A Workflow Management System Front End Designed for Augmented Reality Headsets

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Summary

In recent years, augmented reality (AR) technology has become widely researched and applied for almost all domains, e.g., healthcare, logistics, or manufacturing [1–4]. AR combines real and synthetic information interactively and in real-time within a real environment. Synthetic objects react to and align with the real environment, thus creating an immersive experience while preserving the user's ability to see and navigate the environment. This contrasts AR with virtual reality, which offers full immersion [5]. So-called AR systems (ARS) implement AR in information systems (IS) to create an AR experience for users and can utilize a wide range of wearables, headsets, handhelds, or stationary systems (e.g., [4, 6–8]). While AR, in the narrow sense, is just an information output principle and could, therefore, address all human senses, contemporary research and product development focuses on visual and acoustic output (cf. [9]). Multiple commercial products are available today, with more in development, e.g., the Microsoft HoloLens 2 [10] or the Varjo-XR-3 [11]. These modern headset-based ARSs feature rich sensors to track their environment and own position within, e.g., high-resolution cameras, microphones, GPS, accelerometers, gyroscopes, and magnetometers (e.g., [10, 11], cf. [9]). Leveraging these sensors, modern headset-based ARSs offer context-aware capabilities, e.g., recognizing predefined "image targets" or anchoring synthetic contents to real objects, which stay put when the ARS is moving. This makes modern headset-based ARSs interesting for the field of business process management, especially workflow execution support.

The context-aware provision of information during workflow execution, i.e., providing the right information at the right time and in the right place, is a well-known challenge for organizations [12]. Well-known tools to support the provision of information during workflow execution and the collaboration, coordination, and communication between workflow participants within organizations are workflow management systems (WFMS) [13]. Modern implementations of WFMS have evolved much from older understandings as "organizationally aware groupware" [14]. Still, the well-known definition by the Workflow Management Coalition (1995) [15] of a WFMS as a system that defines, interprets, instantiates, and manages the execution of workflows with software, integrates external applications and interacts with human workflow participants still applies (cf. [16]). In the scope of this dissertation, workflows are defined as the subset of business processes that are actually executable by workflow participants. Workflows are composed of workflow events and workflow tasks linked with control flows. Some workflow tasks are intended for human execution, so-called user tasks [15].

Based on their characteristics, the combination of AR and WFMS technology seems promising to address the everlasting challenge of organizations to optimize information provision during workflow execution. Headset-based ARS could use their sensors to gather relevant context information from the environment, which could then be processed by a WFMS to steer the path of workflows. Instructions and supplementary and general information about a workflow or task could be presented within the ARS headset but also be enriched with synthetic content, e.g., 3D objects, to support the user during workflow execution with AR.

Inspired by this grand vision for the intersection of AR, workflows, and WFMS, a wide range of ARSs has already been proposed, researched, and developed in recent years, addressing some individual aspects of this vision (cf. [9]). Although a large empirical base has not yet been established and clearly not all types of workflows are well-suited for AR support, increased task efficiency, i.e., reduction of error rates, execution times, cognitive loads, or required training, has already been observed in the domains of collaborative planning, assembly, service, maintenance, warehouse picking, process training, and process modeling (e.g., [4, 17–22]). Based on these findings and the technical characteristics of AR and WFMS, it seems plausible that "hands-on" workflows are generally well-suited for AR support, while document-oriented administrative workflows are less suitable.

During workflow task execution, modern headset-based ARSs can support users in manifold ways, e.g., by providing task descriptions and instructions with text and images, visually highlighting important objects, marking spots for tool placement, or demonstrating handles (e.g., [6, 23, 24]). Besides supporting the execution of workflow tasks in a narrow sense, headset-based ARSs are also utilized to enable workflow control and management. However, the currently supported functions are very limited

and are provided in isolation, e.g., advancing backward and forward through a workflow's tasks or switching to a task of a different workflow (e.g., [6, 23, 24]). This is the case for ARSs in the scientific literature as well as commercial products, e.g., Microsoft's Dynamics 365 Guides [25], optimized for Microsoft's HoloLens AR headset.

This limited range of functions contrasts with the rich workflow management and control functions of modern WFMSs (e.g., Camunda [26] or SAP Signavio [27]), which are in line with the well-known reference architecture for WFMSs by the Workflow Management Coalition [15], e.g., instantiating, pausing and canceling workflow instances, generating filtered lists or inspecting workflow instance variables [15, 26]. Indeed, the contemporary landscape of ARSs in support of workflows presents itself as heavily use case-driven, with ARSs being developed and "hard-coded" for specific use cases. In contrast, the workflows in modern WFMSs are decidedly not hard-coded but the result of the WFMS interpreting formal workflow models. These visual models can then be quickly adapted to change an organization's workflow.

In the state of the art, therefore, opportunity costs arise for organizations in those business scenarios in which workflow participants are both executing AR-supported workflows with ARSs and need to use workflow management and control functions. These opportunity costs are the results of the workflow inefficiencies incurred due to the general inability of contemporary ARSs to offer WFMS front end capabilities, i.e., comprehensive workflow management and control functionalities [15], which consequently requires workflow participants to use additional devices, e.g., PCs, notebooks, tablets or smartphones. This creates media breaks and takes time, e.g., for taking out a tablet, logging in, etc. Also, in general, carrying additional devices does not tend to increase user satisfaction. Additionally, the capability of modern ARSs to track and recognize hand gestures (e.g., Microsoft HoloLens [10]) enables workflow participants to use an AR UI with dirty hands or gloves, while usage of other devices might be impossible. Especially small devices like tablets or smartphones, which would be easiest to carry and switch to, are difficult to operate with dirty hands or gloves.

The unresolved ***fourfold challenge*** in these business scenarios is, therefore, *to provide workflow participants with 1) a headset-based ARS that 2) enables AR-based workflow execution support and the associated efficiency gains, as well as 3) comprehensive workflow management and control capabilities, while 4) ensuring usability*.

An ARS that meets this fourfold challenge is henceforth termed **HoloWFM**, leaning on the aesthetic quality of the UI, enabling *holographic workflow management* for the name.

The existing research points to an obvious answer to the fourfold challenge outlined above: providing comprehensive workflow management and control functionalities in the same ARS that also provides AR task support. However, while the apparent theoretical potential and business scenario challenges have attracted interest within the IS research community and commercial IT industry to integrate AR and WFMSs, resulting in numerous research projects and commercial products (e.g., [6, 10, 11, 23–25]), hitherto no commercialized or conceptualized headset-based ARS addresses the fourfold challenge outlined above. In this dissertation, extensive literature reviews (see Chapters 3 and 4) demonstrate that commercialized and conceptualized headset-based ARSs in the literature can only offer general orientation, but useful, formalized, and directly applicable knowledge is not available for IS designers, IS architects, and IS developers to support the design, development, and instantiation of this novel type of headset-based ARS that addresses the fourfold challenge defined above. This gap in the IS knowledge base is the research gap addressed by this dissertation.

Therefore, the goal of this dissertation is as follows:

Goal: To develop and ensure the usefulness of artifacts that support IS researchers, IS designers, and IS developers during the design, development, and instantiation of HoloWFMs, i.e., headset-based ARSs that enable AR-based workflow execution support for workflow participants, provide comprehensive workflow management and control capabilities and ensure usability.

To methodically design these artifacts, this dissertation utilizes a multi-cyclical design science research (DSR) approach based on the method by Vaishnavi and Kuechler [28, 29]. In three design cycles, the three main contributions of this dissertation are designed, developed, and evaluated: a taxonomy, a design theory, and a reference architecture.

In the **first design cycle**, a taxonomy of contemporary ARSs supporting workflow execution is developed to address the lack of a well-formulated vocabulary of important characteristics of such systems. Based on an extensive literature review to identify real ARSs, a taxonomy with 14 dimensions and 83 characteristics is produced and positively evaluated. The categorization of real ARSs during the development of the taxonomy is then used as a basis for cluster analysis, developing three archetypes of ARSs supporting workflow execution that summarize the state of the art.

The developed taxonomy provides a novel analytical lens for existing ARSs, focusing on support for workflow execution, in contrast to related taxonomies and frameworks [30–35]. It can be used – inter alia – to better understand the ARS domain, classify existing ARSs, and design new ARSs. E.g., three research projects originated from this dissertation’s taxonomy, revolving around three novel ARSs (projects ALIS, DITIP, and ARWINA, see Chapter 6).

In the **second design cycle**, a design theory was developed to define the design requirements of a HoloWFM and design principles to address these in general. Based on two moderated focus groups, a design theory consisting of four design requirements and nine design principles, as well as a user interface design, were developed and positively evaluated. The taxonomy developed prior is then used to characterize the designed HoloWFM artifact. As HoloWFM extends the state of the art, the taxonomy is extended as well to incorporate its feature spectrum.

The design theory’s design requirements and design principles were gathered empirically with the moderated focus groups and thus indicated current sentiments, phenomena, and state of practice. More importantly, the design theory provides a high-level blueprint to guide the design and development of a HoloWFM by offering rather abstract design requirements and design principles. It also provides more actionable guidance on a lower level of abstraction with the formulated design features.

In the **third design cycle**, a reference architecture is systematically derived from the design theory. To that end, a total of nine design features are developed that represent one possible implementation-oriented specification of the design principles. These design features are then operationalized in five diagrams in the notation of the Unified Modeling Language (UML), formalizing HoloWFM use cases, component structures, and sequence flows between components and software classes. These are finally documented according to the standard for reference architecture descriptions ISO 42010 [36]. The developed reference architecture is then positively evaluated via instantiation as a prototype and an expert survey.

The reference architecture description demonstrates how a design theory and UML diagrams can be linked systematically and how ISO 42010:2011 can be operationalized to document the developed design knowledge. This had not been previously demonstrated in the DSR literature. Therefore, the reference architecture description contributes a novel methodology to the IS community. Further, the UML diagrams add to the prescriptive knowledge base by providing tangible design knowledge. In line with the well-known benefits of reference architectures (cf. Chapter 2.4), researchers and practitioners can more easily implement a HoloWFM or similar IS. As many studies use prototype implementations to test certain functions or scenarios, this dissertation could provide tangible benefits to other researchers. Also, the reference architecture can be expanded to incorporate new stakeholder requirements and new technologies, thus serving as a basis for future research endeavors.

Judging by a total of twelve positive **evaluation** events throughout the research project, the goal of this dissertation has been fulfilled. Three novel artifacts have been developed, which are useful for IS designers, IS architects, and IS developers when designing, developing, or instantiating a HoloWFM. One application of these artifacts will be the project ARWINA (see Chapter 6), which continues this dissertation's initial motivation to integrate AR and WFMS to support workflow execution and aims at extending this dissertation's results with a novel approach to managing workflow knowledge.

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List of Abbreviations

AR .... Augmented Reality

ARWINA .... Augmented Reality, Workflow and Knowledge Integration for an Innovative Object-oriented Process Guidance at Industrial Plants

API .... Application Programming Interface

ARS .... Augmented Reality System

BPMN .... Business Process Model and Notation

CAD .... Computer-aided Design

CM .... Context-aware Mode

CON .... Conciseness

DF .... Design Feature

DP .... Design Principle

DR .... Design Requirement

DSR .... Design Science Research

DT .... Design Theory

ECIS .... European Conference on Information Systems

EE .... Effort Expectancy

EPC .... Event-driven Process Chain

EXP .... Explanatory Power

EXT .... Extendibility

FEDS .... Framework for Evaluation in Design Science Research

HMD .... Handbuch der maschinellen Datenverarbeitung (Manual of Machine Data Processing)

HUD .... Heads-up Display

IDM .... Instructional Design Method

IEC .... International Electrotechnical Commission

IEEE .... Institute of Electrical and Electronics Engineers

IS .... Information System

ISO .... International Standard Organization

MFG .... Moderated Focus Group

MM .... Main Menu

OEC .... Objective Ending Condition

PAM ....Partitioning Around Medoids

PE ....Performance Expectancy

QM ....Quick-access Menu

QR...............Quick Response

RA ....Reference Architecture

RAD ....Reference Architecture Description

REST...........Representational State Transfer

RMFG ....Reconvened Moderated Focus Group

RQ...............Research Question

SEC ....Subjective Ending Condition

SI ....Scale Item

TAM ....Technology Acceptance Model

UI ....User Interface

UML............Unified Modeling Language

UPGMA.......Unweighted Pair-group Method Using Arithmetic Averages

UPGMC ......Unweighted Pair-group Method Using Centroids

UX ....User Experience

WFMS.........Workflow Management System

WPGMA......Weighted Pair-group Method Using Arithmetic Averages

WPGMC......Unweighted Pair-group Method Using Centroids

WSS ....Within-cluster Sum of Squares

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1 Motivation and Research Gap

In recent years, augmented reality (AR) technology has become widely researched and applied for almost all domains, e.g., healthcare, logistics, or manufacturing [1–4]. AR combines real and synthetic information interactively and in real-time within a real environment. Synthetic objects react to and align with the real environment, thus creating an immersive experience while preserving the user's ability to see and navigate the environment. This contrasts AR with virtual reality, which offers full immersion [5]. So-called AR systems (ARS) implement AR in information systems (IS) to create an AR experience for users and can utilize a wide range of wearables, headsets, handhelds, or stationary systems (e.g., [4, 6-8]). While AR, in the narrow sense, is just an information output principle and could, therefore, address all human senses, contemporary research and product development focuses on visual and acoustic output (cf. [9]). Multiple commercial products are available today, with more in development, e.g., the Microsoft HoloLens 2 [10] or the Varjo-XR-3 [11]. These modern headset-based ARSs augment not only information output but also possess rich sensors to track their environment and own position within, e.g., high-resolution cameras, microphones, GPS, accelerometers, gyroscopes, and magnetometers (e.g., [10, 11], cf. [9]). Leveraging these sensors, modern headset-based ARSs offer context-aware capabilities, e.g., recognizing predefined "image targets" or anchoring synthetic contents to real objects, which stay put when the ARS is moving. These technical characteristics make modern headset-based ARSs interesting for the field of business process management, especially workflow execution support, management, and control, as demonstrated by the amount of research articles utilizing them (e.g., [37, 38], cf. [9]).

The context-aware provision of information during workflow execution, i.e., providing the right information at the right time and in the right place, is a well-known challenge for organizations [12]. Well-known tools to support the provision of information during workflow execution and the collaboration, coordination, and communication between workflow participants within organizations are workflow management systems (WFMS) [13]. Modern implementations of WFMS have evolved much from older understandings as "organizationally aware groupware" [14]. Still, the well-known definition by the Workflow Management Coalition (1995) [15] of a WFMS as a system that defines, interprets, instantiates, and manages the execution of workflows with software, integrates external applications and interacts with human workflow participants still applies (cf. [16]). In the scope of this dissertation, workflows are defined as the subset of business processes that are actually executable by workflow participants. Workflows are composed of workflow events and workflow tasks linked with control flows. Some workflow tasks are intended for human execution, so-called user tasks [15].

Based on their characteristics, the combination of AR and WFMS technology seems promising to address the everlasting challenge of organizations to optimize information provision during workflow execution. Headset-based ARS could use their sensors to gather relevant context information from the environment, which could then be processed by a WFMS to steer workflows. Instructions and standard information of a workflow or tasks could be presented within the ARS headset but also enriched with synthetic content, e.g., 3D objects, to support the user during workflow execution with AR.

Inspired by this grand vision for the intersection of AR, workflows, and WFMS, a wide range of ARSs has already been proposed, researched, and developed in recent years, addressing some individual aspects of this vision (cf. [9]). Although a large empirical base has not yet been established and clearly not all types of workflows are well-suited for AR support, increased task efficiency, i.e., reduction of error rates, execution times, cognitive loads, or required training, has already been observed in the domains of collaborative planning, assembly, service, maintenance, warehouse picking, process training, and process modeling (e.g., [4, 17–22]). Based on these findings and the technical characteristics of AR and WFMS, it seems plausible that "hands-on" workflows are generally well-suited for AR support, while document-oriented administrative workflows are less suitable.

During workflow task execution, modern headset-based ARSs can support users in manifold ways, e.g., by providing task descriptions and instructions with text and images, visually highlighting important objects, marking spots for tool placement, or demonstrating handles (e.g., [6, 23, 24]). Besides supporting the execution of workflow tasks in a narrow sense, headset-based ARSs are also utilized to enable workflow control and management. However, the currently supported functions are very limited and are provided in isolation, e.g., advancing backward and forward through a workflow's tasks or switching to a task of a different workflow (e.g., [6, 23, 24]). This is the case for ARSs in the scientific literature as well as commercial products, e.g., Microsoft's Dynamics 365 Guides [25], optimized for Microsoft's HoloLens AR headset.

This limited range of functions contrasts with the rich workflow management and control functions of modern WFMSs (e.g., Camunda [26] or SAP Signavio [27]), which are in line with the well-known reference architecture for WFMSs by the Workflow Management Coalition [15], e.g., instantiating, pausing and canceling workflow instances, generating filtered lists or inspecting workflow instance variables [15, 26]. Indeed, the contemporary landscape of ARSs in support of workflows presents itself as heavily use case-driven, with ARSs being developed and "hard-coded" for specific use cases. In contrast, the workflows in modern WFMSs are decidedly not hard-coded but the result of the WFMS interpreting formal workflow models. These visual models can then be quickly adapted to change an organization's workflow.

In the state of the art, therefore, opportunity costs arise for organizations in those business scenarios in which workflow participants are both executing AR-supported workflows with ARSs and need to use workflow management and control functions. These opportunity costs are the results of the workflow inefficiencies incurred due to the general inability of contemporary ARSs to offer WFMS front end capabilities, i.e., comprehensive workflow management and control functionalities [15], which consequently requires workflow participants to use additional devices, e.g., PCs, notebooks, tablets or smartphones. This creates media breaks and takes time, e.g., for taking out a tablet, logging in, etc. Also, in general, carrying additional devices does not tend to increase user satisfaction. Additionally, the capability of modern ARSs to track and recognize hand gestures (e.g., Microsoft Hololens [10]) enables workflow participants to use an AR UI with dirty hands or gloves, while usage of other devices might be impossible. Especially small devices like tablets or smartphones, which would be easiest to carry and switch to, are difficult to operate with dirty hands or gloves.

One example of problematic business scenarios are those which involve workflow participants wanting to execute individual, AR-supported workflow tasks of different workflow instances at the same location "in one go" before switching to another location. The workflow participant would then want to quickly switch between different workflows and tasks, which is difficult and, therefore, inefficient and cumbersome. Another example of problematic business scenarios are those in which a workflow participant operates a tool (e.g., a drill), and only one hand is free. The workflow participant could still operate an AR UI with a finger, crude hand gestures, voice commands, or eye-gazing in order to control the AR workflow task support. Switching devices in this scenario, however, would be additionally cumbersome, take even more time, and still create media breaks.

The unresolved ***fourfold challenge*** in these business scenarios is, therefore, *to provide workflow participants with 1) a headset-based ARS that 2) enables AR-based workflow execution support and the associated efficiency gains, as well as 3) comprehensive workflow management and control capabilities, while 4) ensuring usability.*

Henceforth, the term "comprehensive workflow management and control capabilities" refers to the reference architecture for WFMS and the workflow management and control capabilities defined therein ([15], p.31-35). For the term "usability," this dissertation follows the definition in ISO 9241-11:2018, i.e., usability means enabling users to achieve their workflow goals effectively (e.g., "how much of the workflow goals were achieved?"), efficiently (e.g., "How many resources were needed to achieve the workflow goals?"), and satisfactorily (e.g., "How did the users feel during workflow execution?") [39].

The existing research points to an obvious answer to the fourfold challenge outlined above: providing comprehensive workflow management and control functionalities in the same ARS that also provides AR task support. However, while the apparent theoretical potential and business scenario challenges have attracted interest within the IS research community and commercial IT industry to integrate AR and WFMSs, resulting in numerous research projects and commercial products (e.g., [6, 10, 11, 23–25]), hitherto no commercialized or conceptualized headset-based ARS addresses the fourfold challenge outlined above, as extensive literature reviews during this dissertation verify (see Chapters 3 and 4).

