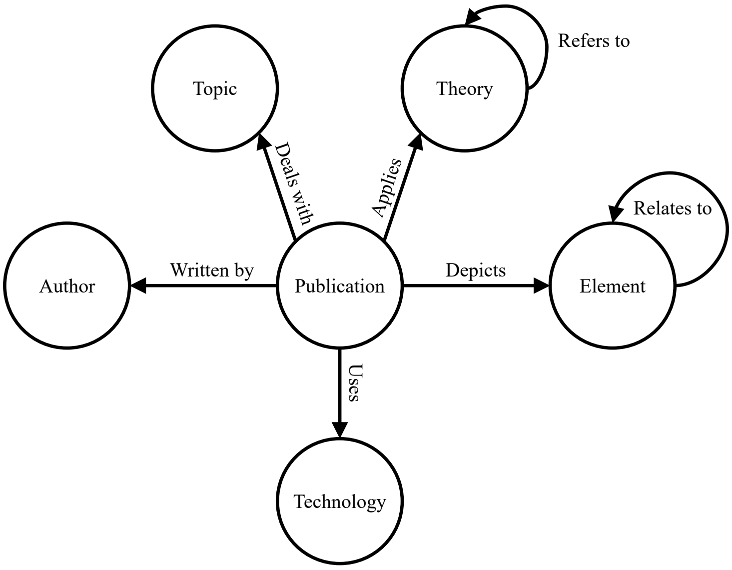

Figure 48. Nodes and relationships (adapted from Song, Watson, Zhao, and Kelley, 2021)

17.3.3 Knowledge Extraction and Synthesis

Song, Watson, Zhao, and Kelley (2021) recommend using the graph database tool Neo4j for knowledge synthesis. In Neo4j, graphs coded as Cypher files can be visualized, and networks of multiple graphs can be created. Knowledge can then be extracted and synthesized using queries, such as known from relational databases.

Knowledge extraction includes, for example, the extraction of node or relationship frequencies in a graph. Knowledge synthesis encompasses merging multiple graphs or calculations within a network of graphs to gain a deeper understanding of the coherences between publications. The results from the knowledge extraction and synthesis are presented in the following.

Table 40. Labels and number of nodes

Label	Number of nodes
Publication	103
Author	269
Element	450
Technology	6
Theory	56
Topic	20
Nodes total	904
Relationships total	2299

17.4 Result

After coding and importing the publications to Neo4j, the graph database contains 103 publication nodes, 269 different author nodes, 450 element nodes, six AR technology type nodes, 56 theory nodes, and 20 topic nodes. In sum, there are 904 nodes with 2299 relationships (see Table 40). Each paper is visualized as exemplarily shown in Figure 49. The blue node in the center represents the publication by Harborth and Pape (2017), with the citation as the display name. The publication node also holds the DOI and a UUID as attributes. Although the DOI is unique, we added a UUID because not all publications have a DOI. The author nodes are visualized in light green, and the WRITTEN_BY relationship holds the authors' order. In this case, the USED_TECHNOLOGY (orange node) is mobile AR, and the publication DEALS_WITH Pokémon Go (red node). The publication APPLIES UTAUT2 as a theory (dark green node), which is partly reflected in the SEM elements. The publication DEPICTS the elements (pink nodes) of the model, which can relate to each other. The RELATES_TO relationship between elements can store a description of the relationship and the hypothesis to which it belongs.

Figure 49. Example graph visualization of a publication (Harborth & Pape, 2017)

17.4.1 Elements

The element nodes represent the actual SEM or causal model. They are central to knowledge extraction and synthesis. Of the 103 publications, the most commonly used element and "hidden champion" among them is Perceived Usefulness, which is, e.g., used in the Technology Acceptance Model (TAM) (Davis, 1989). The same applies to Perceived Ease of Use, Attitude, and Behavioral Intention, indicating the relevance of TAM and acceptance models. Table 41 shows the ten most used elements in terms of the number of publications in which the element is used.

To analyze the elements of the graph network in more detail, following Song, Watson, Zhao, and Kelley (2021), we calculate outdegree centrality, indegree centrality, and betweenness centrality, which provide information about the influence and importance of certain elements. The outdegree centrality counts the number of outgoing relations of a node, i.e., how many other nodes are influenced by it. If the outdegree centrality of a node is high, it means that it has a significant impact on other nodes and is a fundamental antecedent in models.