Three contemporary solutions stand out for coming closest to meeting this challenge. All three solutions involve the AR headset Microsoft HoloLens, running Windows 10 Holographic as an operating system. This enables the user to use different applications, such as the Microsoft Edge web browser. One solution to the fourfold challenge above is for the workflow participant to use the web browser to access a web-based WFMS front end and utilize its provided workflow execution support, management, and control functions. However, while available WFMSs (e.g., Camunda [26] or SAP Signavio [27]) offer web-based front ends and comprehensive workflow management and control functions, they do not offer AR-based task support. Another solution utilizes AR workflow task support via Microsoft Dynamics 365 Guides, which offers – inter alia – synthetic task instructions anchored to real objects, 3D-animated demonstration of handles, and 3D target guidance for component placement. However, workflow management and control functions are largely missing. The third solution would combine both the Microsoft Edge web browser and Microsoft Dynamics 365 Guides workflow support software. However, it is not possible for Microsoft Dynamics 365 Guides to communicate with a WFMS and, therefore, not possible for a web-based WFMS front end to manage and control the same workflows. The underlying reason for this is that the workflows in Microsoft Dynamics 365 Guides are not formally modeled workflows, interpreted by a WFMS, but rather "mini-apps," incompatible with workflow model standards like BPMN [40]. Also, "alt-tabbing," i.e., switching quickly between applications, is not possible with the Microsoft HoloLens. Therefore, inefficiencies would still occur in business scenarios where this is necessary, like those outlined above.

Even though the existing and conceptualized headset-based ARSs can serve as an orientation, as the HoloLens-based example above illustrates, the challenge for IS designers, IS architects, and IS developers to design, develop, and instantiate a novel type of headset-based ARS that addresses the fourfold challenge defined above is not trivial, and many aspects are a priori unclear. E.g., what are the characteristics of such a novel type of headset-based ARS, and which meta-requirements for its design must be considered? What are general principles of design and architecture that are reusable across multiple scenarios and organizations, and how could these be instantiated with currently available technology?

In this dissertation, extensive literature reviews (see Chapters 3 and 4) demonstrate that commercialized and conceptualized headset-based ARSs in the literature can only offer general orientation, but useful, formalized, and directly applicable knowledge that answers questions like those above, is not available for IS designers, IS architects, and IS developers to support the design, development, and instantiation of this novel type of headset-based ARS that addresses the fourfold challenge defined above. This gap in the IS knowledge base is the research gap addressed by this dissertation.

2 Research Design

2.1 Multi-cyclical Design Science Research

As outlined above, the research gap addressed by this dissertation is constituted by the absence of design knowledge for an ARS that addresses the fourfold challenge outlined in Chapter 1. An ARS that meets this fourfold challenge is henceforth termed **HoloWFM**, leaning on the aesthetic quality of the UI, enabling *holographic workflow management* for the name. Therefore, the goal of this dissertation is as follows:

Goal: To develop and ensure the usefulness of artifacts that support IS researchers, IS designers, and IS developers during the design, development, and instantiation of HoloWFMs, i.e., headset-based ARSs that enable AR-based workflow execution support for workflow participants, provide comprehensive workflow management and control capabilities and ensure usability.

In general, *artifacts* are artificially built objects resulting from design processes [41]. They are part of the *prescriptive knowledge base* of the IS domain, which stands in contrast to the *descriptive knowledge base*, constituted of *phenomena* (e.g., observations or measurements) and *sense-making* (e.g., natural laws or patterns) [42]. In the context of IS research, artifacts can be categorized as *constructs* (e.g., vocabularies or taxonomies), *models* (e.g., conceptual models or software architecture models), *methods* (e.g., procedures or algorithms), *instantiations* (e.g., software prototypes), and *design theories* [42].

To methodically design such artifacts, the established research paradigm in the IS discipline is *design science research* (DSR). Multiple DSR methodologies are available within the DSR paradigm. Overall, they are similar in that artifacts are systematically designed and evaluated, but each method emphasizes different aspects and has slightly different steps [43]. For this research project, the method by Vaishnavi and Kuechler was chosen because it explicitly focuses on the development of theoretically sound design requirements (DRs) and design principles (DPs) to guide IS development (see Chapter 2.3 for DRs and DPs) [28, 29, 43]. These DRs and DPs offer high reusability across multiple application scenarios and are thus beneficial to IS researchers, IS designers, and IS developers alike.

The procedure by Vaishnavi and Kuechler involves five steps: 1) awareness of problem, 2) suggestion, 3) development, 4) evaluation, and 5) conclusion.

In the first step, **Awareness of Problem**, the characteristics of a research problem are specified. This can include the use of multiple methods and drawing on multiple sources, e.g., developments in the industry or related research domains, literature reviews, or qualitative studies. The type of problems addressed are usually problem-solving focused in their approach, rather than questions or problems that are answered through explanation. In the first step, criteria for a later evaluation are already considered. The output of the first step is a formal or informal *proposal* for a new research effort [29].

In the second step, **Suggestion**, a novel artifact (or multiple artifacts) is envisioned, delivering new functionalities based on a novel configuration of existing or new elements, or both. This is a creative step, which is usually non-repeatable. The suggested artifact can be partially specified, e.g., regarding its goals or high-level characteristics. Thus, the output of the second step is a formal or informal *vision* for a novel artifact, fulfilling the research proposal and addressing the prior identified problem [29].

In the third step, **Development**, the suggested artifact is fully developed and implemented. Depending on the type of artifact, i.e., construct, model, method, instantiation, or design theory [42], different development methods are applied. The implementation itself can rely on well-known state-of-the-art tools and methods. The novelty of the artifact primarily lies in the design, not the development method. Thus, the output of the third step is a *novel artifact* [29].

In the fourth step, **Evaluation**, the artifact's quality is ascertained. The methods and specifics depend on the artifact type and goal of the research project [29]. A frequent goal is to establish an artifacts utility [44]. Depending on the evaluation results, changes can be made to the developed artifacts. Thus, the output of the fourth step is an *evaluation result*, indicating the quality of the artifact [29].

In the fifth step, **Conclusion**, the results of the design cycle are reflected upon. This can end the current research project or prompt another design cycle or new research effort altogether [29]. As communication is very important in research [44], the conclusion must make a strong case for the contribution of the results to the IS knowledge base strong case for its knowledge contribution [42].

The **research design of this dissertation** features three design cycles, each addressing these five steps and building on the previous cycle. This iterative multi-cyclical DSR approach mirrors the exploratory nature of the research project and the evolving awareness of the key problems in each design cycle over the course of the research project. As such, the research questions evolved during the research project as well. In Figure 1, the key aspects of the research project of this dissertation are summarized and mapped to a three-cycled DSR approach based on Vaishnavi and Kuechler [29]. As implied in Figure **1** by the arrows from the steps Development, Evaluation, and Conclusion back to Awareness of Problem, the insights during a design cycle are key to developing an awareness of the problems in the next design cycle.

Three artifact types were developed during this research project to fulfill the goal stated above: a taxonomy, a design theory, and a reference architecture. These address different levels of abstraction and thus provide IS researchers, IS designers, and IS developers with comprehensive support when designing, developing, and instantiating a HoloWFM. These three artifacts are the main contributions of this dissertation.

In the following chapters, each artifact type is briefly characterized, and corresponding research questions (RQ) are defined. The research gaps and related work for each artifact are further detailed as part of the chronological description of the design cycles in Chapters 3-5. The individual implications of the developed artifacts for theory and practice are further detailed in Chapter 7.

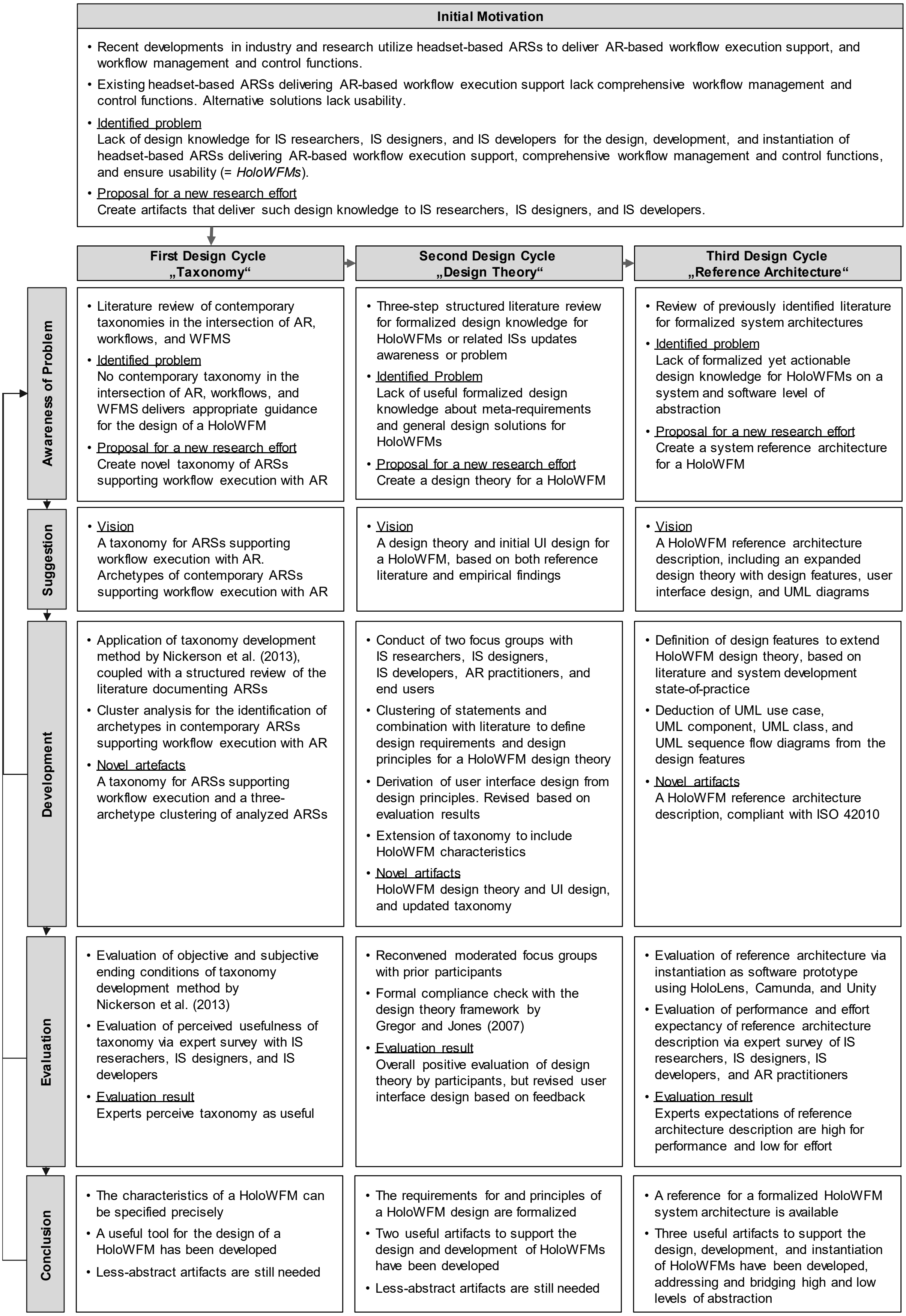


Figure 1. Summary of the consecutive design science research cycles.

2.2 Taxonomy

One type of tool to support IS development on a high level of abstraction are taxonomies. A taxonomy can be defined as a set of dimensions, each containing a set of characteristics, which together exhaustively represent the possible expressions of their respective dimension [45]. By abstracting the real complexity of objects to these dimensions and characteristics, taxonomies can be used to formally describe a specific IS class by its expression of taxonomy characteristics [45]. Taxonomies, thus, allow for an easier comparison of similarities and differences between objects. Further, taxonomies contribute to the IS knowledge base by providing a precise vocabulary of a domain and a set of defined constructs, thus establishing a foundation for future research efforts [44, 46]. When analyzing groups of objects, the aggregated expressions of the taxonomy, i.e., the frequent common occurrence of characteristics or their common absence, can generate additional insights [47]. Taxonomies cannot only be utilized to describe and classify phenomena but can also function as a foundation for sensemaking [42] and theory building [48]. In reference to the five IS theory types defined by Gregor (2006) [49], taxonomies can be utilized as theories for *analysis* (Type I, [49], p. 620). These represent the most basic forms of theory [49] and have been termed *taxonomic theories* [50, 51]. Taxonomic theories can serve as a foundation to develop other theories, e.g., explanatory theories or design theories, as the dimensions and characteristics of the taxonomies provide fundamental constructs and relationships [49, 50, 52].

In the state of the art, only a few individual taxonomies of AR, workflow, and WFMSs are available, and only two address the intersection of these domains. First, Klinker et al. (2018) address both workflows and AR by providing a taxonomy of suitable use cases for AR-supported service workflows [30]. Second, the framework by Fellmann et al. (2017) focuses on assistance systems for work processes in smart factories [35]. The framework is not focused on workflow execution support but contains aspects of workflows and WFMS, e.g., the degree of human interaction control with the system. The related work in the state of the art is further detailed in Chapter 3.3.1.

While the existing studies are useful in their own right, the intersection of AR, workflows, and WFMSs could be described in much greater granularity and detail, e.g., regarding utilized workflow models or the specific type of AR task support. In the status quo, a precise vocabulary and understanding of the possible descriptive constructs in this intersection of technologies are lacking. This, in turn, complicates the comparison between ARSs supporting workflow execution and the identification of patterns within the literature. In the context of the fourfold challenge laid out in the previous section, the formal characterization of ARSs, the identification of relevant related literature and research gaps, and steering new research efforts become more difficult. To enable those potential benefits, a novel taxonomy is necessary, which characterizes ARSs with a focus on their specific contributions to supporting workflow execution. Consequently, the first RQ is defined as:

RQ 1: *What are the dimensions and characteristics of a taxonomy of augmented reality systems supporting workflow execution?*

While taxonomies are valuable instruments, by themselves, they are just tools to characterize objects but do not *per se* offer insights into the currently existing population of objects – in the case of this dissertation, ARSs in support of workflow execution. To archive such insights, the taxonomy can be used to characterize existing objects, and methods of exploratory data analysis can then be utilized to identify patterns within this characterization data and to develop archetypal patterns or *archetypes* (e.g., [53–55]). These archetypes thus concisely summarize the status quo and provide valuable orientation for practice-oriented members of this dissertation's target audience of IS researchers, IS designers, and IS developers. Therefore, the second RQ is defined as:

RQ 2: *What is a meaningful set of archetypes of augmented reality systems supporting workflow execution, and what are the characteristics of these archetypes?*

Both RQs are addressed in the first design cycle, which developed a novel taxonomy and archetypes of ARSs in support of workflow execution. The first design cycle is detailed in Chapter 3.

2.3 Design Theory

Design theories (DTs) can be used to define the design requirements (DRs) and design principles (DPs) for the design of a class of ISs [56]. While the DRs describe the general objectives of the DT and function as meta-requirements for a class of ISs, the DPs provide abstract solution principles to address these [56, 57]. Together, DRs and DPs embody a general design solution for a set of design problems encountered during the design of a class of ISs [56]. In general, DPs can be descriptive or prescriptive, the latter stating how an artifact should be instantiated to fulfill the DRs [58]. To further specify the DPs, design features (DFs) can be defined, which represent one possible set of technically-oriented approaches to operationalize the DPs. Even though not a required part of a DT (cf. [56]), DFs can be utilized to document how DPs could be implemented in a specific instance (see, e.g., [59, 60]). The DFs, thus, provide less-abstract design knowledge and can, e.g., serve as a foundation to systematically develop UML diagrams and textual descriptions for a system or software architecture. Hence, the design knowledge provided by DTs bridges the "abstraction gap" between the rather abstract DRs and DPs and actionable system and software architectures via the less-abstract DFs. As DTs are similar to reference architectures in their function, well-known advantages of these should apply to DTs as well, i.e., reduced development time, development risks, and improved collaboration via a better common understanding of the problem domain [61–63]. In terms of the five theory types defined by Gregor (2006), DTs can be categorized as theories for *design and action* (Type V, [49], p. 620).

In the state of the art, however, no conceptualized or commercialized ARS addresses the fourfold challenge laid out above. The related work in the state of the art is further detailed in Chapter 4.1. As such, no DT is available to provide guiding design knowledge to IS researchers, IS designers, and IS developers when designing, developing, or instantiating a HoloWFM. Thus, opportunity costs can be incurred by, e.g., increasing the necessary time to design, develop, and instantiate a HoloWFM, increasing development risk, or impeding collaboration and communication due to diverging understandings of the problem domain (cf. [61–63]). To avoid these opportunity costs for IS researchers, IS designers, and IS developers when designing, developing, or instantiating a HoloWFM, the third RQ is defined as:

RQ 3: *What are the design requirements, design principles, and design features of a HoloWFM?*

The third RQ is addressed in the second and third design cycles, detailed in Chapters 4 and 5, respectively. In the second cycle, a tentative DT was defined, including DRs and DPs. In the third design cycle, the DT was extended with DFs and finalized, thus answering RQ 3.

2.4 Reference Architecture Description

An actionable, low-abstract tool to support IS development is a reference architecture (RA) [61, 63, 64]. An RA is an architecture that distills the essence of existing architectures for a certain problem domain and provides a template and guidance to develop solution architectures for specific problem instances in the same domain [61–64]. As the *problem instance environment* differs, e.g., for different companies, the RA gets adopted into a unique *solution instance architecture*, also based on the specific *stakeholder requirements*, e.g., end-user requirements. The solution instance architecture, then, is finally implemented into a *solution instance system* (Figure 2) [61–64]. An RA can contain multiple elements, e.g., models, figures, or text.

RAs provide value in numerous ways [61–64]. When utilized for collaboration, an RA can improve the common understanding of problem domains and systems by providing a common lexicon and terminology. Important concepts are clarified. Functions and qualities above the system level, the relevant context, and consequent design decisions are documented to foster a common understanding and ease the application of the RA for specific problem scenarios. With improved communication, interoperability between systems and organizational units can improve as well. The RA itself facilitates a common architectural vision by functioning as a focal point for information exchange, which in turn focuses and aligns the efforts of multiple people and teams. As RAs capture past experiences, lessons learned, and best practices, their utilization generally reduces development risks and time, helps spread best practices, and can serve as instruments of knowledge management in organizations [61–64].

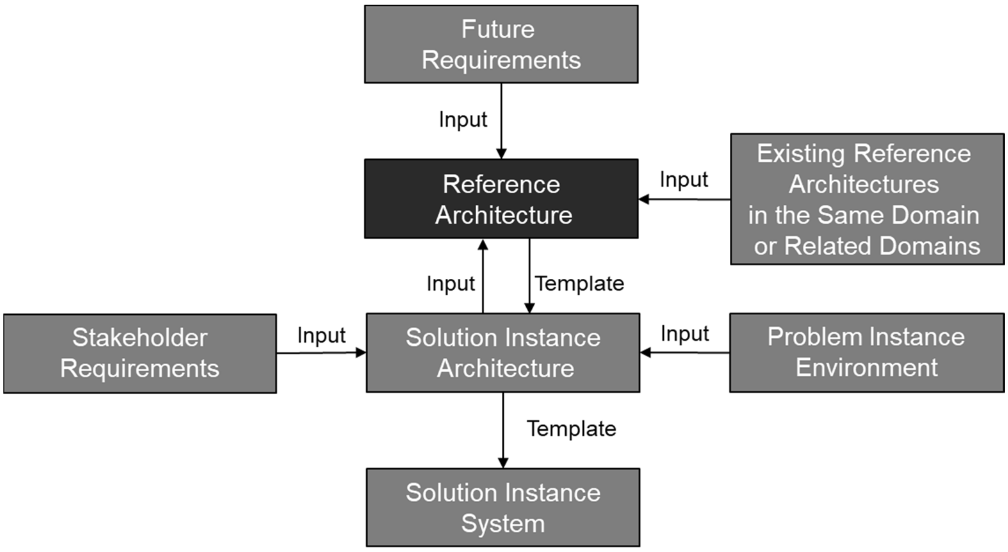


Figure 2. Reference architecture inputs. Own depiction, based on [61, 65].

A standard for describing architectures is provided by ISO/IEC/IEEE 42010:2011(E) *Systems and software engineering — Architecture description* [36]. Hence, a RA description (RAD) should include: 1) a RAD identifier, 2) overview information, 3) the RADs stakeholders and their concerns, 4) a definition for each RA viewpoint, i.e., the target audience's perspective, in the RAD, 5) exactly one RA view for each defined RA viewpoint, possibly containing multiple models, 6) RAD correspondence rules, RAD correspondences, and known inconsistencies among the RAD's content, and 7) rationales for architecture decisions made. Notably, ISO/IEC/IEEE 42010:2011(E) does not specify which models or modeling languages must be utilized to constitute an RA view. Thus, appropriate contents for an RA view include, e.g., DTs, reference UI designs, and UML diagrams. As such, the RAD developed in this dissertation includes the DT.

In the state of the art, no RAD or components, e.g., UML diagrams, for a HoloWFM are available. Additionally, very few architectures are provided by recent studies for AR-based IS supporting workflow execution, management, or control. Of these, most are highly abstract or do not utilize documentation and modeling standards (e.g., [4, 23, 66]). Thus, they are unusable for a proper RAD, as defined above. The related work in the state of the art is further detailed in Chapter 5.1.

Thus, in the state of the art, well-known advantages of RAs, e.g., reduced development time, risks, and improved collaboration via a better common understanding of problem domains, systems, and software [61–63], are unavailable for IS researchers, IS designers, and IS developers aiming at designing, developing, or instantiating a HoloWFM. Consequently, to close this research gap the fourth RQ is defined as:

RQ 4: *What are the models, model elements, and textual descriptions of a reference architecture for a HoloWFM?*

The fourth RQ was addressed in the third design cycle, which is detailed in Chapter 5.

2.5 Prototype Instantiation

In IS research, an *instantiation* is a type of artifact that can be used to demonstrate the feasibility of a more abstract artifact type, i.e., a software prototype can show the feasibility of an IS RA [42, 67]. In this case, a software prototype instantiates an abstract IS RA with specific hardware and software available in the problem instance environment, considering the requirements of relevant stakeholders (cf. Figure 2) [61, 65]. Such an instantiation can simply serve to ensure that an abstract solution is actually instantiatable with currently available technology or in a realistic setting. This is not necessarily the case, as an RA could also be developed to address future requirements in such a way that the RAD can only be operationalized with future technologies (cf. Figure 2 and [61, 65]). A software prototype then demonstrates that an RA is instantiatable *now,* and with what set of hardware and software, at least one instance can be realized. Thus, a HoloWFM software prototype instantiation serves as an orientation for IS researchers, IS designers, and IS developers aiming at designing, developing, or instantiating a HoloWFM.

Another important function of a prototype instantiation is to evaluate the corresponding abstract architecture [42, 67]. Following the framework for the evaluation of IS by Sonnenberg and vom Brocke [67], *evaluation activity 3* can be performed via a *demonstration with a prototype* [67]. Such a prototype not only demonstrates that the underlying abstract architecture actually works, especially key architectural concepts (cf. Chapter 5.3.1.6), and can serve to reveal weaknesses in the architecture.

Consequently, to ensure the feasibility of the HoloWFM RAD with currently available technology and especially of key architectural concepts, the fifth RQ is defined as:

RQ 5: *Can a software prototype of a HoloWFM reference architecture description be instantiated with currently available technology to demonstrate the feasibility of the reference architecture, especially key architectural decisions?*

To answer the fifth RQ, the RAD developed to address RQ 4 is instantiated first as a solution instance architecture (cf. Figure 2) and then as a software prototype in the evaluation phase of the third design cycle, which is detailed in Chapter 5.4.2.

2.6 Evaluation Strategy

The overall evaluation strategy follows the *framework for evaluation in design science research* (FEDS) by Venable et al. (2017) [68]. The FEDS characterizes evaluation events on two dimensions: formative-summative and artificial-naturalistic.

Within the terminology of the FEDS, formative and summative evaluations are distinguished by their functional purpose rather than a difference in methodology or setting [68]. Early evaluations are more formative as their function is to positively influence the ongoing research project. Summative evaluations measure and judge the outcomes of development and thus appear later in the research project [68].

The method and setting of an evaluation are characterized by the artificial-naturalistic dimension. Artificial evaluations are set in artificial environments and are, thus, reductionist, i.e., they reduce the complexity of reality. Examples include laboratory experiments, simulations, theoretical/logical arguments, and mathematical proofs. Artifical evaluations can be empirical or non-empirical. In contrast, naturalistic evaluations explore the performance of a solution technology in its real environment, i.e., with real people, real systems, and in real settings [69], typically within a real organization. Naturalistic evaluations are always empirical and include – inter alia – case studies, field studies, field experiments, and surveys.

Most evaluations during a research project are neither fully artificial nor fully naturalistic but exhibit characteristics of both archetypes. Venable et al. group the sets of performed evaluations into evaluation strategies, which correspond to different risks and challenges during a research project ([68], Table 1). Four archetypical evaluation strategies are defined, depicted in Figure 3, from top to bottom: 1) Human Risk & Effectiveness, 2) Quick & Simple, 3) Technical Risk & Efficacy, and 4) Purely Technical [68]. These paths are depicted in Figure 3.

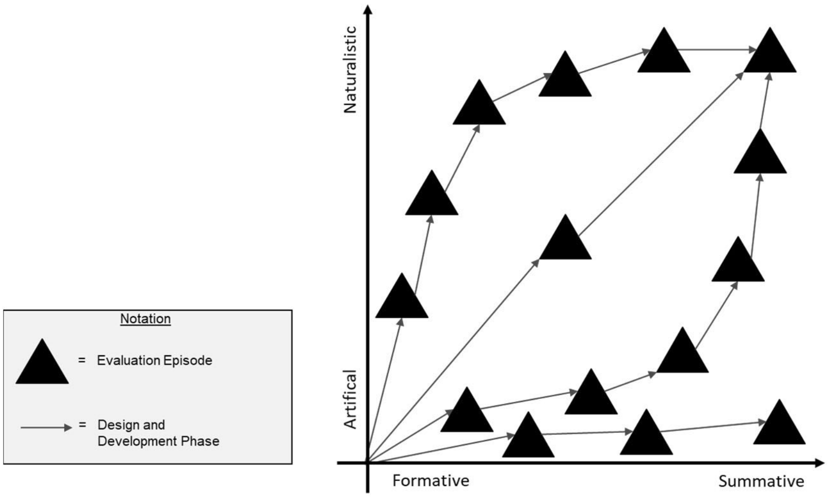


Figure 3. Evaluation strategies of the framework for evaluation in design science research [69].

The goal of this dissertation is to develop multiple artifacts to support the target audience of IS researchers, IS designers, and IS developers during the design, development, and instantiation of a HoloWFM. Multiple risks and challenges relevant to the FEDS can be identified and are described below.

One major risk of this research project is technically oriented. The artifacts must be technically correct to deliver value to the target audience. If not, the benefits of taxonomies, DTs, and RAs outlined in the previous chapters can't be realized fully or at all. Instead, HoloWFM misdevelopments might even incur costs to IS researchers, IS designers, and IS developers.

Another risk is user-oriented. It must be ensured that the target audience finds the artifacts useful and usable. However, the developed artifact types are well-known in the IS community, and their general usefulness has been established. It remains to ensure that the specific artifact instantiations within this dissertation are perceived as useful or that the expected necessary effort to use meets the target audience's expectations. Thus, the user-oriented risks are only minor risks.

One major challenge is that, in the scope of this dissertation, it is prohibitively expensive to finalize a "polished" HoloWFM instantiation, i.e., implementing a complete and compelling AR UI. While an AR UI design was developed in the second design cycle (see Chapter 4.3.4), actually instantiating this AR UI would be prohibitively expensive. Instead, only an "unpolished" HoloWFM prototype instantiation is implemented, which is nonetheless sufficient for the evaluation of this dissertation as the key architectural concepts and decisions (see Chapter 5.3.1.6) were validated. Indeed, the implementation of a polished AR UI and prototype would only reflect programming and media design expertise. An evaluation of a polished prototype, thus, would overly evaluate programming and media design skills, not the underlying artifacts that supported the programming of that polished prototype, i.e., those artifacts that were developed to fulfill the goal of this dissertation.

Given these risks and challenges, the *Technical Risk & Efficacy* strategy archetype fits this dissertation best since 1) a major risk is technically oriented, 2) user-oriented risks are minor, 3) it is prohibitively expensive to evaluate with a polished prototype, and 4) it must be established that the benefits to the target audience stem from the developed artifacts, i.e., the models of the HoloWFM RA, and not something else (e.g., UI design and programming skills) ([68], Table 1).

In contrast, the *Quick & Simple* strategy is not fitting, as the research project and designed artifacts are complex, and major technical risks and uncertainties exist. The *Purely Technical* strategy does not apply either, as there are social aspects to the artifacts, i.e., they will be utilized by humans. The *Human Risk & Effectiveness* strategy is not appropriate, as it is not cheap to evaluate with a real system, users, and settings, and no major design risk is social- or user-oriented ([68], Table 1).

2.7 Evaluation of Taxonomy

Taxonomies as an artifact type are well-known in IS research [41] and are used in numerous IS studies (cf. [70]). Thus, their general usefulness is not in question. However, no specific evaluation method for taxonomies in the IS domain has been widely accepted in the IS community. Indeed, there does not even seem to be a consensus on whether taxonomies need to be evaluated at all. In a large analysis of studies developing taxonomies, Kundisch et al. [70] find that only 56 out of 160 (35 %) analyzed studies evaluate their developed taxonomy.

Within this group, a total of 73 % utilize *illustrative scenarios*, either by describing and/or classifying real-world objects (58 %) or existing research (15 %), and the other 27 % use a variety of qualitative and quantitative methods ([70], p. 427). Thus, the study by Kundisch et al. [70] suggests that the most appropriate and specific evaluation method for a taxonomy is to rigorously construct the taxonomy in the first place by analyzing real-world objects and existing research. This is exactly the approach taken by the taxonomy development method by Nickerson et al. [45], who call these approaches Empirical-to-Conceptual and Conceptual-to-Empirical, respectively [45]. This method is also by far the most used taxonomy development method [70] and is consequently utilized in this dissertation (see Chapter 3.3.1). The evaluation method *illustrative scenario* is intuitively understandable as taxonomies built rigorously (e.g., with the method by Nickerson et al. [45]) on real-world data cannot be "wrong" per se, as they just represent a specific perspective (that of the authors) on the underlying data. If the taxonomy is built for a specific purpose, which should generally be the case, then for at least that purpose, the taxonomy should be useful.

Another evaluation method counted in the study by Kundisch et al. [70] are surveys, which are used by 5 % of studies with evaluations. These surveys usually utilize only a small number of participants to ascertain the usability of taxonomies, e.g., [71] use 9 participants, and [72] use 7 participants. A low number of participants have established themselves in IS usability research. As Caine [73] finds in a survey of 432 IS-related usability studies with varying methods, sample sizes of 12 participants were present in 10 % of all studies and, as such, the most common number of participants, with an additional 20 % of studies reporting ten or less participants [73]. These findings are in line with numerous arguments for specific methods that a small number of participants are sufficient to gain some insights or at least do not threaten the descriptive analysis of survey results. E.g., Hwang and Salvendy [74] show that after 12 participants in *Think Aloud* sessions, *Cognitive Walkthroughs*, and *Heuristic Evaluations*, the discovery rate of problems rises only marginally. Julious [75] shows that small sample sizes of 12 participants are enough to sufficiently reduce the risk that the survey result is purely random. Guest et al. [76] show that 6 participants in an interview series were able to provide 73 % of all data collected, with an additional 19 % of data collected from the 7^{th} to 12^{th} participants, for a total of 92 % of data. For usability studies, Macefield [77] summaries the arguments of a number of secondary studies and concludes that depending on the specific scenario, for "problem discovery, a group size of 3-20 participants is typically valid, with 5-10 participants being a sensible baseline range" and "for comparative studies where statically significant findings are being sought, a group size of 8-25 participants is typically valid, with 10-12 participants being a sensible baseline range" [77].

Therefore, for the evaluation of the novel taxonomy developed in this dissertation, the following evaluation events are performed in the stated order, which are also depicted in an overview in Figure 4 in Chapter 2.10:

1) The development method by Nickerson et al. (2013C was utilized to rigorously construct the taxonomy on the basis of real-objects, thus performing an evaluation with *illustrative scenarios* as defined by Kundisch et al. [70].

2) Ex-ante evaluation of the *objective ending conditions* [45] during the taxonomy development, following the taxonomy development method by Nickerson et al. (2013) [45].

3) Ex-post evaluation of the *subjective ending conditions* of the taxonomy development method by Nickerson et al. (2013) [45] and the *perceived usefulness* [78] of the taxonomy via an expert survey of n_1=11 participants.

4) The taxonomy was utilized to envision three novel ARSs, corresponding to anti-patterns in the concept matrix of the characterized ARSs of the taxonomy development phase. These ARSs are the development goal of three research and development projects further described in Chapter 6, under *Secondary Projects*.

5) The taxonomy developed in the first design cycle was extended in the second design cycle with characteristics to describe HoloWFM, which was developed in the second design cycle and was finally used for the characterization of HoloWFM. On the one hand, this is an evaluation via an *illustrative scenario* as defined by Kundisch et al. [70]. On the other hand, this demonstrates the *extendibility* of the taxonomy, which is an important attribute of a taxonomy according to Nickerson et al. [45] (see SEC4 in Table 4) and was evaluated at the end of the first design cycle.

As discussed in Chapter 2.6, this dissertation follows the *Technical Risk & Efficacy* archetype for evaluation since the major risk is technically oriented, and technical correctness is the most important factor for the developed artifacts (cf. [68]). As such, the rigorous development with the method by Nickerson et al. [45] (events 1-3) is very important. As the novel taxonomy is meant to answer RQ 1 (see Chapter 2.2), the decisive evaluation criterion is whether the novel taxonomy can describe a HoloWFM. This is evaluated in event 5. As such, whether the taxonomy is generally perceived as useful (event 4) contributes to the value of the developed artifact but is less important for this dissertation's DSR project. As such, the sample size is small but still in line with established and accepted practices as discussed above.

2.8 Evaluation of Design Theory

Design theories are well-established artifacts in IS research and are recognized as a separate type of artifact [42]. As such, their general usefulness is not in question. A number of quality criteria exist for DTs. Regarding the general structure, their constitution by DRs, DPs, and optionally DFs is well established [56, 57, 59, 60]. In more detail, Jones and Gregor [79] define six obligatory and two optional components every DT should include. Multiple works exist regarding the formulation of DRs or DPs, e.g., Fu et al. [58] distinguish between descriptive and prescriptive DP formulations and present a template for their articulation.

The majority of publications containing DPs lack proper validation of them, as Fu et al. [58] find. According to Fu et al., in those studies that did evaluate their DPs, the most common evaluation approach is the application of the DPs for the actual design of an artifact [58], i.e., produce an *instantiation*-type artifact [42].

This approach to evaluation is in line with an older approach to the evaluation of DTs, the conceptual framework of *projectability* by Goodman (1955) [80], which is recommended by Baskerville and Pries-Heje [81]. According to this framework, a DT is *actually projected* when it's instantiated. When this *projection* is successful, i.e., no observation in opposition to the DT is made, but not all possible instantiations have been examined, a DT is *projectable*. The more frequently a DT is actually projected, the more entrenched it becomes [80].

Similar to *illustrative scenarios* in the context of taxonomies (see Chapter 2.7), building DTs on a sound basis can be understood as an evaluation. To ensure this, the methodological approach to DP development by Möller et al. [82] can be consulted. This method distinguishes two basic principles for developing DPs. A *reflective* approach would first define a specific problem, then design an artifact to solve this problem, and finally extract DPs ex-post from the developed artifact. The alternative strategy – utilized in this dissertation – is the *supportive* approach. This procedure would first identify a suitable knowledge base, elicit DRs, and then formulate DPs, which finally aid in designing the problem-solving artifact [82]. A fitting knowledge base for the development of a DT for a type of IS is the potential users of that IS. As such, the findings related to usability studies, discussed in the previous Chapter 2.7, apply also to DTs. Thus numerous types of small studies may be used to gain insights into the DRs, DPs, and DFs of an IS and evaluate them (see Caine [73] for usability study types).

One approach to gathering DRs and DPs in line with the *supportive* approach by Möller et al. [82] is to utilize *moderated focus groups* (MFG). An MFG is a qualitative research method where a moderator guides a group discussion and which relies on the interaction between participants to generate insights [83]. The number of MFGs necessary for reliable results is highly debated in the literature. The empirical findings of Guest et al. [84] suggest that two to three MFGs are sufficient. Regarding the number of participants, based on the usability studies discussed in the previous Chapter 2.7, groups of 10-12 are most likely sufficient to gain most insights. The same participants can also be utilized in so-called *reconvened moderated focus groups* to evaluate the DRs and DPs that were defined on the basis of the MFGs [85]. The RMFGs then check if the expectations of the original participants were met, discuss further aspects, topics, concepts, theories, or issues in greater depth, evaluate them under consideration of new information, or both [85].

To systematize the statements by the participants of MFGs and RMFGs, the well-known methodology of Gioia et al. [86] can be utilized, which distills first-order concepts and second-order themes from the verbalized statements of the participants. The extracted second-order themes then can serve as an empirical basis for developing of DRs and DPs or the systematic evaluation of them.

As such, for the evaluation of the HoloWFM DT developed in this dissertation, the following evaluations are performed in the orders stated below, which are also depicted in an overview in Figure 4 in Chapter 2.10:

1) Conduct of two MFGs [83] with n_2=12 and n_3=10 participants, consisting of IS researchers, IS designers, and IS developers experienced in the workflow and AR domain, in order to gather DRs and DPs for a HoloWFM.
2) Conduct of RMFGs [85] with n_4=12 and n_5=10 participants, consisting of IS researchers, IS designers, and IS developers experienced in the workflow and AR domain, in order to evaluate a tentative DT and UI design.
3) Formal compliance check with the DT framework by Gregor and Jones (2007) [79] regarding the anatomy of the tentative DT.
4) Demonstration of *projectability* of the final DT (including DFs) by *projecting* the DT as a HoloWFM RA, following the conceptual framework of projectability by Goodman (1955) [80].
5) Evaluation of *performance expectancy* and *effort expectancy* [82] of the final DT via an expert survey of n_6=13 IS researchers, IS designers, and IS developers with experience in the workflow and AR domain.

2.9 Evaluation of Reference Architecture Description

Reference architectures are well-established *model*-type artifacts [42]. As they provide value in numerous well-known ways [61–64], their general usefulness has been established (see Chapter 2.4).

Based on their primary functions as templates [61–64], the preeminent and obvious evaluation method for RADs is to instantiate them as *solution instance architectures* (cf. Chapter 2.4) and test if they work. Producing a software prototype as an *instantiation*-type artifact [42] is also defined as *evalauation activity 3* in the *framework for DSR evaluation activities and criteria* by Sonnenberg and vom Brocke [67].

A major problem with instantiations of software prototypes from reference architectures is, that it might be prohibitively expensive to do so. This problem was also identified in the FEDS framework [68] and is one reason why the *Technical Risk & Efficacy* evaluation strategy was chosen as a template (see Chapter 2.6). One approach can be to instantiate a partial prototype, demonstrating the feasability of some important aspects, while not realizing other, less pivotal aspects ([67, 68]).