Table 41. Top ten elements and the number of publications that contain the element

Element	**Number of publications**
Perceived Usefulness	26
Perceived Ease of Use	24
Attitude	14
Perceived Enjoyment	13
Behavioral Intention	12
Flow	10
Enjoyment	10
Satisfaction	9
Purchase Intention	8
Intention to Use	8

The outdegree centrality of the elements with more than ten outgoing relations is shown in Table 42. *Perceived Ease of Use* and *Perceived Usefulness* are antecedents for 34 and 33 other nodes, respectively, indicating that they have a high impact on the graph network. This is consistent with our findings that *Perceived Ease of Use* and *Perceived Usefulness* are the elements used by most publications, and TAM – to which they belong – is the most used theory. Taking a closer look at the TAM, these two elements tend to be at the beginning, i.e., on the left-hand side of the model, which underlines our results. Moreover, *Flow* as part of Flow Theory (Csikszentmihalyi & LeFevre, 1989; Montgomery et al., 2004) is an essential and influential element for other nodes. *Anthropomorphism* is also noteworthy because it is only used in three publications but is one of the most predictive elements with twelve outgoing relations.

Indegree centrality describes how many ingoing relations a node has, i.e., whether the node is a frequent outcome element (Song, Watson, Zhao, & Kelley, 2021). Table 43 shows the most influential outcome elements with more than 16 ingoing relations. *Behavioral Intention* is the element with the highest indegree centrality with 52 ingoing relations. This is consistent with the TAM, as the behavioral intention stands on the model's right side as an outcome. The *Intention to Use*, for example, is an outcome of a model because the indegree centrality (18 incoming relations) is higher than the outdegree centrality (3 outgoing relations).

Betweenness centrality describes the degree to which a node stands between two other nodes in the graph. A high betweenness centrality, therefore, means that the

Table 42. Element outdegree centrality

Element	Outdegree centrality
Perceived Ease of Use	34
Perceived Usefulness	33
Perceived Enjoyment	19
Interactivity	16
Attitude	15
Flow	14
Anthropomorphism	12
Enjoyment	11
Satisfaction	11

Table 43. Element indegree centrality

Element	Indegree centrality
Behavioral Intention	52
Perceived Usefulness	39
Attitude	34
Flow	24
Satisfaction	24
Perceived Ease of Use	22
Attitude Towards Using	18
Intention to Use	18
Enjoyment	18

node is highly influential because it explains the flow of causality (Song, Watson, Zhao, & Kelley, 2021). The ten elements with the highest betweenness centrality are listed in Table 44. In our case, *Perceived Usefulness* and *Flow* achieve the highest value with a betweenness centrality of over 5000.

After focusing on the most used and influential elements, the question arises if there are unique elements that are only used in one research model. Our results show that 97 elements are used by more than one publication. Conversely, 353 elements are only used by one single publication and research model.

17.4.2 Technologies

The technologies used in the publications match the AR technologies described in the related work section. It is noticeable that mobile AR is by far the most used technology, with 70 publications (see Table 45). The second most publications do

Table 44. Element betweenness centrality (rounded to whole numbers)

Element	Betweenness centrality
Perceived Usefulness	5341
Flow	5203
Achievement	4727
Attitude	3930
Satisfaction	3385
Intention to Use	3241
Enjoyment	2974
Trust	2087
Perceived Value	1790
Gender	1785

not specify the technology and describe independent concepts such as touchless interaction performance independent from hardware (Habibi & Chattopadhyay, 2021). AR glasses are only mentioned in eight out of 103 publications, followed by desktop AR and projection-based AR. One publication thematizes a comparison of different technologies.

Table 45. Technologies and the number of publications that contain the technology

Technology	Number of publications
Mobile AR	70
Not specified	15
AR Glasses	8
Desktop AR	7
Projection-Based AR	2
Comparison	1

17.4.3 Theories

Regarding theories, there are a few outstanding ones that are used in multiple publications. Table 46 shows the theories that are used in at least three publications. The most popular is the TAM (Davis, 1989), with 29 publications applying it. With distance behind is the Stimulus-Organism-Response (S-O-R) Theory (Bitner, 1992; Jacoby, 2002) being used by eleven publications. The Uses and Gratifications Theory (UGT) (Sheldon, 2008), as well as Flow Theory (Csikszentmihalyi & LeFevre, 1989; Montgomery et al., 2004), are each used eight times. The acceptance theories Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003) and the further developed Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) (Venkatesh et al., 2012) are used four times. This again speaks for the high relevance of technology acceptance in AR-related SEMs. Further, the Experience Economy Theory (Pine & Gilmore, 2013) and the Cue Utilization Theory (Olson & Jacoby, 1972; Richardson et al., 1994) are used in three publications.