Another approach, that was (as far as known) first demonstrated in this disseration, is to systematically link DRs and DPs, which can be rigorously defined with established methods (see Chapter 2.8), to models of an RA via DFs, e.g., DFs can point to specific elements in an UML component diagram. This can – in a sense – bridge the "rigor gap" if an extensive prototype-based study cannot be conducted.

Lastely, as RADs directly relate to IS development, the usability studies discussed in Chapter 2.7 can be drawn upon. As such, multiple qualitative or quantitative instruments, e.g., expert surveys, can be utilized to ascertain an RADs usefulnes in more general terms than a specific prototype-scenario.

Therefore, for the HoloWFM RAD developed in this dissertation, the following evaluations are performed, which are also depicted in an overview in Figure 4 in Chapter 2.10:

1) The RAD was systematically developed on the basis of the DRs, DPs, and DFs within the context of the conceptual framework of *projectability* by Goodman (1955) [80].
2) Demonstration of the *feasibility* of the developed HoloWFM RAD via instantiation as a software prototype, following the framework by Sonnenberg and vom Brocke [67] an demonstrating key architectural concepts.
3) Ealuation of *performance expectancy* and *effort expectancy* [87] of the RAD via an expert survey of n_6=13 IS researchers, IS designers, and IS developers with experience in the workflow and AR domain.

2.10 Overview of Artifact Evaluation Events

In this research project, a total of 12 distinct evaluation events were performed. Below, a brief description of each event is provided. The evaluations are further detailed in their respective design cycle's evaluation phase, described in Chapters 3-5. In Figure 4, the evaluation events are mapped to the two-dimensional representation of the FEDS [68].

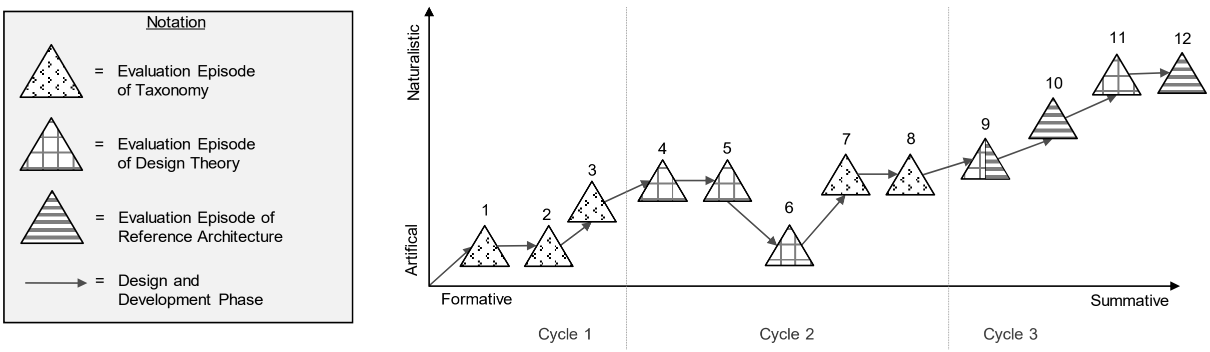


Figure 4. Evaluation events of the dissertation mapped to the framework for evaluation in design science research by Venable et al. (2017) [68].

#	Artifact	Description of evaluation event
1	Taxonomy	The development method by Nickerson et al. (2013) [45] was utilized to rigorously construct the taxonomy on the basis of real-objects, thus performing an evaluation with *illustrative scenarios* as defined by Kundisch et al. [70].
2	Taxonomy	Ex-ante evaluation of the *objective ending conditions* [45] during the taxonomy development, following the taxonomy development method by Nickerson et al. (2013) [45].

Table 1. Evaluation events of the developed artifacts.

#	Artifact	Description of evaluation event
3	Taxonomy	Ex-post evaluation of the *subjective ending conditions* of the taxonomy development method by Nickerson et al. (2013) [45] and the *perceived usefulness* [78] of the taxonomy via an expert survey of n_1=11 participants.
4	DT (DRs, DPs)	Conduct of two *moderated focus groups* [83] with n_2=12 and n_3=10 participants, consisting of IS researchers, IS designers, and IS developers experienced in the workflow and AR domain, in order to gather DRs and DPs for a HoloWFM.
5	DT (DRs, DPs), UI design	Conduct of *reconvened moderated focus groups* [85] with n_4=12 and n_5=10 participants, consisting of IS researchers, IS designers, and IS developers experienced in the workflow and AR domain, in order to evaluate a tentative DT and UI design.
6	DT (DRs, DPs)	Formal compliance check with the DT framework by Gregor and Jones (2007) [79] regarding the anatomy of the tentative DT.
7	Taxonomy	The taxonomy was utilized to envision three novel ARSs, corresponding to anti-patterns in the concept matrix of the characterized ARSs of the taxonomy development phase. These ARSs are the development goal of three research and development projects further described in Chapter 6, under *Secondary Projects*. This is an evaluation via *illustrative scenario* as defined by Kundisch et al. [70].
8	Taxonomy	The taxonomy developed in the first design cycle was extended in the second design cycle with characteristics to describe HoloWFM, which was developed in the second design cycle, and was finally used for the characterization of HoloWFM. On the one hand, this is a evaluation via *illustrative scenario* as defined by Kundisch et al. [70]. On the other hand, this demonstrates the *extendibility* of the taxonomy, which is an important attribute of a taxonomy according to Nickerson et al. [45] (see SEC4 in Table 4) and was evaluated at the end of the first design cycle.
9	DT (DRs, DPs, DFs), RAD	Demonstration of *projectability* of the final DT (including DFs) by *projecting* the DT as a HoloWFM RA, following the conceptual framework of projectability by Goodman [80].
10	RAD	Demonstration of the *feasibility* of the developed HoloWFM RAD via instantiation as a software prototype, following the framework by Sonnenberg and vom Brocke [67].
11	DT (DRs, DPs, DFs)	Evaluation of *performance* and *effort expectancy* [87] of the final DT via an expert survey of n_6=13 IS researchers, IS designers, and IS developers with experience in the workflow and AR domain.
12	RAD	Evaluation of performance and effort expectancy [87] of the RAD via an expert survey of n_6=13 IS researchers, IS designers, and IS developers with experience in the workflow and AR domain.

Table 1 (continued). Evaluation events of the developed artifacts.

2.11 Knowledge Contribution Assessment

A systematic approach to assessing whether a DSR project has delivered a valuable contribution to the IS knowledge base is to assess the maturity of the artifacts in the targeted *application domain* and corresponding *solution domain*. This is the approach of the DSR Knowledge Contribution Framework by Gregor and Hevner [42], depicted as a 2x2 matrix in Figure 5. Depending on the maturity of the solution domain and application domain, Gregor and Hevner postulate four archetypical types of contributions: 1) improvement, 2) invention, 3) routine design, and 4) exaptation [42].

A low maturity of the application domain means that the specific challenges, problem contexts, and interdependencies between sub-problems are not well understood. A high maturity in this domain, thus, means that the challenges, problems, and contexts are already well understood and articulated. A low maturity of the solution domain similarly means that no effective solution artifacts exist to address the challenges and (sub-)problems in an application domain. In contrast, a high solution domain maturity is present that effective artifacts already exist [42].

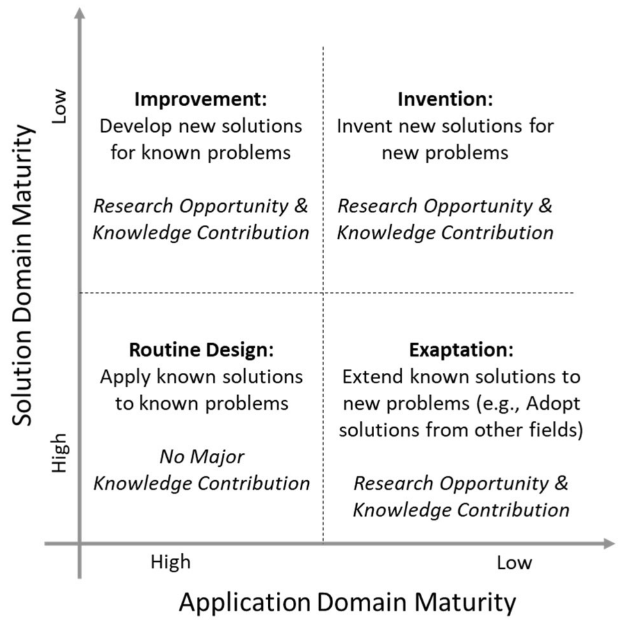


Figure 5. Design science research knowledge contribution framework by Gregor and Hevner [42].

Regarding the maturity of the application domain maturity, as described in Chapter 1, some ARSs offer some workflow management and control functions while supporting the execution of workflows with AR. However, no ARS in the state of the art prior to this dissertation addressed or aimed at the fourfold challenge of a HoloWFM. This was systematically ascertained in the structured literature reviews in the first and second design cycles (see Chapters 3.3.1 and 4.1) and is most succinctly apparent in Chapters 4.3.5 and 4.3.6, where the taxonomy of characteristics of contemporary ARSs that support workflow execution with AR, developed in the first design cycle, is extended to include the characteristics of a HoloWFM. Within the literature analyzed during the structured literature reviews in the first and second design cycles, there seems to be no awareness of the existence of the fourfold challenge or of the possibility of holistically integrating WFMS front end functionalities in an ARS that supports workflow execution with AR. Therefore, the application domain maturity was assessed to be middle-to-low, as individual parts of the fourfold HoloWFM challenge are addressed in the literature.

The solution domain maturity is assessed to be middle-to-high. As the goal of the dissertation was to design artifacts that support IS researchers, IS designers, and IS developers during the design, development, and instantiation of HoloWFMs, the artifact types that could be considered were reasonably clear from the beginning. Indeed, no new artifact types were developed, but known artifact types, i.e., a taxonomy, a DT, and a RAD, were instantiated for the fourfold HoloWFM challenge. However, considerable research effort was necessary to instantiate these artifact types, as the state-of-the-art ARSs and literature prior to this dissertation could only offer some general guidance for the development of the solution artifacts of this dissertation

In conclusion, the maturity assessment indicates that the contributions of this dissertation would best be classified as an exaptation to the state of the art, with some parts leaning towards being an invention, improvement, or routine design (Figure 6).

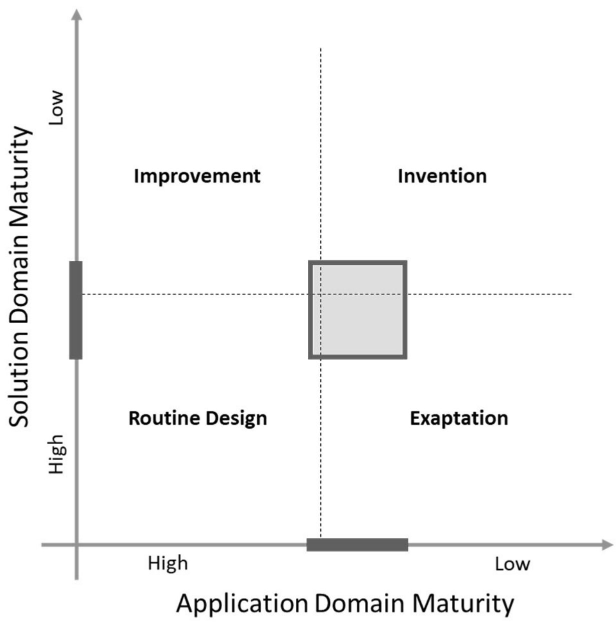


Figure 6. Assessment of the application domain and solution domain maturity prior to the contributions of this dissertation, mapped to the DSR Contribution Framework by Gregor and Hevner [42].

2.12 Core Contributions of the Dissertation

Four publications are core contributions of this dissertation. These roughly correspond to the three design cycles presented in Chapter 2.1 and are:

- **Damarowsky, Johannes** / Kühnel, Stephan / Seyffarth, Tobias / Sackmann, Stefan (2022): *Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung - Entwicklung und praktische Anwendung einer Taxonomie*. In: HMD - Praxis der Wirtschaftsinformatik, Special Issue, Vol. 59(1), 2022 [9].

- **Damarowsky, Johannes** / Kühnel, Stephan / Seyffarth, Tobias / Böhmer, Martin (2023): *Understanding Augmented Reality Systems for Workflow Support – A Taxonomy and Archetypical Patterns. S*ubmitted to: Electronic Markets - The International Journal on Networked Business (awaiting decision) [88].

- **Damarowsky, Johannes** / Kühnel, Stephan (2022): *Conceptualization and Design of a Workflow Management System Front End for Augmented Reality Headsets*. In: 30th European Conference on Information Systems (ECIS 2022) [16].

- **Damarowsky, Johannes** / Kühnel, Stephan / Böhmer, Martin / Sackmann, Stefan (2023): *A Reference Architecture for a Workflow Management System Front End Designed for Augmented Reality Headsets*. In: 31st European Conference on Information Systems (ECIS 2023) [89].

These first two publications contain content from the first design cycle. The 2022 article Damarowsky et al. (2022) [9] in the journal *HMD – Praxis der Wirtschaftsinformatik* contained the taxonomy and the 2023 article Damarowsky et al. (2023) [88] in the journal *Electronic Markets* additionally contains the developed archetypes. These publications, thus, answer RQ 1 and RQ 2, respectively. The latter publication is currently in submission and awaits a decision.

The third publication Damarowsky and Kuehnel (2023) [16] contains the second design cycle and was published at the *30th European Conference on Information Systems*. It addresses the third research question (RQ 3) tentatively by presenting the design requirements and design principles of a HoloWFM.

The fourth core contribution of this dissertation, Damarowsky et al. (2023) [89], contains the third design cycle and was published at the *31st European Conference on Information Systems*. By defining design features, the design theory is extended, and RQ 3 is finally answered. The presented reference architecture addresses RQ 4. A software prototype instantiation with currently available hardware and software is also presented, answering RQ 5. An overview is depicted below.

	Design Cycle 1 (Chapter 3)		Design Cycle 2 (Chapter 4)	Design Cycle 3 (Chapter 5)	
	RQ 1	RQ 2	RQ 3	RQ 4	RQ 5
Damarowsky et al. (2022): *Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung - Entwicklung und praktische Anwendung einer Taxonomie*. In: HMD - Praxis der Wirtschaftsinformatik, 59(1), 2022 [9].	X				
Damarowsky et al. (2023): *Understanding Augmented Reality Systems for Workflow Support – A Taxonomy and Archetypical Patterns*. Submitted to: Electronic Markets [88].	X	X			
Damarowsky and Kühnel (2022): *Conceptualization and Design of a Workflow Management System Front End for Augmented Reality Headsets*. In: ECIS 2022 [16].	X		X		
Damarowsky et al. (2023): *A Reference Architecture for a Workflow Management System Front End Designed for Augmented Reality Headsets*. In: ECIS 2023 [89].			X	X	X

Table 2. Core contributions of the dissertation and addressed research questions.

3 Design Cycle 1: ARS Taxonomy and Archetypes

3.1 Awareness of Problem

In the first design cycle of this dissertation, the goal was to ensure that an adequate taxonomy in the intersection of AR, workflows, and WFMSs exists to support IS researchers, IS designers, and IS developers in the high-level design of a HoloWFM. In the identified state of the art, this was not the case. Only a few taxonomies addressing AR, workflows, or WFMSs are available, and only two directly addressed the intersection of AR, workflows, and WFMS.

First, Klinker et al. (2018) [30] address both workflows and AR by providing a taxonomy of suitable use cases for AR-supported service workflows. Characterizing the intended application scenarios for an ARS is valuable but only indirectly supports the actual design of an ARS or HoloWFM. Second, the framework by Fellmann et al. (2017) [35] focuses on assistance systems for work processes in smart factories. With 13 dimensions and 39 characteristics, it is reasonably detailed. It addresses ARSs in that the "level of immersion" can be characterized as "augmented reality," "virtual reality," or "none." The framework is not focused on workflow execution support but contains some aspects of workflows, e.g., the degree of human interaction control with the system. However, the level of granularity is high, e.g., the specific type of AR or workflow execution support.

There are a number of other taxonomies and frameworks that contain some aspects of AR, ARSs, workflows, or WFMS, but no holistic approach to the intersection of these technologies [31–34, 90–93], which are detailed in Chapter 3.3.3. As such, in the state of the art, there was some guidance for IS researchers, IS designers, and IS developers for the high-level design of a HoloWFM, but many opportunities to improve upon it. E.g., the type of AR and workflow execution support could be characterized in much greater detail, and other technical aspects of WFMS could be included.

As such, the *identified problem* in the first step of the design cycle was the absence of a taxonomy to provide adequate support to IS researchers, IS designers, and IS developers in the high-level design of a HoloWFM. Consequently, in the first step of the first design cycle, *a new research effort was proposed* to create a novel taxonomy of ARSs supporting workflow execution with AR.

3.2 Suggestion

In the second step, a quick survey of contemporary AR systems inspired the initial *vision* for a taxonomy of ARSs supporting workflow execution with AR. In the contemporary research literature, a wide range of different ARSs is discussed, which differ, e.g., in the hardware used, the AR formats presented, or the workflow supports provided.

Figure 7. Augmented reality system presented by Blanco-Novoa et al. (2018) [38].

In Figure 7, the first example is provided by Blanco-Novoa et al. [38]. In this work, shipyards are supported through the use of mobile ARSs that utilize smartphones to augment reality with synthetic content. Using a built-in camera, visual markers, e.g., QR codes, can be recognized and then the camera image can be overlaid with context-sensitive synthetic content, e.g., material descriptions.

In contrast to mobile ARSs, Hou et al. [94] demonstrate a fixed ARS. Here, cameras and projectors are used to support users with additional content while executing an analog construction instruction (Figure **8**). The presented ARS allows the user to work hands-free and avoids the need to pull in additional devices or wear them on the body.

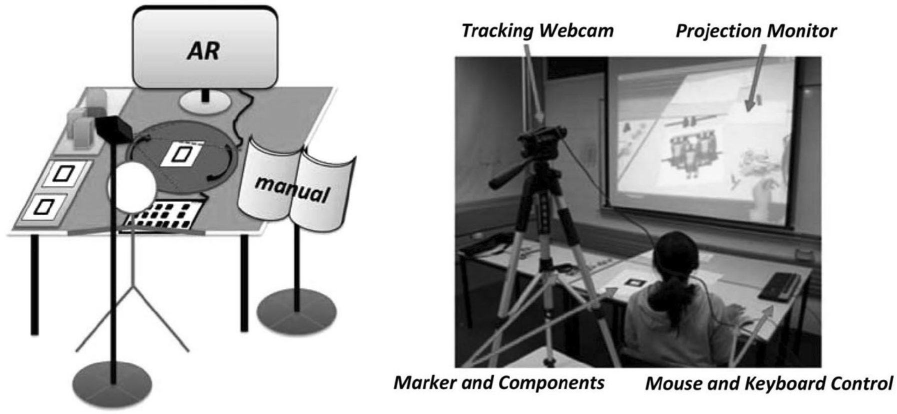


Figure 8. Stationary ARS by Hou et al. (2013) [94].

A third implementation option of ARSs is shown by Liu et al. [37]. For a medical context, this example provides particularly immersive synthetic content via an AR headset. Figure 9 shows how precise feedback is visualized on whether a medical instrument is held at the correct angle (green) or not (red) via the calculation of the relative positions between the AR headset, the marker cube highlighted in blue, and the recognized bone model.