Table 46. Theories and the number of publications that contain the theory

Theory	Number of publications
TAM	29
S-O-R Theory	11
UGT	8
Flow Theory	8
UTAUT	4
UTAUT2	4
Experience Economy Theory	3
Cue Utilization Theory	3

17.4.4 Topics

In sum, nine topics are used in at least two publications. The most popular topics are shopping or retail thematic publications, with 43 publications (see Table 47). Pokémon Go is the use case for 18 publications, followed by education and training cases. Only three publications consider gaming aside from Pokémon Go. Privacy and health care are each subject of two papers, and two publications deal with AR content visualization in general.

Table 47. Topics and the number of publications that contain the topic

Topic	Number of publications
Shopping/ Retail	43
Pokémon Go	18
Tourism	11
Education	8
Training	4
Gaming	3
Privacy	2
AR content	2
Health care	2

17.4.5 Authors

Out of 269 authors, only a few wrote more than two publications. This shows that the field of SEMs and causal modeling regarding AR is wide-ranging and diverse authors contribute to it. Only one author (Philipp A. Rauschnabel) is part of six publications (Hinsch et al., 2020; Rauschnabel et al., 2015; Rauschnabel et al., 2019; Rauschnabel et al., 2018; Rauschnabel et al., 2017; tom Dieck, Jung, & Rauschnabel, 2018). In four publications, David Harborth cooperated with Sebastian Pape (Harborth & Pape, 2017, 2019, 2020, 2021). Tseng-Lung Huang published three papers (T.-L. Huang, 2019, 2021; T.-L. Huang & Liu, 2021) and 21 authors have two publications. The remaining 244 authors are only related to one publication.

17.4.6 Synthesis of Technologies, Theories, and Topics

When taking a closer look at technologies, it is interesting to understand which theories apply in the context of which technologies. Table 48 shows the theories that are at least used in three publications in combination with the technology used. We eliminated the papers that did not specify a technology or use multiple technologies in comparison for simplification reasons because they are not relevant here. Mobile AR is used in all the theories, which underlines the importance and diffusion of mobile AR technologies. Publications regarding AR glasses apply acceptance theories such as TAM or UTAUT, in addition to S-O-R Theory and UGT. Desktop AR is combined with the UTAUT2 and the Cue Utilization Theory. Projection-based AR is not used in combination with one of the most common theories.

We did the same analysis regarding AR technologies, but in combination with topics that are at least used in two publications (see Table 48). Shopping and retail are prevalent topics, used in combination with all technology types. Because Pokémon Go is a mobile application, publications only consider mobile AR in publications. Tourism, training, and gaming are likewise only used in combination with mobile AR. Education settings use mobile AR and desktop AR, which might be explainable by hardware accessibility. Privacy and health care are both relevant for mobile AR and AR glasses.

Table 48. Applied theories and topics itemized by technology

		Mobile AR	AR glasses	Desktop AR	Projection-based AR
Theory	TAM	x	x	-	-
	S-O-R Theory	x	x	-	-
	UGT	x	x	-	-
	Flow Theory	x	-	-	-
	UTAUT	x	x	-	-
	UTAUT2	x	-	x	-
	Experience Economy Theory	x	-	-	-
	Cue Utilization Theory	x	-	x	-
Topic	Shopping/ Retail	x	x	x	x
	Pokémon Go	x	-	-	-
	Tourism	x	-	-	-
	Education	x	-	x	-
	Training	x	-	-	-
	Gaming	x	-	-	-
	Privacy	x	x	-	-
	AR content	-	-	-	-
	Health care	x	x	-	-

17.4.7 AR Glasses-Specific Analysis

The results indicate that the use of AR glasses in publications containing SEMs or causal models is sparse, although they are one of the first associated technologies when considering AR. This fact justifies a closer look into publications concerning AR glasses. Overall, we found eight publications. Figure 50 visualizes all publications, elements, theories, and topics related to AR glasses technology. In sum, 50 elements are used regarding AR glasses (see pink nodes in Figure 50). In the center of the graph is a dense cluster of elements having many relationships and interdependencies. Nonetheless, only the element Perceived Usefulness is used in two publications, and all the other elements are used once.