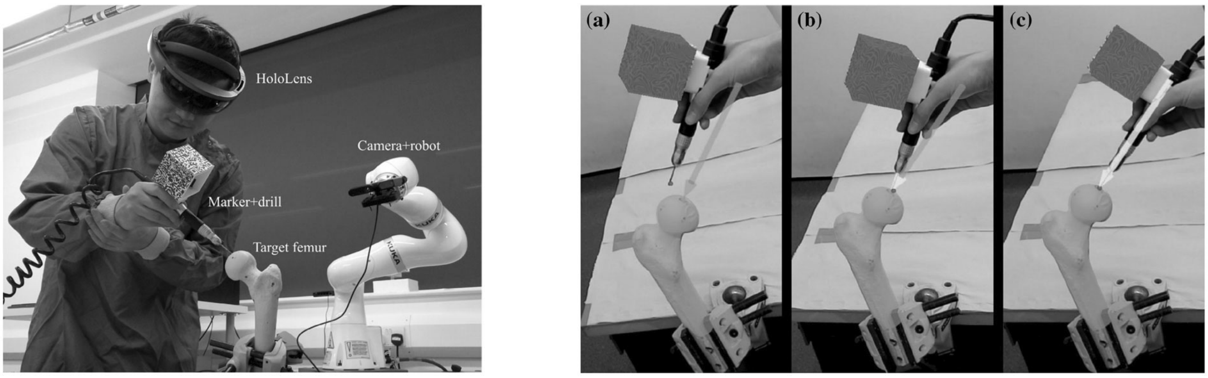


Figure 9. Augmented reality systems presented by Liu et al. (2018) [37].

In order to be able to describe and compare the three exemplary ARSs in a common nomenclature, some dimensions and characteristics already suggest themselves. For example, the type of end-user device utilized for implementation - smartphone, stationary device, or AR headset - appears to be obviously appropriate. All three ARSs use QR codes or visual markers to represent the synthetic content immersively with the real objects. The representation of the synthetic content - text, images, 2D and 3D shapes - also seems appropriate for comparison. Especially the provided workflow execution support is a most interesting dimension for practice. While the example in Figure 7 provides generally helpful information for workflow execution, the ARS in Figure 8 gives the user specific instructions for the next action based on the sensor information. In Figure 9, the sensor information is used to detect a deviation in the current execution of a workflow task and provide the user with a precise, immersive correction instruction.

This exemplary comparison of these ARSs shows clear differences as well as first approaches to dimensions and characteristics of a possible taxonomy to describe ARSs for supporting workflow execution. Consequently, the examples also raise the question of what other relevant dimensions and characteristics exist to classify ARSs comprehensively. Further, given the apparent wide range of ARSs, the question arises if clear trends in the design of ARSs can be identified, i.e., can any archetypical patterns or archetypes be identified in the data?

3.3 Development of Taxonomy and Archetypes

The research approach in the development step was two-part (Figure 10). First, the taxonomy was developed by implementing the well-known taxonomy development method by Nickerson et al. (2013) [45] in steps 1-6, detailed in Chapter 3.3.1. Afterward, a 4-step cluster analysis approach to develop the archetypes was implemented, numbered steps 7-10, described in Chapter 3.3.2.

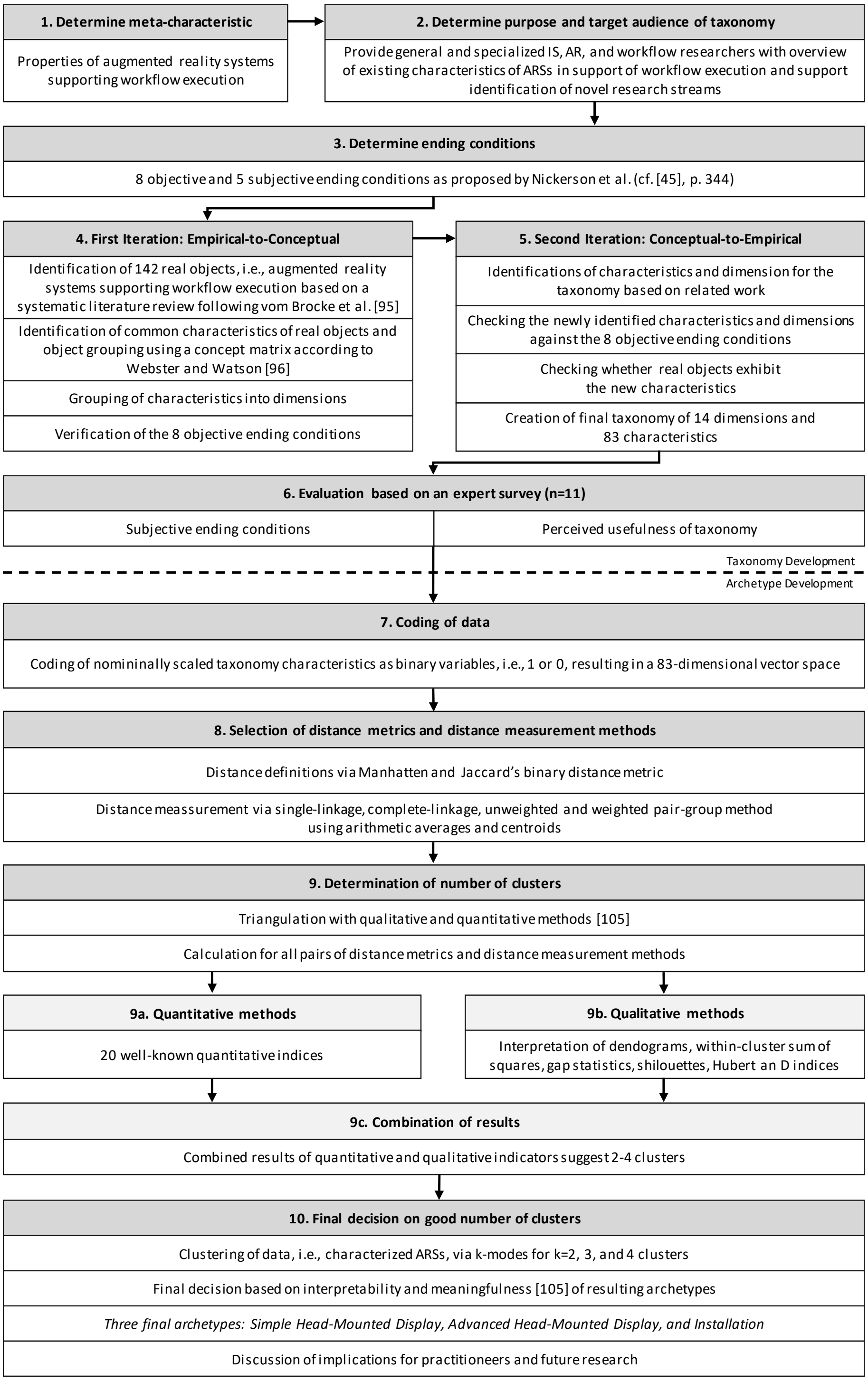


Figure 10. The research approach in the development step of the first design cycle. Steps 1-6 adapted from the taxonomy development Nickerson et al. (2013) [45].

3.3.1 Taxonomy Development

The approach to developing a taxonomy for ARSs supporting workflow execution is based on the well-known method of Nickerson et al. (2013) [45]. As Kundisch et al. (2021) [70] point out in their analysis of recent taxonomies, about two-thirds of the taxonomies published in IS journals since 2013 follow this methodological approach. The taxonomy development approach contains six steps.

Step 1 was to define a meta-characteristic, which serves as the most comprehensive characteristic at the highest level of abstraction and forms the basis for deriving dimensions and respective (sub)characteristics. For this dissertation's taxonomy, the meta-characteristic was broadly defined as *properties of ARSs supporting workflow execution* [45].

Step 2 is to define the taxonomy's purpose and target user group [45]. The latter are IS researchers, IS designers, and IS developers, who want to obtain an understanding of the existing characteristics of ARS support workflow execution with AR and want to design a HoloWFM on a high level of abstraction by formally specifying its characteristics

Step 3 is the definition of ending conditions that are used to determine when the resulting taxonomy is satisfactory. For this, the eight objective ending conditions (OEC1-8) and five subjective ending conditions (SEC1-5) proposed by Nickerson et al. (2013) [45] are shown in Table 3 and Table 4, respectively.

OEC1	All objects or a representative sample of objects have been examined.
OEC2	No object was merged with a similar object or split into multiple objects in the last iteration.
OEC3	At least one object is classified under every characteristic of every dimension.
OEC4	No new dimensions or characteristics were added in the last Iteration.
OEC5	No dimensions or characteristics were merged or split in the last iteration.
OEC6	Every dimension is unique and not repeated.
OEC7	Every characteristic is unique within its dimension.
OEC8	Each cell is unique and is not repeated.

Table 3. Objective ending conditions (OEC) by Nickerson et al. (2013) [45].

SEC1	Concise	Does the number of dimensions allow the taxonomy to be meaningful without being unwieldy or overwhelming?
SEC2	Robust	Do the dimensions and characteristics provide for differentiation among objects sufficient to be of interest?
SEC3	Comprehensive	Can all objects or a (random) sample of objects within the domain of interest be classified? Are all dimensions of the objects of interest identified?
SEC4	Extendible	Can a new dimension or a new characteristic of an existing dimension be easily added?
SEC5	Explanatory	What do the dimensions and characteristics explain about an object?

Table 4. Subjective ending conditions (SEC) by Nickerson et al. (2013) [45].

In **Step 4**, the taxonomy is iteratively constructed, with two approaches available: 1) the Empirical-to-Conceptual approach, where real objects – in this context ARSs – are identified, analyzed, and grouped by their dimensions and characteristics, and 2) the Conceptual-to-Empirical approach, where dimensions and characteristics are first conceptualized independently of real objects.

The development of the novel taxonomy was initiated with the Empirical-to-Conceptual approach (Figure 10, Step 3). Since Nickerson et al. recommend conducting a literature review to identify real objects (cf. p. 345), a structured literature review was conducted on relevant ARSs, following the method by vom Brocke et al. (2009) [95]. This well-known method was chosen as it results in a comprehensible, stringent, and sound literature review. It was chosen over alternative approaches, as it either incorporates them [96] or is more widely cited (e.g., [97]).

A summary of the structured literature review is depicted in Figure 11 and hereinafter briefly described. To obtain a broad basis of search results, a total of five databases were searched with the search string *<”augmented reality” AND ("app*" OR "system" OR "tool")>*. Following [95], the resulting 3.290 search results were subsequently selected in 5 steps: 1) duplicate removal, 2) title-based selection, 3) abstract-based selection, 4) full text-based selection, and 5) backward search.

The five selection steps were guided by four inclusion criteria. First, to ensure relevance and timeliness, articles must be published after 2010, coinciding with the release of relevant consumer products, e.g., Google Glass (2012) and Microsoft HoloLens (2015). Second, articles must be in English. Third, articles discussing ARS prototypes but also designs were included if they were complete and specific enough, i.e., no articles about individual functions. Fourth, the described ARS must address a human-oriented workflow or workflow task in some capacity, e.g., no ARSs for purely educational purposes or enhanced situational awareness without specific relation to a workflow.

The resulting set of literature included 60 articles describing ARSs supporting workflow execution. To identify the characteristics and dimensions of relevant ARSs, an author-centric analysis was performed, as described by Webster and Watson [96]. This revealed that some articles describe the same ARS, reducing the set of real objects to be analyzed from 60 to 49. A subsequent backward search yielded 905 results in total. After performing the same steps as above, 93 relevant ARSs were identified. Finally, a total of 142 ARSs were documented in a concept matrix as recommended by Webster and Watson [96], based on which their characteristics were analyzed and the ARSs grouped into dimensions. The complete concept matrix is included as part of Appendix B. Following the comments on ex-ante evaluations by Pries-Heje et al. [98], the 8 OECs were already considered at this stage of development. The taxonomy and its detailed description is presented in the next Chapter 3.3.2.

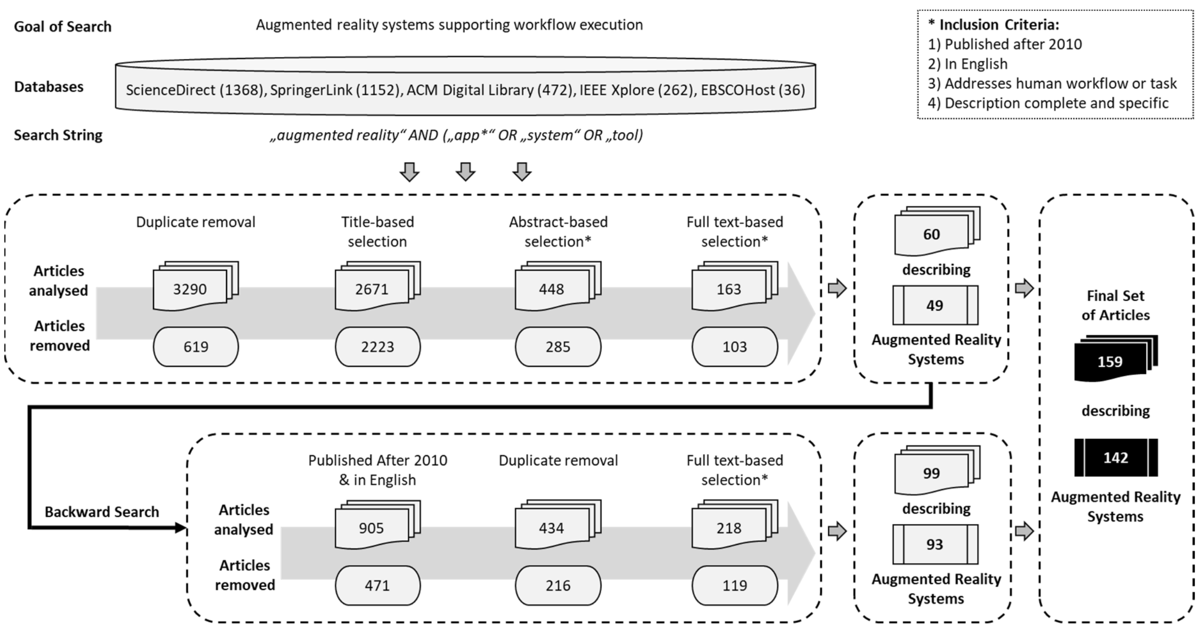


Figure 11. The literature search process for ARSs supporting workflow execution.

Step 5 of the taxonomy development method servced to verify that the OECs were met. Therefore, the taxonomy development procedure was continued with the implementation of the Conceptual-to-Empirical approach [45]. The goal was to cross-check the taxonomy with existing taxonomies of ARSs and RAs for AR and WFMS for contradictions and additional characteristics. These taxonomies were identified during the structured literature review but are not included in the final result set of 152 articles. To increase comprehensibility, the detailed comparison between the novel, developed taxonomy and the identified, existing taxonomies [32, 34, 35, 90–92] is described in Chapter 3.3.3, after the next. This comparison found no contradiction or additional characteristics that must be added to the novel taxonomy.

Lastly, there exist multiple "theoretical" characteristics within the literature which were not previously identified in the analysis of the 142 ARSs, e.g., acoustic and mechanical tracking, smell and taste as output, or various workflow management functions [15, 31, 33, 93]. However, in line with OEC3 (cf. [45], p. 344), these characteristics were not considered during development as they have not yet been used to support workflow execution or have not yet characterized any identified ARSs. However, in the second design cycle, the taxonomy was extended with multiple workflow-related characteristics to describe HoloWFM, which met the inclusion criteria of OEC3 at that stage of development.

Step 5, the Conceptual-to-Empirical approach as a second iteration, thus confirmed the identified dimensions and characteristics of the first iteration's Empirical-to-Conceptual approach (step 4), and no modification of the taxonomy, i.e., insertion of new elements, renaming, swapping, splitting, merging, promotion or demotion of elements, was necessary (cf. [70], p. 10). All 8 OECs were, therefore, fulfilled. All objects were examined (OEC1). No objects were merged or split (OEC2). Only characteristics of real ARSs were incorporated (OEC3). In the last iteration, no new dimensions or characteristics were added (OEC4) or merged or split (OEC5). The uniqueness of dimensions (OEC6) and their respective characteristics (OEC7) is ensured. Every cell of the taxonomy is unique (OEC8).

Step 6, the evaluation of the taxonomy, is detailed in Chapter 3.4, in which the five SECs were examined together with the perceived usefulness.

During the development of the taxonomy, it became clear that Nickerson et al.'s requirement of mutual exclusivity of characteristics within a dimension would collide with the reality of ARSs. To fulfill this requirement, most dimensions would need to include many combinations of characteristics for their cells. This would make the taxonomy highly unwieldy and thus collide with SEC1, i.e., the taxonomy should be concise ([45], p. 344). Thus, it was decided to incorporate dimensions that contain non-mutually exclusive characteristics, in line with other works [53, 99–101]. The final taxonomy is shown in Figure 12 and detailed in the following section.

3.3.2 Taxonomy Description

Group	Dimension	Characteristics				
Device	Type	Wearable (10)	Head-mounted (70)			
		One-hand Handheld (22)	Two-hand Handheld (29)	Stationary Device (53)		
	Architecture	Single Device (70)	Connected Devices (40)	Integrated Devices (37)		
	User System*	Single-user (100)	Multi-user (42)			
	Output	Projector (15)	Optical See-through (15)	Video See-through (77)		
		Stationary Loudspeaker (3)	Mobile Loudspeaker (20)	Haptic Output (6)		
Tracking System	ARS Position Tracking	Image Targets (68)	Relative to Visual Feature-tracked Objects (43)	Spatial Map (13)		
		Position Tracking via Networked External Optical Sensors (4)	Inertial and Orientation (26)			
		GPS Position Tracking (3)	RFID Position Tracking (2)	None (27)		
	Object Tracking	Visual Marker-based (65)	Visual Feature-based Object Tracking (61)			
		Object Tracking via Networked External Optical Sensors (1)	GPS Object Tracking (1)	RFID Object Tracking (3)	Magnetic (5)	None (23)
	User Interaction Tracking	Hand Gestures (23)	Eye-tracking (6)	Body Pose (4)		
		Mechanical & Touch (60)	Speech (21)	Pointer (3)	None (52)	
Synthetic Content	Representation	Text (78)	Image (64)	Video (19)		
		2D Form (97)	3D Form (92)	Animation (23)	Acoustic (14)	Haptic Representation (6)
	Visual Alignment	Fixed (42)	Proximity (98)	Non-transparent Overlay (50)	Transparent Overlay (52)	
	User Interaction	None (83)	Selection (49)	Manipulation (29)		
	Content Control	Manual (6)	Automatic (51)	Hybrid (82)		
Workflow	Workflow Processing*	Implicit Workflow (96)	Implicit Workflow Task (36)			
		Modelled Workflow & Implicit Workflow Engine (10)				
	Workflow Management	None (105)	Instantiate Workflow (18)	Navigate to Next or Previous Workflow Task (20)		
		Cancel Workflow (2)	Change Workflow Path (8)			
		Workflow Task Overview (7)	Switch Workflow Task (4)			
	Workflow Task Support	Process Prescription (4)	Visualise Non-visible Real Objects (32)	Real-time Data (17)		
		Automatic Deviation Detection (10)	Instruction (61)	Demonstration (5)		
		Routing (6)	Telephone (2)	Remote Assistance (18)	Teleoperation (15)	
		Documentation (17)	Data Entry (13)	Data Scanning (3)		
		Process Modelling (1)	Synthetic Object Modelling (1)			
		Auxiliary Information (127)	Workflow Training (9)			

*Note: * = dimension with mutually exclusive characteristics. (#): quantity of characteristics identified in the analyzed 142 ARSs.*

Figure 12. Taxonomy of augmented reality systems supporting workflow execution.

For clarity, the dimensions were organized into four groups: 1) device, 2) tracking system, 3) synthetic content, and 4) workflow. These are detailed in the following subsections. All characteristics are based on analyzed ARSs.

Group: Device

Some ARSs are implemented with multiple components or user-facing devices so that these ARSs express multiple characteristics in multiple dimensions. The **dimension "type"** includes *wearables* which are worn on the body and are mainly implemented as smartwatches, *head-mounted* devices, e.g., AR headsets, *one-hand handhelds*, e.g., smartphones, *two-hand handhelds*, e.g., tablets, and *stationary devices*, which can only be used at predefined locations. The **dimension "architecture"** describes the physical makeup of an ARS. All components of an ARS can be physically integrated into a *single device*, e.g., an AR headset. Alternatively, the *connected devices* can be physically separate, e.g., headset and smartphone. If components are, however, (semi-)permanently connected, they are referred to as *integrated devices*. The **exclusive dimension "user system"** describes how many persons can perceive the same synthetic content simultaneously, either one (*single-user)* or multiple *(multi-user)*. The **dimension "output"** could, in principle, address all human senses. However, only visual, acoustic, and haptic were identified as mediums. *Projectors* are stationary devices that project images locally onto surfaces and objects, while *optical see-through* devices use semi-transparent displays as projection surfaces. *Video see-through* devices overlay synthetic information on camera feeds. Acoustic output can be delivered either by (semi-)permanently installed *stationary loudspeakers* or *mobile loudspeakers,* e.g., headphones. *Haptic* output is delivered to worn devices via vibration.