Eight theories are applied to publications (see dark green nodes in Figure 50). Table 49 lists the theories in combination with the publication in which they are used.

As described in the last section, acceptance theories, S-O-R, and UGT are applied. The theories Big Five Theory of Human Personality, TOE Framework, ESP, and Media Richness Theory are each used by one publication. Topics are visualized as red nodes in Figure 50. In sum, six different topics are addressed in the publications (see Table 50). The topics, except for the popular ones described above, Assembly, Hardware, and Industry, are each subject to one publication.

Table 49. Theories used in publications using AR glasses as technology

Theory	Publication
TAM	(Dehghani et al., 2020; Holdack et al., 2020; Schuster et al., 2021)
UTAUT	(Dehghani et al., 2020; Schuster et al., 2021)
UGT	(Dehghani et al., 2020; Rauschnabel et al., 2018)
Big Five Theory of Human Personality	(Rauschnabel et al., 2015)
TOE Framework	(Masood & Egger, 2019)
ESP	(Dehghani et al., 2020)
Media Richness Theory	(de Amorim et al., 2022)
S-O-R Theory	(de Amorim et al., 2022)

17.5 Discussion

Our analysis shows that the most used elements and the elements with the highest outgoing centrality come from TAM, i.e., it is the most influential theory with the most influential element nodes. This is consistent because TAM is the most used theory in our database. Consequently, TAM is overrepresented in causal AR models. However, papers applying TAM mainly refer to the acceptance of a specific use case or AR application, and there is no overarching model explaining the acceptance of AR. The results show that there is a large number of once-used elements. This could be due to the inconsistent naming of elements between different publications. Although we normalized naming to a certain degree, it was not everywhere possible.

Some very specified publications with niche use cases may propose customized naming of the elements, which could be one explanation for many unique elements. Surprisingly, the Gender element is in the top ten of betweenness centrality. One explanation could be that gender often functions as a moderator in causal models, and – as suggested by Song, Watson, Zhao, and Kelley (2021) – we coded moderators as a triangular relationship between two elements.

Table 50. Topics used in publications using AR glasses as technology

Topic	**Publication**
Shopping/ Retail	(de Amorim et al., 2022; Dehghani et al., 2020; Holdack et al., 2020)
Assembly	(Schuster et al., 2021)
Hardware	(Rauschnabel et al., 2015)
Health Care	(Klinker et al., 2020b)
Industry	(Masood & Egger, 2019)
Privacy	(Rauschnabel et al., 2018)

Mobile AR is the leading technology in our graph database. One explanation could be that it is the easiest to assess because the hardware is available and reasonably priced. Because the main topics, shopping, retail, and Pokémon Go, are mostly consumer applications, it underlines the argument regarding available and affordable hardware. The analysis shows that the constructs applied are not AR-specific but rather general. Additionally, the conceptual models mainly utilized, namely TAM and UTAUT, have been developed in an era prior to the recent possibilities of IS, especially AR. Thus, a thorough assessment of the timeliness of these constructs, as suggested by (Compeau et al., 2022), could help develop a common set of constructs that can be applied to AR in general and not specific representations such as mobile AR.

The breadth of authors and corresponding backgrounds can be seen as a cause for the diverse use of theories. Different experiences and prior training could be the origin of such heterogeneity.

Although Pokémon Go is the second most popular topic, the analysis shows that there definitely is more than Pokémon Go. The topic varies immensely from shopping