Group: Tracking System

An ARS does not need to track objects, its own position, or user interaction to select the right synthetic content. Thus, all dimensions in this group are complemented by *None*. The **dimension "ARS position tracking"** describes how the ARS tracks its position with respect to the environment or specific objects in order to select, display, or align synthetic information with real objects. Many ARSs track their position only in relation to objects to display synthetic content in the correct perspective, as the ARS's relative position can be calculated from the distortion of tracked *image targets*, e.g., QR codes or images. Alternatively, *visual feature-based object tracking* calculates the ARS's relative position based on the known shape of an object. Similarly, an ARS can scan the local environment and create a *spatial map* to track its own position as well as "spatial anchors" within so that the user can fix synthetic objects on any real surface. *Networked external optical sensors*, e.g., a set of infrared cameras, can track visual markers on objects and infer their spatial orientation from the combined data. Specifically designed *inertial and orientation* sensors consist of accelerometers, gyroscopes, or magnetometers. Position information can also be obtained by using network-oriented sensors like *GPS* or *RFID* tags and sensors. The **dimension "object tracking"** includes similar *characteristics: visual marker- and visual feature-based tracking, networked external optical sensors, GPS, and RFID*. Additionally, objects can be tracked *magnetically*, which is especially utilized for medical devices. The **dimension "user interaction tracking"** includes predefined *hand gestures*, which are usually recognized via optical sensors. *Eye-tracking* tracks the direction of gaze via pupil movements or visibility. Also, the general *body pose* of the user can be used for interaction, e.g., tilting the head. Using mechanical and tactile sensors (e.g., buttons or touch screens), *mechanical & touch* can be performed. Finally, microphones enable *speech* control, and *pointers* can be used for interaction, e.g., a laser pointer tracked by an ARS's cameras.

Group: Synthetic Content

All ARSs utilize some form of synthetic content; otherwise, they are not considered an object of interest for this dissertation's taxonomy. The **dimension "representation"** correlates with the dimension "output" but describes a different aspect of the synthetic content. Consequently, it is differentiated between *text*, *images*, *videos*, *2D forms*, *3D forms*, *animations*, *acoustic*, and *haptic* representations. The **dimension "visual alignment"** describes the alignment of synthetic visual content with the environment from the user's perspective. It can be *fixed* in place, stay in *proximity* to an object or marker, or congruently overlay it, either as a *non-transparent overlay* or *transparent overlay*. In the analyzed ARSs, all acoustics were aligned as user-centric, although this could theoretically be different. The **dimension "user interaction"** broadly describes how the user interacts with the synthetic content during workflow task execution, either not at all (*none*), *selecting* content (e.g., menu items), or *manipulating* synthetic content, e.g., changing the color, shape, scaling, position, orientation or inserting and deleting objects into and from the scene. The **dimension "content control"** specifies how synthetic content during workflow task execution is instantiated. *Manual* control requires user input for every single instantiation, while *automatic* requires none. In *hybrid* approaches, some content is triggered automatically, others manually.

Group: Workflow

In this group, a broad approach is taken, and some edge cases of the usual definitions of workflows and WFMS are included. The **exclusive dimension of "workflow processing"** describes the formal representation and processing of workflows. An *implicit workflow* exists when the sequence of synthetic contents presented by an ARS is structured by logical stages, phases, triggers, or conditions, i.e., not all synthetic content is presented all the time. For example, in Metzger et al. [7], synthetic instructions are ordered in a workflow and become visible after appropriate voice commands. Vice versa, in an *implicit workflow task*, all content is always presented. E.g., in [3], medical instruments are always visualized during a surgical workflow task. A modeled workflow describes the structure of the synthetic content in some formalized notation, e.g., Petri nets or XML schemas. In this case, the ARS utilizes a *modeled workflow and implicit workflow engine*, which interprets the model and controls the presentation of the appropriate synthetic content. However, no analyzed ARS explicitly mentioned a workflow engine or WFMS.

The **dimension "workflow management"** describes a user's possibilities to control and manage workflow instances. Most analyzed ARSs offer *none*. Some ARSs allow the user to *instantiate a workflow* deliberately, to *navigate to the next or previous workflow task*, or to *cancel a workflow instance*, e.g., via a visual menu. When the workflow is branched, some ARSs can *change the workflow path* based on the user's input. Some ARSs can manage multiple active tasks and present the user with a *task overview*, i.e., showing running and/or assigned tasks, or let the user *switch workflows tasks*, i.e., execute a task from another workflow instance. As elaborated above, to fulfill OEC 3, only actually identified characteristics in existing ARSs were included in this dimension, even though the WFMS RA by the WFMC is much more extensive [15]

The **dimension "workflow task support"** specifies how synthetic content supports the user during workflow execution. *Process prescription* can be utilized to select the next best task to reach the workflow's goals. This requires an active complex processing of the relevant context to reason about the next best task, usually involving some form of process prediction and/or process simulation. For example, in Makris et al. [6], an ARS supports a machine disassembly workflow by simulating the possible motions of parts and then selects the next best part to remove by the number of possible motions. Passive workflow guidance is provided by *visualizing non-visible real objects*, e.g., visually occluded but magnetically tracked medical instruments during surgery. Also, *real-time data* can provide guidance, e.g., data from handheld measuring devices or database queries. Such data can also present the results of an *automatic deviation detection*, which detects if a workflow task is being performed incorrectly, has not yet been completed, or is completed erroneously, e.g., a medical instrument's deviation from the proper insertion angle. More active guidance is provided by *instructions*, which signal to the user what should be done and can include visual guidance on how to perform a task or handle. In a *demonstration,* this guidance is contextually specific and animated, e.g., showing where to attach and how to turn a wrench to screw in a specific bolt. Similarly, contextually specific in regards to an ARS's real-world location is dynamically *routing* a user to a specific location. For collaborative forms of workflow guidance, experts can be called in via *telephone* or more complex *remote assistance*, which enhances video telephony by simultaneously granting access to the user's field of view and other sensor inputs. This allows the remote experts to create guiding synthetic content, e.g., draw annotations in the user's field of view. An ARS can provide the user with new AR-based ways to execute workflows and tasks. Quasi the reverse of remote assistance, *teleoperation* allows the programming, controlling, and general interaction with machines or robots via an AR UI. The ARSs sensor inputs during a workflow task can be recorded as *documentation*, e.g., videos of the users' field of view. Going beyond the use of navigation and administrative menus, the user can perform manual *data entry* via text input, speech recognition, or multiple-choice selections. A semi-automatic variant of data entry is *data scanning,* in which the user directs the ARS's sensors in a specific way to collect some specific data, e.g., scanning a barcode. Also, a kind of data entry, *process modeling* encompasses a set of special synthetic contents and functions to document a workflow or process in a formal model, e.g., in the Event-driven Process Chain (EPC) notation. Similarly, *synthetic object modeling* describes the modeling, construction, stacking, assembly, etc., of synthetic objects during a computer-aided design (CAD) workflow. All supportive synthetic content that cannot be classified more specifically in the above characteristics is termed *auxiliary information,* e.g., highlighting interesting real objects. Finally, while all workflow execution, in principle, can serve as an instrument of training and many ARSs are developed and tested in artificial demonstration scenarios, *workflow training* refers to special kinds of synthetic content and functions to explicitly facilitate training or is developed explicitly for training scenarios, e.g., the user needs to repeat a training task until some execution speed is reached or a workflow is executed on a virtual training object.

3.3.3 Comparison with Existing Taxonomies of ARSs Supporting Workflow Execution

Multiple taxonomies were identified during the structured literature review, which are related to the novel taxonomy of this dissertation [32, 34, 35, 90–92].

3.3.3.1 Wang et al. (2013): Enabling Technologies of Augmented Reality

Wang et al. (2013) [32] perform an extensive literature review on ARSs. As part of their results, they characterize the identified ARSs in two respects. First, in their table 3 (p. 6, [32]), two characteristics of the dimension *User System* of this dissertation's taxonomy are described: "Single-user system" and "collaboration." The latter is equivalent to the characteristic *multi-user* of this dissertation's taxonomy, so these characteristics are no contradiction. More extensively, in Wang et al.'s table 5, they categorize their literature search results in terms of AR implementation (p. 8, [32]), depicted in Figure 13.

Number of articles classified by the categories of AR implementations (enabling technologies).

Categories of AR implementations	Number of papers	Relative percentage
Media representation		
a. Text, symbol and indicator	3	4.3
b. 2D image/video	6	8.7
c. 3D wireframe	2	2.9
d. 3D data	2	2.9
e. 3D model	51	73.9
f. Animation	5	7.3
Total	69	100.0
Computing unit		
a. Desktop,	29	47.5
b. Tablet/laptop	21	34.4
c. Hand-held	9	14.8
d. Wearable computers	2	3.3
Total	61	100.0
Interaction devices		
a. 2D-based input	53.7	47.5
b. 2D imitated controller input	1	1.7
c. Hand-held free space input	6	9.8
d. Gestural input	4	6.6
e. Tangible input	21	34.4
f. Embodied input	0	0.0
Total	61	100.0
Registration method		
a. Video see through,	46	93
b. Optical see through	3	7
Total	49	100.0
Display		
a. Monitor-based display	22	38.6
b. Monitor-based stereo glasses	0	0.0
c. Head-mounted display with monitor-based output	25	43.9
d. Video see-through HMD output	2	3.5
e. Optical see-through HMD output	8	14.0
Total	57	100.0
Trackers		
a. Magnetic	4	6.9
b. Mechanical	0	0.0
c. Acoustic	0	0.0
d. Inertial	1	1.7
e. Optical	39	67.3
f. Global tracking system: GPS	5	8.6
g. Hybrid system	9	15.5
Total	58	100.0

Figure 13. Table 5 of Wang et al. (2013) (p. 8, [32]).

While generally in line with this dissertation's taxonomy, the findings of [32] partly differ in the level of abstraction and wording. E.g., this dissertation's taxonomy refers to "two-handed handhelds," but Wang et al. differentiate "tablets" and "laptops" [32]. However, a more fine-grained breakdown of the characteristics in the taxonomy of this dissertation, such as described above, would unnecessarily inflate the taxonomy and would, therefore, not be consistent with OEC2 (cf. [45], p. 344). As such, no changes were made to this dissertation's taxonomy in light of Wang et al. [32].

3.3.3.2 Van Krevelen and Poelman (2010): Characteristics of Visual AR Displays

Van Krevelen and Poelman (2010) [34] performed a literature review to identify contemporary AR display technology. Their findings are summarized in their table 1 (p.3, [34]), which lists multiple implementation-oriented characteristics of ARSs, depicted in Figure 14.

Positioning	Head-worn				Hand-held	Spatial		
Technology	**Retinal**	**Optical**	**Video**	**Projective**	**All**	**Video**	**Optical**	**Projective**
Mobile	+	+	+	+	+	–	–	–
Outdoor use	+	±	±	+	±	–	–	–
Interaction	+	+	+	+	+	Remote	–	–
Multi-user	+	+	+	+	+	+	Limited	Limited
Brightness	+	–	+	+	Limited	+	Limited	Limited
Contrast	+	–	+	+	Limited	+	Limited	Limited
Resolution	Growing	Growing	Growing	Growing	Limited	Limited	+	+
Field-of-view	Growing	Limited	Limited	Growing	Limited	Limited	+	+
Full-colour	+	+	+	+	+	+	+	+
Stereoscopic	+	+	+	+	–	–	+	+
Dynamic refocus (eye strain)	+	–	–	+	–	–	+	+
Occlusion	±	±	+	Limited	±	+	Limited	Limited
Power economy	+	–	–	–	–	–	–	–
Opportunities	Future dominance	Current dominance			Realistic, mass-market	Cheap, off-the-shelf	Tuning, ergonomics	
Drawbacks		Tuning, tracking	Delays	Retro-reflective material	Processor, Memory limits	No see-through metaphor	Clipping	Clipping, shadows

Figure 14. Table 1 of van Krevelen and Poelman (2010) (p.3, [34]).

While their table 1 has a different scope and focus than the taxonomy developed in this dissertation and, thus, is not fully applicable, some characteristics described therein are comparable, e.g., the categories "Head-worn" and "Hand-held" (Figure 14). correspond to the dimension *Type* of this dissertation's developed taxonomy (Figure 12).

Some characteristics are very technical, i.e., "brightness" or "contrast." This level of detail was almost never present in the 142 analyzed ARSs in the fourth step of the taxonomy development method (cf. Chapter 3.3.1). Also, these characteristics are dependent on the utilized AR device, e.g., Microsoft's HoloLens [10] has a specific resolution. However, many different ARSs can be built with the HoloLens to support workflow execution. Capturing this variety while maintaining the analytical lens of workflow execution support was the goal of the taxonomy developed in this dissertation (see the defined meta-characteristic in step 1, Chapter 3.3.1). As such, no changes were made to this dissertation's taxonomy based on the findings of van Krevelen and Poelman (2010) [34].

3.3.3.3 Limbu et al. (2019): The ID4AR Framework

The ID4AR framework was developed by Limbu et al. (2019) [90] and describes eleven types of synthetic instructions called "instructional design methods" (IDM), depicted in Figure 15. All but one IDM correspond to the characteristics in the dimension *Workflow Task Support* of this dissertation's developed taxonomy (Figure 12), while the IDM "haptic feedback" is a characteristic in the dimension *Output* in the group *Device*.

IDM	Description	Visuals
Directed focus	Visual pointer for relevant objects outside the visual area of the trainee.	
Point of view video	Provides expert point-of-view video which may provide perspectives not available in a third person.	
Annotations	Allow a physical object to be annotated by the expert during task execution (similar to sticky notes but with more modalities).	
Ghost track	Allows visualization of the whole-body movement of the expert or the earlier recording of the trainees themselves for imitation and reflection.	
Highlight objects of interest	Highlight physical objects in the visual area indicating to the trainee that the expert marked it as an object of interest.	
Object enrichment	Virtually amplify the effect of the process to enable trainees to understand the consequences of certain events or actions in the process which may be too subtle to notice.	

IDM	Description	Visuals
Contextual information	Provide information about the process that is frequently changing but is important for performance.	
3D models and animation	3d models and animations assist in easy interpretation of Complex models and phenomena which require high spatial processing ability.	
Interactive virtual objects	Interactable virtual objects to practice with physical interactions relying on the 3d models and animation.	
Cues and clues	Cues and clues are pivots that trigger solution search. They can be in any form of media but should represent the solution search with a single annotation.	
Haptic feedback	Lightweight force feedback for perception and manipulation of authentic objects by means of haptic sensor, to provide feedback and guidance.	

Figure 15. ID4AR framework bei Limbu et al. (2019) [90].

These eleven IDMs are defined without consideration of workflows, workflow management, or the underlying ARSs, and as such, the framework does not have the same scope or aim as this dissertation's taxonomy (see the defined meta-characteristic in step 1, Chapter 3.3.1). The ID4AR framework does not contradict this dissertation's taxonomy, although it takes a structured and more fine-grained approach than Limbu et al. [90]. As such, no changes were made to this dissertation's taxonomy based on the findings of Limbu et al. (2019) [90].

3.3.3.4 Bräker et al. (2021) A Taxonomy of Augmented Reality Interactions

Another approach to formalize the interaction techniques enabled by ARS is the taxonomy by Bräker et al. (2021) [91], depicted in Figure 16. They also utilize the taxonomy development method by Nickerson et al. [45], and their meta-characteristic is *user interaction within services in the realm of AR*, which differs from the meta-characteristic of this dissertation's taxonomy, defined in Chapter 3.3.1 as *properties of ARSs supporting workflow execution*. Consequently, the selected set of ARSs is different, and some of the dimensions and characteristics differ markedly. However, other characteristics and dimensions are similar, e.g., the dimension "D_1 Users per device" has the same characteristics as this dissertation's taxonomy dimension *User System* (Figure 12). The dimensions D_2 – D_4 are contained in the dimensions *Type* (D_2), *User Interaction Tracking* (D_3), and *Representation* (D_4) of this dissertation's taxonomy. The dimensions D_5 – D_7 are interesting and represent the different scope and goal of Bräker et al.'s taxonomy but are incompatible with this dissertation's taxonomy and its meta-characteristic, i.e., the kind of object selected (D_5 and D_6) has no relevance to this dissertation's taxonomy and the characteristics of the dimension D_7 "sequence of interactions" are not useful to characterize an ARS in the context of workflow execution support.

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	Ges-tures	Free body move-ment	Gaze	Sensor	Eye-track-ing	Video/ image	BCI	Gene-ric 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						

Figure 16. Taxonomy of augmented reality interactions by Bräker et al. (2021) [91].

3.3.3.5 Hertel et al. (2021): A Taxonomy of AR Interaction Techniques

In Figure 17, a taxonomy of AR interaction techniques by Hertel et al. (2021) [92] is depicted. There are two groups of dimension: "task" and "modality." They also utilize the taxonomy development method by Nickerson et al. [45] and define their meta-characteristic as *people, activities, context, and technologies*." A better descriptor of the taxonomy's purpose is their underlying research question, which asks for *immersive AR interaction techniques currently investigated in the literature and their characteristics*. As such, their goal and meta-characteristic differs markedly from this dissertations's meta-characteristic, which is defined as *properties of ARSs supporting workflow execution* (cf. Chapter 3.3.1).

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 17. Taxonomy of AR interaction techniques by Hertel et al. (2021) [92].

As the focus of Hertel et al. is quite different from this dissertation's taxonomy, it is not surprising that the dimensions and characteristics differ strongly. Most of these characteristics were not present in the 142 analyzed ARSs. However, some could have been taken up, e.g., the division of *Eye Gaze* and *Head Gaze*. However, to ensure the conciseness (SEC 1) of this dissertation's taxonomy, which is already quite extensive, and due to its different focus, such more granular characteristics were not included in this dissertation's taxonomy.

3.3.3.6 Fellmann et al. (2017): A Framework for Assistance Systems to Support Work Processes in Smart Factories

A framework for assistance systems for work processes in smart factories is presented by Fellmann et al. (2017) [35] and depicted in Figure 18. The taxonomy has a different focus than this dissertation's taxonomy and contains multiple dimensions that are not relevant to it, i.e., the *Generation of Information*, aspects of the *Intelligence* of the assistance system, and the *Robustness* and *Technology Readiness Level* of the assistance system. The dimensions *Presentation*, *Control*, and *Output* are partially or fully included in this dissertation's taxonomy, i.e., the characteristics in the dimension *Control* of Fellmann et al.'s framework mean the same as the characteristics of the dimensions *Content Control* of this dissertation's taxonomy (cf. Figure 12). The *User Involvement*, *Input*, and *Extent of Immersion* do not apply to the focus of this dissertation's taxonomy. As such, the framework by Fellmann et al. does not reveal any contradictions but also does not imply necessary changes to this dissertation's taxonomy.

Information	
Generation	Presentation
Manual	Basic
Partly automated	Intermediate
Automated	Complex

Intelligence		
State detection	Context Sensitivity	Learning Aptitude
No	No	No
Tools	Task	
Machine / Product	Environment	Yes
User	User	

Interaction				
Control	User Involvement	Input	Output	Extent of Immersion
Human	Low	Traditional	Visual	None
Cooperation	Middle		Haptic / Tactile	Augmented Reality
Machine	High	Modern	Acoustic	Virtual Reality

System Characteristics		
Transportability	Robustness	Technology Readiness Level
Stationary	Low	Low (1-3)
Restricted	Middle	Middle (4-6)
Unrestricted	High	High (7-9)

Figure 18. Framework for assistance aystems to aupport work processes in smart factories by Fellmann et al. (2017) [35].

3.3.4 Archetype Development

3.3.4.1 Overall approach

Introduction

The developed taxonomy enables the precise characterization of ARSs due to the number of dimensions and characteristics. During the development process, 142 ARSs were analyzed and characterized with the taxonomy and the corresponding concept matrix is available as part of Appendix B. This concept matrix can be utilized to gain further insights into the state of the art of ARSs supporting workflow execution by developing archetypes. These effectively summarize the state of the art and offer another high-level tool to design ARSs supporting workflow execution as they state which archetypes exist and what their characteristics are and thus enable a quick orientation during the first steps of design.

To develop archetypes, in general, ***cluster analysis*** is utilized, which is part of *exploratory data analysis*. While the general aim remains to analyze sets of data objects to identify interesting characteristics, the goal of cluster analysis specifically is to facilitate exploratory data analysis by developing meaningful subgroups (*clusters*) from a set of data objects. These clusters are based on similarities – in the widest sense – among objects and are not predefined, i.e., the cluster analysis identifies clusters in the first place [102]. The precise definition of a cluster is a debated topic within the literature, including notions that the criterion for a "good" *clustering*, i.e., a set of clusters resulting from an applied *clustering algorithm*, is ultimately subjective [103]. From a large number of available cluster algorithms, the appropriate algorithm often needs to be chosen experimentally [104]. That choice depends on the goals of the cluster analysis but also on the inherent subjectivity in choosing "good" clusterings [103, 104].

Ultimately, in order to define the archetypes, the k-modes algorithm was utilized. This algorithm, however, can produce *k* clusterings for any given integer *k*. Therefore, clusterings for all reasonable numbers of clusters could be generated, e.g., k=2-15, and then choose a good clustering based on interpretability and meaningfulness based on real-world observations [105]. To first reduce the number of analyzed clusterings and second, to inform the final decision, therefore, *triangulation* was utilized, i.e., the combination of quantitative and qualitative methods [105].

More generally, criteria to determine the number of clusters can be ***external*** or ***internal criteria***. External criteria use an independently obtained partition, which is defined a priori to the clustering process [106]. However, external criteria are often not available for empirical data sets, as is the case for the data for this taxonomy. Therefore, an *internal criterion analysis* was utilized, which determines the "goodness" of a fit between input data and clustering results by using information from the clustering process itself [107]. The quantitative and qualitative indicators in the utilized triangulation approach require choices for a specific distance metric and distance measurement method, which define and measure the distances between data objects, i.e., characterized ARSs. These are discussed below.

Coding and Dimensionality of Data

The choice of distance metric depends on the coding of the data. In this case, a **binary coding of characteristics** is utilized to interpret the expression of the nominally scaled characteristics in this dissertation's taxonomy, i.e., 1 = ARS has this characteristic; 0 = ARS does not have this characteristic.

The **dimensionality of the *data vector space*** suggests itself as either the number of dimensions (14) or the number of characteristics (83) of this dissertation's taxonomy. Related works [53, 99] chose the number of dimensions of their taxonomy as the dimensionality of their binary data. To treat all dimensions equally, they normalized the value range to [0;1] for each dimension, i.e., for a taxonomy dimension with n characteristics, the value range is $[0, i/n, ..., 1]$ and $i = 1, ..., n$.

For this dissertation's taxonomy, however, this would mean that two ARSs, each offering five different sets of workflow task support functions, would both be positioned at 5/17 on the corresponding workflow task support dimensions of the 14-dimensional data vector space. This would then only describe and compare ARSs by the number of supported workflow task support functions and thus lessen the distinctiveness between ARSs. Applying this example to the rest of this dissertation's taxonomy, which contains multiple dimensions with high numbers of characteristics, would mean greatly reducing the distinctiveness between ARSs in the data vector space and a consequent loss of information.

This dissertation, therefore, opts for an 83-dimensional data vector space, with each dimension corresponding to a characteristic in the taxonomy and a binary value range of [0,1]. Table 5 shows an excerpt from the thusly coded data, which corresponds to the concept matrix that is part of Appendix B.

Characteristic / ARS ID	1	2	3	4	5	6	7	8	9	…	142
Type: Wearable	0	0	0	0	0	0	0	0	0	…	0
Type: Head-mounted	1	0	1	1	1	1	1	0	0	…	0
Type: One-hand Handheld	1	1	0	0	0	0	1	1	1	…	1
Type: Two-hand Handheld	0	0	0	0	0	0	1	0	0	…	1
Type: Stationary Device	0	0	1	0	0	0	0	0	0	…	0
…	…	…	…	…	…	…	…	…	…	…	…
Workflow Task Support: Workflow Training	0	0	0	0	0	0	0	0	0	….	0

Table 5. Example of binary coded data vector space.

Distance Metric and Distance Measurement

Since the data is, thus, binary, the standard Euclidian distance metric is not appropriate. Two well-known alternative distance metrics for binary data are the Manhattan distance and Jaccard's distance (e.g., 53, 99). The ***Manhattan distance*** for two objects A and B is defined as the sum of differing dimensions [108]. For this dissertation's 83-dimensional data, this means that the distance is an integer between 0 and 83. ***Jaccard's distance*** defines the distance between two objects A and B as the ratio of 1) the sum of different dimensions to 2) the sum of the different dimensions plus those dimensions, which are positive for both objects [109, 110]. Thus, the distance is a real number between 0 and 1.

To measure the distance between the clusters and select the next two clusters to merge, multiple well-known approaches are available for binary data [111]. One group of approaches compares individual members of clusters. The two clusters, A and B, with the minimum distance between any two of their members d(a,b) can be chosen, also known as ***single-linkage*** or *single link clustering* [112, 113]. This approach gives more importance to the regions where the clusters as closest and thus neglects the overall cluster structures, thus making it a *local* similarity-based approach [111]. The reverse approach is the merging of the two clusters with the maximum distance between any two of their members, also known as ***complete-linkage*** or *complete link clustering* [114]. This method also considers the overall shapes of the clusters and generally leads to more compact clusters. It is, however, also sensitive to outliers [111].

A second group of approaches considers cluster averages. The distance between two clusters can be measured by calculating the average pair-wise distances for all members of the clusters. This can be done via the ***unweighted pair-group method using arithmetic averages*** (UPGMA), which simply calculates the average distance between the cluster [115]. This method can be extended by considering the average distances of previously merged clusters, known as the ***weighted pair-group method using an arithmetic average*** (WGPMA) [115]. Another approach is to measure the distances between the centroids between two clusters, known in its simple form as the ***unweighted pair-group method using centroids*** (UPGMC) [115]. For this approach, the distance between the centroids of previously merged clusters can also be considered, known as the ***weighted pair-group method using centroids*** (WPGMC) [116]. The key formulas for the distance metrics and distance measurements are available as part of Appendix F.

3.3.4.2 Number of clusters

Quantitative Methods

A great variety of indices are available to calculate the ideal number of clusters for a data set. E.g., the well-known *R* package *NbClust* implements 30 such indices [117] (See Appendix F for the key formulas of the indices). However, as Dimitriadou et al. [118] find in a comparison of clustering indices for different binary data sets, the reliability of available indices to find good clusterings depends heavily on the underlying data set [118]. Therefore, the resulting clusterings can only be a supportive factor in the final decision for the appropriate clustering. As the data does not suggest otherwise, all 30 indices from the *R* package *NbClust* were utilized, each with the Manhattan distance and Jaccard's distance, as well as the distance measuring methods single-linkage, complete-linkage, UPGMA, WPGMA, UPGMC, and WPGMC. The utilized indices of the *NbClust* package are detailed in Charrad et al. [117]. Some indices did not work for the data as there were too many zeros, though. The Hubert Index and D Index are qualitative methods and are discussed later. To ensure a degree of interpretability and meaningfulness of the clustering, an upper limit of 15 clusters for the indices was chosen, following the recommendations of the *R* package *NbClust* [117]. The complete results for the 19 remaining indices are available as part of Appendix F, and a summary of the prescribed number of clusters for each pair of distance metrics and the measurement methods is available as part of Appendix F.

Qualitative Methods

As part of the triangulation approach [105], this dissertation oriented itself methodically on established works [53, 99] and utilized a number of qualitative approaches, detailed below. Where applicable, the methods for all combinations of distance metrics and measurement methods were implemented.

One graphical indicator is the calculation of the **within-cluster sum of squares** (WSS) (also known as the *(total) intra-cluster variance)*, which measures the compactness of the clusters and produces a graph that monotonically declines with the number of clusters. An appropriate number of clusters is then indicated with an "elbow" in the graph, i.e., the number of clusters from where onwards a significant, roughly elbow-shaped flattening of the decrease appears [119]. For implementation, the software *R* was utilized via the *fviz_nbclust()* function of the *factoextra* package. As a clustering algorithm, the *Partitioning Around Medoids* (PAM, "cluster::pam") (also known as *k-medoids*) was used, as it is more robust to outliers than the standard *k-means* algorithm and measures dissimilarities instead of summed Euclidian squares, suited for the binary data [120]. See Appendix F for the plots. For the data here, this flattening is not very distinct, but four (main) clusters mostly fulfill these criteria, with a possibility of eight sub-clusters contained therein.

An approach to formalize the "elbow heuristic" and support the decision-making process is **gap statistics**. These compare the WSS for each number of clusters k with their expected values under a null reference distribution of the data. The gap statistic then indicates the "gaps" between the clusterings with k clusters and a random uniform distribution of points [119]. The gap statistics test was implemented in *R* with the *fviz_nbclust()* function from the *factoextra* package. The *PAM* clustering method was utilized. See Appendix F for the plots. Following the interpretation of gap statistics by Tibshirani et al. [119], the plots indicate four well-separated clusters and eight less-separated sub-clusters within. Even smaller, less defined clusters are indicated as well.

Another criterion for deciding on a good number of clusters is the **average silhouette** approach. This method measures the quality of clusterings with *k* clusters by how well the objects lie within their respective clusters, with high values indicating good fits [120]. Again, *R* was used for implementation, using the *fviz_nbclust()* function from the *factoextra* package. Also, used the *PAM* clustering method was chosen again. The plots indicate two clusters as the best choice. See Appendix J for the plots.

The plots of the **dendrograms** are available as part of Appendix F. For both distance metrics, the centroid methods UPGMC and WPGMC did not lead to a *monotone distance* measure, i.e., the resulting dendrograms exhibited so-called inversions or reversals and thus yielded no insightful interpretation. The single-linkage method produced a stairway-formed dendrogram, i.e., each cluster contained approximately one less object than the previous. The interpretation of the remaining dendrograms suggested two, three, five, or six clusters.

The **Hubert Index** and the **D Index** are graphical indices contained in the *NbClust* package. The plots are depicted as part of Appendix F. For both indices, a good number of clusters is indicated by a significant "knee" in the plot, corresponding to a significant peak in the plot of the second differences (right-hand side of the plots) [117]. The indices suggest mostly three but also four to seven clusters.

3.3.4.3 Combination of results

The quantitative and qualitative results show a strong tendency towards 2-4 clusters, but other clusterings are also suggested. An overview of the results of the quantitative indices, the qualitative indices, and the combined results are included as part of Appendix F. Table 6 shows an excerpt for the dominant results of two to four clusters.

	Manhattan distance						Jaccard's distance					
No. of clusters	Single-linkage	Complete-linkage	UPGMA	WPGMA	UPGMC	WPGMC	Single-linkage	Complete-linkage	UPGMA	WPGMA	UPGMC	WPGMC
2	13	5	13	3	2	2	2	10	10	3	10	10
3	14	3-4	3	8	2-3	2-5	1	1	2-4	9-10	2	4
4	2	3-5	3-4	2	2	2-3	3	2	4-5	4	5	2

Table 6. Combined suggested cluster numbers from qualitative and quantitative indications.

Subsequently, the K-Modes algorithm was utilized via the *R* function *kmodes()* of the *klaR* package to produce 2, 3, and 4 archetypes and these were discussed among the researchers co-authoring this part of the dissertation regarding their interpretability and meaningfulness based on real-world observations [105]. Based on these criteria, ***three archetypes*** were the most meaningful and interpretable. The alternative two and four archetype solutions are shown as part of Appendix F, and the three archetypes are profiled in Table 7 and discussed in the next chapter below.

3.3.5 Archetype Descriptions

	Archetype 1 „Advanced HMD“	Archetype 2 „Simple HMD“	Archetype 3 „Installation“
Type	Head-mounted	*	Stationary Device
Architecture	Single Device	Single Device	*
User System	Single-user	Single-user	Multi-user
Output	Optical See-through	Video See-through	Video See-through
ARS Position Tracking	Relative to Visual Feature-tracked Objects	Image Targets	*
Object Tracking	Visual Feature-based Object Tracking	Visual Marker-based Object Tracking	*
User Interaction Tracking	*	Mechanical & Touch	None
Representation	Text, Image, 2D Form, 3D Form	Text, Image, 2D Form, 3D Form	2D Form, 3D Form
Visual Alignment	Proximity	Proximity	*
User Interaction	Selection	None	None
Content Control	Hybrid	Hybrid	Automatic
Workflow Processing	Implicit Workflow	Implicit Workflow	Implicit Workflow Task
Workflow Management	None	None	None
Workflow Task Support	Instruction, Auxiliary Information	Auxiliary Information	Auxiliary Information

* = archetype is not strongly specified, i.e., exhibits no strong characteristic in this dimension.

Table 7. Archetypes of ARSs supporting workflow execution with AR.

The three developed archetypes of ARSs supporting workflow execution with AR summarize the state of the art and were utilized at the end of the first design cycle to gain a first high-level understanding of what the characteristics of a HoloWFM could be and framed the later development process.

The **first ARS archetype (*Advanced HMD*)** utilizes a head-mounted, single device for a single user, presenting information with an optical see-through display, e.g., a Microsoft HoloLens. Objects are tracked via visual features, and the ARS calculates its position relative to these objects. AR support for workflows is provided by instructions for tasks and auxiliary information. These are visualized via text, image, 2D, and 3D forms and presented in proximity to tracked objects. The user can select certain synthetic content, e.g., items in an AR menu, and the content is controlled hybrid. However, the first archetype is not characterized by a dominant mode of user interaction tracking. The ARS internal representation of workflows is implicit, and no workflow management functions are provided.

The **second ARS archetype (*Simple HMD*)** is also a single-user, single-device system but utilizes see-through video technology, similar to VR headsets. The ARS calculates its position via recognition of image targets and tracks objects similarly with visual markers. User interaction is tracked via mechanical and touch inputs, also utilized for hybrid content control. However, the archetype is also characterized by offering no user interaction with the synthetic content itself, i.e., the user can control which AR content is presented but can not interact with it actively. This content is auxiliary information in support of task execution, presented in the proximity of recognized visual markers, and can be text, images, 2D and 3D forms. The internal representation of workflows is implicit, and no workflow management functions are provided.

The **third ARS archetype (*Installation*)** is a stationary device for multiple simultaneous users. The synthetic content takes the form of 2D and 3D forms, viewed through a display of sorts, i.e., video see-through, explaining how multiple users can see the same content. The information displayed is auxiliary information aimed at supporting specific workflow tasks rather than entire workflows, i.e., a series of tasks. No user interaction is possible, and consequently, no user interaction tracking takes place, and the synthetic content is controlled automatically. The third archetype is not characterized by an ARS position or object tracking method. Unsurprisingly, the archetype also does not utilize visual alignment.

The defined three archetypes do not represent every ARS in the literature but provide an overview and condense the state of the art of ARS in support of workflow execution, management, and control. In this regard, the archetypes represent the underlying data well in that none of them use explicit workflow modeling or offer workflow management functions. Also, the provided workflow task support is very limited, i.e., instructions and generally auxiliary information. This represents clear opportunities for research and development projects for ARSs supporting more numerous and complex workflow management and control functionalities and workflow execution support. Especially when further exploring the underlying dataset, it is clear that most analyzed ARSs focus on specific application scenarios and singular functions. Proof of concepts and demonstrations of innovative approaches to specific problems are clearly valuable for the IS knowledge base. However, it is probable that significant challenges and research opportunities would arise through the integration of multiple different approaches and the consideration of multiple application scenarios ARS simultaneously.

The general lack of workflow management and control functions as well as workflow execution support in the analyzed ARSs may be explained by the lack of formal workflow modeling. Only 10 ARSs use some kind of formal modeling for the logical structure of the synthetic content, none used BPMN, and none explicitly mentioned a workflow engine or WFMS to process these workflow models. Therefore, one promising avenue of research seems to be the integration of ARSs with well-known concepts of workflow management, i.e., workflow management systems (c.f. [15]) and workflow modeling via BPMN.

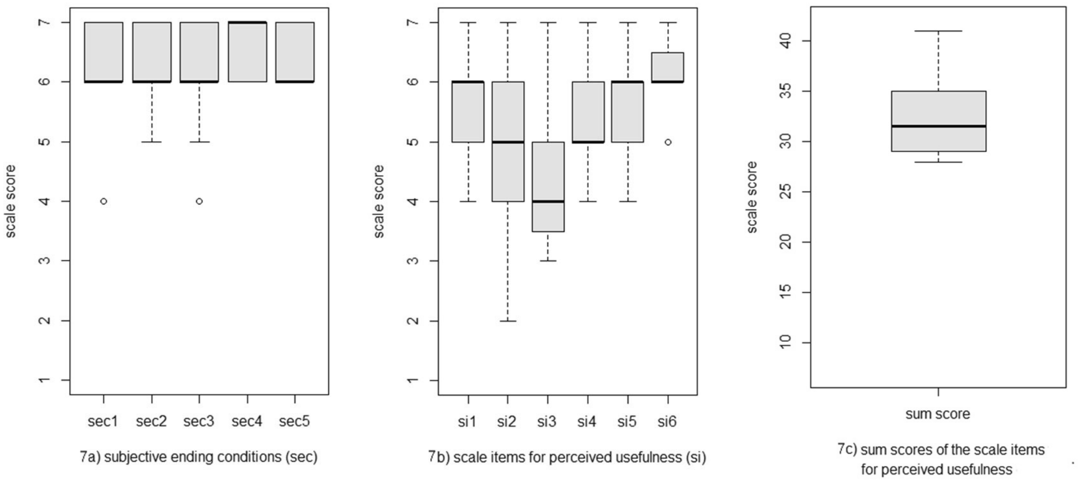
3.4 Evaluation

As described in Chapter 2.7, the evaluation of the taxonomy in the first design cycle comprises four steps: 1) the rigorous development of the taxonomy according to the method by Nickerson et al. [45] 2) an ex-ante evaluation of the OECs, 3) an ex-post evaluation of the SECs, and 4) a summative evaluation of the perceived usefulness of the taxonomy. While the first step was executed continuously during taxonomy development, the second step, the ex-ante evaluation, was performed during iterations 1 and 2 (Figure **10**, steps 4-5) of the taxonomy development process, in which the OECs were already considered (see Chapter 3.3.1).

Regarding the third step of the evaluation, Nickerson et al. [45] highlight the importance of the SECs (cf. Table 4). To assess these conditions and to realize a evaluation of the perceived usefulness of the taxonomy – the fourth step – an expert survey was conducted via questionnaire. The assessment of perceived usefulness is directly recommended by Nickerson et al. for summative evaluations and is also one of the most commonly used evaluation criteria for taxonomies [45, 121]. Since the perceived usefulness is a construct that is not directly measurable, this dissertation relied on the six well-known scale items (SIs) by Davis (1989) [78] as part of the summative evaluation: quickness (SI1), performance (SI2), productivity (SI3), effectiveness (SI4), ease (SI5), and overall utility (SI6). Both SEC and SI were specified for the application context of this dissertation, i.e., for a taxonomy for classifying ARSs supporting workflow execution (SECs) and for applying the taxonomy for task accomplishment (SIs), such as for ARS selection.