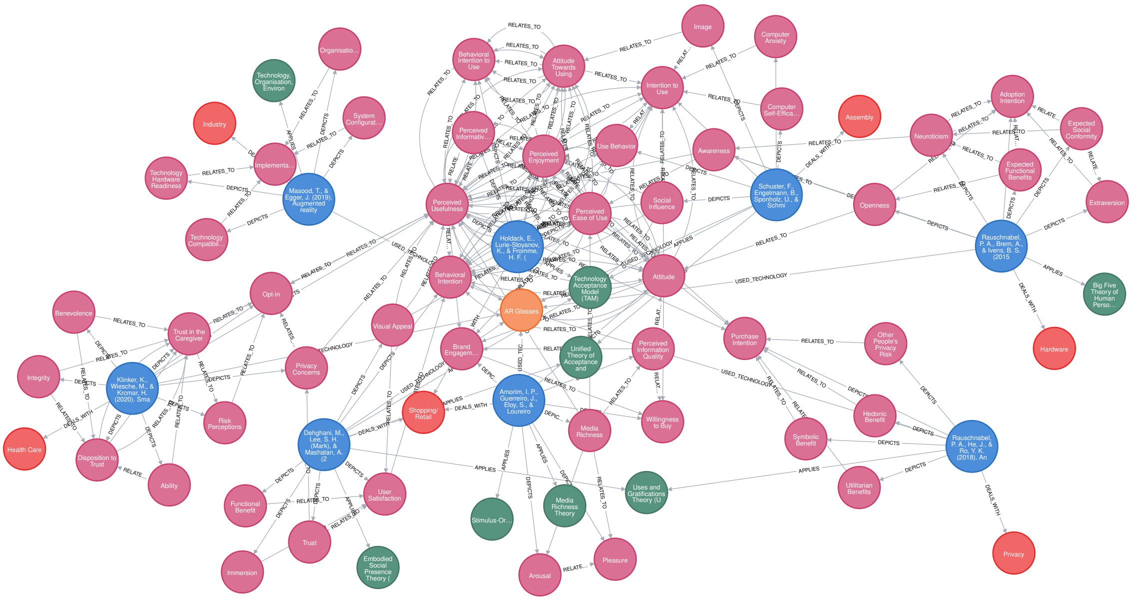

Figure 50. Overview of all nodes related to AR glasses

and consumer studies to the health care and manufacturing industry. However, most publications deal with shopping, retail, or the AR game Pokémon Go. This could be explained by the use of AR technologies because mobile AR is the most used technology, and most retail papers use mobile AR, and Pokémon Go obviously is restricted to mobile AR. The fact that privacy is the topic of papers dealing with mobile AR and AR glasses is particularly interesting because AR glasses suddenly need new privacy requirements (Rauschnabel et al., 2018). Healthcare-related publications also use mobile AR and AR glasses, which can be explained by the fact that AR glasses bear great potential for hands-free working (Klinker et al., 2020b).

By doing the analysis, it becomes apparent that the field of research on AR is relatively immature and explorative in its nature. There are no established measures and underlying theories that build the core foundation of SEM or causal modeling regarding AR. This could be the case as there is a lack of specific theories on AR and its adoption, or the rather generally established theories are deemed appropriate and interchangeable. Thus, following Compeau et al. (2022), assessing the elements regarding their appropriateness to represent recent information system use could be beneficial for further research on AR.

From a methodical perspective, the approach to analyzing SEMs or causal models using a graph database is highly supportive. It provides better structuring and easier information extraction and synthesis by querying. The Codasaurus tool (Song, Watson, Zhao, & Kelley, 2021) aims to simplify the coding process to make the approach accessible without learning Cypher coding. Our research has shown that the core idea of Codasaurus is beneficial, but customization is still needed depending on the context. In this regard, a more flexible approach would be valuable.

17.6 Conclusion and Outlook

The rise of AR as a technology that impacts professional and consumer electronics while changing human interaction with information systems is mirrored in research. We analyzed the body of knowledge on conceptual modeling as an avenue to understand the application of AR. Within this corpus, we identified 103 relevant papers that cover a wide range of disciplines, topics, and theoretical approaches. In answering the first research question, we provided a comprehensive overview of which constructs are used to explain causalities related to AR. The results show that most research is done in the domain of mobile AR. As this representation of AR is the most common and widely available, rather pragmatic reasons could lead to this emphasis. Likewise, the topics addressed are driven mainly by consumer electronics, like retail, gaming, and tourism. This could be interpreted as lacking business applications and use cases. Following the second research question, we also explored the theoretical perspectives guiding AR research. The results show that it is worthwhile to further deep dive into the heterogeneity of underlying theories. Based on these findings, future research has manifold avenues to contribute to understanding AR's application and utility. Especially professional, business-oriented research is missing. Nevertheless, with improving HMDs, changes in application and acceptance are interesting. Furthermore, a thorough comparison and synthesis of conceptual models could help strengthen the results and identify potential extensions that would help understand AR in practice. The methodological approach also bears potential for future research. This might include integrating articles that do not use dedicated causal models or include virtual and mixed reality to analyze commonalities and differences.

17.7 Acknowledgments

This research was partly sponsored by the German Federal Ministry for Education and Research in the project WizARd under the reference 02K18D181. Further information can be found at: https://wizard.tu-dortmund.de/.

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