The initial questionnaire included an introductory text about the research project, the taxonomy itself, a short explanation of each dimension and characteristic, and associated questions/statements on the SECs and SIs. For data collection, interval-scaled verbal-numeric 7-point Likert-style scales were used. In a pretest, the initial questionnaire was provided to five experienced testers. The received feedback indicated that additional information about the taxonomy and context of use would be helpful in answering the questions. Therefore, the final questionnaire was supplemented with short examples and a comprehensive handout. To provide transparency and follow principles of scientific rigor, the final questionnaire can be found as part of Appendix F.

In choosing the sample size, this dissertation follows established practice, as discussed in Chapter 2.7, and aimed at 12 participants. Based on an expected response rate of 50%, the questionnaire was sent to a total of 25 experts and 12 completed questionnaires were received (actual response rate: 48%). The respondents included a Senior Manager, an IT Project Manager, an AR Engineer, a Software & Solution Engineer, a Multimedia Designer, a Software Developer, two Heads of Research, and four Research Associates (one postDoc), all working in the ARS and workflow domain. Among the experts, six work in large, 3 in medium-sized, and 2 in micro-companies/organizations.



Note. sec1 = conciseness, sec2 = robustness, sec3 = comprehensiveness, sec4 = extendibility, sec5 = explanatory power, si1 = quickness, si2 = performance, si3 = productivity, si4 = effectiveness, si5 = ease, si6 = overall utility.

Figure 19. Box plots of the evaluation results for the perceived usefulness of the taxonomy.

The results of the expert survey are shown as boxplots in Figure 19. The y-axis of each boxplot corresponds to the interval-scaled verbal-numeric 7-point Likert-style scales from the questionnaire. On the x-axis, the scale items of the SEC (7a), the perceived usefulness (7b), and the sum score of the scale items of the perceived usefulness (7c) are plotted. Each boxplot is composed of the same elements. The median of the data is shown with a bold line. The grey box represents 50% of the data and starts at the 25% quantile (Q1) and ends at the 75% quantile (Q3). The minimum and maximum of the data, both excluding outliers, are marked above and below the grey box with a thin line connected to the box with a dashed line. The outliers are shown as circles and are defined as those data which lie either 1.5 interquartile ranges (Q3-Q1) above Q3 or below Q1. The underlying data for the boxplots can be found as part of Appendix F.

The median (m) of the results for SEC1, SEC2, SEC3, and SEC 5 is, in each case, m=6, and the median of the results for SEC 4 is even m=7. In the evaluation of SEC1 and SEC3, outliers show up at the level of 4 (partial agreement). However, the overall results show a very high level of agreement, indicating the subjective ending conditions to be fulfilled. Consequently, the taxonomy can be considered concise, robust, comprehensive, extendible, and explanatory.

High levels of agreement were also received for SI1, SI5, and SI6, each with a median of m=6. The median of SI4 is m=5, with the voting results fluctuating between 4 (partial agreement) and 7 (strong agreement). The median of SI2 is also m=5 and, thus, above the scale level of a partial agreement but shows a greater fluctuation than SI4 (scale levels 2 to 7). This results from two respondents scoring below the level of partial agreement. The median of SI3 is m=4 (partial agreement). Here, too, the voting results fluctuate quite strongly between the scale levels of 3 and 7. Looking at the medians alone, SI1, SI2, SI4, SI5, and SI6 show a rating above partial agreement, from which it was concluded that the perceived usefulness of the taxonomy was generally rated positively. In particular, the high rating of SI6 with m=6 can be seen as a confirmation of the overall usefulness of the taxonomy. This interpretation is also supported by the boxplot of the sum scores of the perceived usefulness calculated from the sums of the scale items of the questionnaire responses. In this boxplot, on a scale of 7-42, the mean is 32.5, and the median is 31.5.

Due to the large fluctuations in the voting results for SI2 and Si3, contacted the experts were contacted again and offered the possibility to justify results below the scale level of 4 in order to identify possible adaptation potentials for the taxonomy. Three participants responded to this follow-up question. Based on the responses, it appeared that the use of taxonomies is not widespread in practice, which makes it difficult to assess their impact on work performance (SI2) and productivity (SI3). However, it stands to reason that this feedback does not limit the overall usefulness of the taxonomy. It did, however, inspire the archetype development to provide more utility to practitioners.

3.5 Conclusion

Summary of the First Design Cycle

In the first cycle, rigorously following the methodology of Nickerson et al. [45], a taxonomy of ARSs in support of workflow execution was developed based on the analysis of 142 ARSs. The taxonomy, consisting of 14 dimensions and 83 characteristics, was positively evaluated ex-ante with OECs and ex-post with SECs and the perceived usefulness. Thus, the first research question (RQ 1) for the characteristics and dimensions of a taxonomy of augmented reality systems supporting workflow execution was answered.

Building on this dataset, an exploratory data analysis was performed, and three archetypes were developed, summarizing the contemporary state of the art of ARSs in support of workflow execution. These archetypes answer the second research question (RQ 2) for the characteristics of archetypes of augmented reality systems supporting workflow execution.

Limitations of the First Design Cycle

For an adequate interpretation of the results of the first design cycle, the following limitations should be considered. First, the taxonomy was based on the relevant literature identified with the systematic literature review. Although comprehensive, it is possible that some relevant ARSs were missed, and consequently, relevant characteristics and dimensions were not identified, as not all theoretically possible characteristics were included, but only those identified in the analyzed ARSs. However, the amount of analyzed ARSs reduces the probability of missing relevant characteristics. This also means that the taxonomy will require updating as AR technology advances. Known but hitherto not implemented features might be finally realized, e.g., utilization of the sensory channel of smell. Also, some characteristics suggested themselves and might become interesting in the future but were not taken up for the taxonomy since ARSs lacked a detailed description of them, e.g., the operation system (e.g., Windows, Android, iOS, etc.) or the specific device (e.g., Microsoft HoloLens, Varjo XR-3, etc.). Of course, new, hitherto unsuspected characteristics may emerge that are important for an effective overview of ARSs in support of workflow execution.

Second, an inherent weakness of any taxonomy development is the subjectivity of the underlying design decisions. As the comparison with the related work showed, other divisions of characteristics are possible [30–32, 122]. However, the design choices are underpinned by the objective and subjective ending conditions of Nickerson et al. [45] and the evaluation of the taxonomy with experts. Although the number of experts was low, it was in line with established practice (see Chapter 2.7). Nonetheless, more experts would strengthen the validity of the survey results.

Third, the descriptions of the ARSs were often difficult to interpret in the context of the taxonomy as they were often ambiguous, or characteristics had to be inferred indirectly or identified in depictions and figures as they were not described clearly and directly. Of course, this is to be expected as the respective authors could not have been aware of the taxonomy and, thus, which characteristics are relevant to describe an ARS adequately. While some ARSs, therefore, might have been classified erroneously, this demonstrates how the developed taxonomy can be valuable for the IS community.

Fourth, cluster analysis and the choice of clusterings are inherently subjective. While the clustering with three archetypes was based on both quantitative and qualitative indices, other clusterings are possible. Some indices, for example, suggest sub-archetypes as well. Additionally, the k-means algorithm is only a heuristic and can, in principle, yield different archetypes.

Reflections on the Results of the First Design Cycle

Based on the evaluation results, a useful tool for the high-level design of a HoloWFM has been developed. The archetypes provide a first orientation and mental framework for IS researchers, IS designers, and IS developers for the design of a HoloWFM instantiation, and the taxonomy provides detailed characteristics. However, which specific characteristics of the taxonomy actually define HoloWFM remains unclear at the end of the first design cycle. Some suggest themselves, stemming from the archetypes, but others are unknown. Also, the workflow-related characteristics are obviously missing many well-known workflow management and support functions (cf. WFMS RA by the Workflow Management Coalition [15]). These reflections prompted the start of the second design cycle, in which the taxonomy is extended with those characteristics that are necessary to adequately describe HoloWFM – as soon as HoloWFM has been well-defined, in line with the inclusion criteria OEC3. To achieve this level of characterization of HoloWFM, a design theory is developed in the second design cycle. Since archetypes and taxonomies are highly abstract tools for designing, developing, and instantiating ISs, the second DSR cycle also serves to develop an additional less-abstract tool: the HoloWFM DT.

4 Design Cycle 2: Design Theory

4.1 Awareness of Problem

The goal of the second design cycle was to provide IS researchers, IS designers, and IS developers with a DT for a HoloWFM, which formalizes the requirements for a HoloWFM as well as principles of design to address these design requirements (cf. Chapters 2.1 and 2.3).

To ensure that the second design cycle was based on the most up-to-date literature, a total of three structured literature reviews were performed to ascertain the state of the art, following the well-known methodology of vom Brocke et al. [95]. The first two SLRs aimed at identifying the state-of-the-art RAs of WFMSs and AR, which then informed the third SLR for existing approaches to ARSs featuring comprehensive workflow front ends.

The first review, depicted in Figure 20, aimed at identifying WFMS RAs. Since processes and workflow are sometimes used interchangeably, the search string included both terms. Also, not only architectures but ontologies of important WFMS concepts and their relationship could've been interesting and were, thus, included as search terms both. A total of five articles were identified. Lin et al. [123] present a service-oriented architecture for a "visual scientific" WFMS. A cloud-based WFMS for scientific workflows is discussed in Rodriguez et al. [124]. Pourmirza et al. [125] present an architecture for BPM systems, which builds upon the RAs of the Workflow Management Coalition [15] and Grefen et al. [126]. Although interesting, the clearly most representative and important RA for WFMSs is, with 23 mentions in 171 reviewed articles, still the WFMS RA by the Workflow Management Coalition [15].

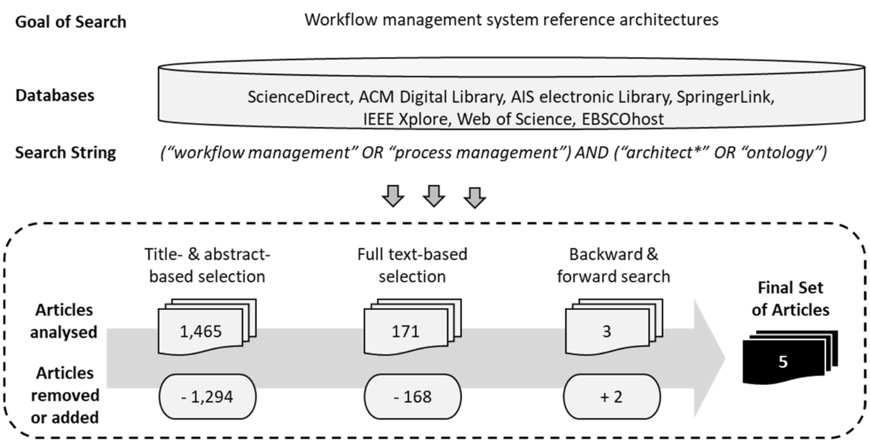


Figure 20. The literature search process for WFMS reference architectures.

The second review, summarized in Figure 21, had the goal of identifying RAs for AR. Since augmented reality and mixed reality are sometimes used interchangeably, the search string included both terms. Also, not only architectures but ontologies of important AR concepts and their relationship could have been interesting and were, thus, included both as search terms. First, an article by Reicher et al. [127] was identified, and a subsequent forward search identified an article by MacWilliams et al. [33], who fully include and extend the former, describing subsystems of ARSs and the relationships between the concepts and components involved.

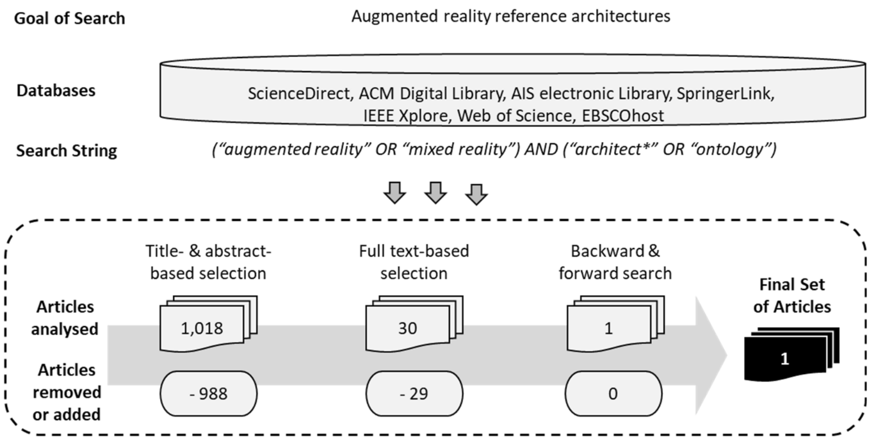


Figure 21. The literature search process for AR reference architectures.

Grounded in the state of the art for WFMSs and AR, the third structured literature review, depicted in Figure 22, thus aimed at identifying ARSs featuring comprehensive WFMS front ends. This review was conducted even though the literature review during the taxonomy development in the first design cycle aimed at identifying a similar set of literature. However, their foci slightly differ. In the first cycle's literature review for taxonomy development, the relevant ARSs should support workflow execution in general. The structured literature review in the second design cycle focused on a subset of these ARSs that support comprehensive WFMS front end functionality, i.e., the workflow management and control capabilities defined in the WFMS RA by the Workflow Management Coalition ([15], p.31-35), as defined in Chapter 1. This subset of ARSs does not necessarily support workflow execution in other ways, i.e., helpful AR-based information without front end capabilities. As such, this third literature review was conducted to rigorously ensure that no relevant ARSs were missed, which could support the definition of the HoloWFM DT in the second design cycle. However, no ARSs could be identified that offered such comprehensive WFMS front end capabilities. Only partial WFMS front end functions were identified in ARSs that were previously known from the first design cycle.

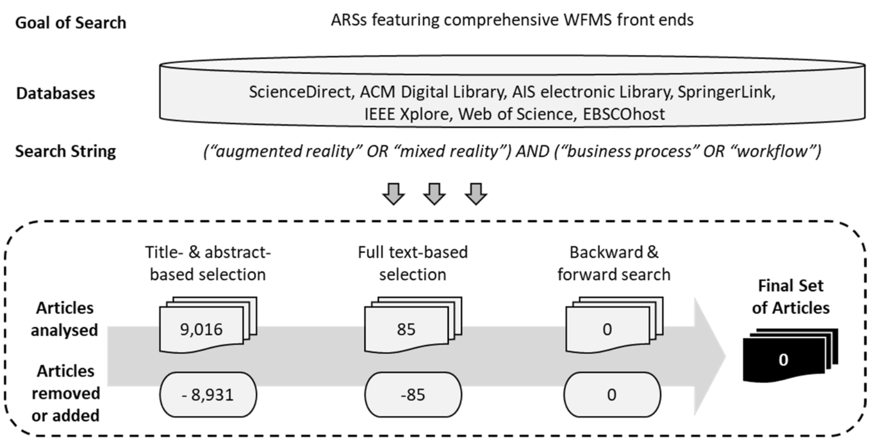


Figure 22. The literature search process for ARSs featuring comprehensive WFMS front ends.

Therefore, the *identified problem* in the awareness of problem phase of the second design cycle was the absence of formalized design knowledge, esp. meta-requirements and general principles of design of HoloWFMs to support IS researchers, IS designers, and IS developers during the design, development, and instantiation of HoloWFMs. Consequently, in the first step of the second design cycle, *a new research effort was proposed* to develop formalized design knowledge in the form of a DT.

4.2 Suggestion

The *vision* for the second design cycle was an initial DT and UI design for a HoloWFM, which were based on empirical findings as well as literature. As the first design cycle revealed, a HoloWFM had not previously been conceptualized. As such, gathering input from potential users was part of the vision for this design cycle.

4.3 Development of Design Theory and UI Design

4.3.1 Methodical Approach to Develop Design Principles

To methodically underpin the development of the DPs and DT, the methodological approach to DP development by Möller et al. [82] was utilized (Figure 23). This method distinguishes two basic principles for developing DPs. A *reflective* approach would first define a specific problem, then design an artifact to solve this problem, and finally extract DPs ex-post from the developed artifact. The alternative strategy – utilized in this dissertation – is the *supportive* approach. This procedure would first identify a suitable knowledge base, elicit DRs, and then formulate DPs, which finally aid in designing the problem-solving artifact [82].

In the second design cycle of this dissertation, two moderated focus groups (MFG) were conducted with the gathered participants representing the knowledge base (see Chapter 4.3.2). During the MFGs, DRs (and partially DPs) were gathered. Finally, DPs were formulated based on the comments of the MFG participants and state-of-practice literature (see Chapter 4.3.3).

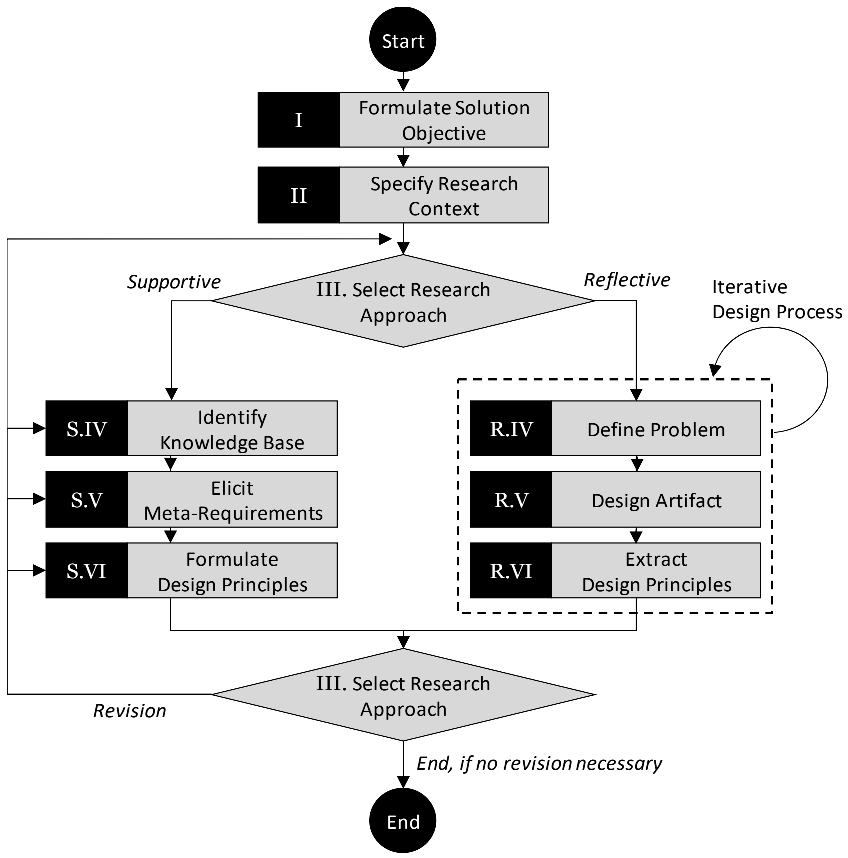


Figure 23. Method for design principle development by Möller et al. [82].

4.3.2 Moderated Focus Groups

To rigorously establish the DRs for HoloWFM, two MFGs were conducted. An MFG is a qualitative research method where a moderator guides a group discussion and which relies on the interaction between participants to generate insights [83]. For the number of groups and participants, the MFGs followed the established practices discussed in Chapter 2.8. Therefore, two MFGs were conducted to identify DRs, and two further MFGs were conducted as part of the evaluation (see Chapter 4.4). All groups consisted of a mix of workflow and AR researchers, AR practitioners, and AR users, all having several years of experience. The first group (n=12) included six IS researchers, two AR UI and user experience (UX) designers, one AR engineer, and three end-users of headset-based ARS. The second group (m=10) included four IS researchers, three AR engineers, and three end-users of headset-based ARS. The MFG procedure consisted of four steps: 1) motivating the research topic, 2) discussing the problem context, 3) protocolling, and 4) evaluating the protocols through manual DR clustering. In both groups, the topic was approached by discussing the previously identified RAs of WFMSs and AR (see Chapter 4.1) to establish a common understanding of the topic.

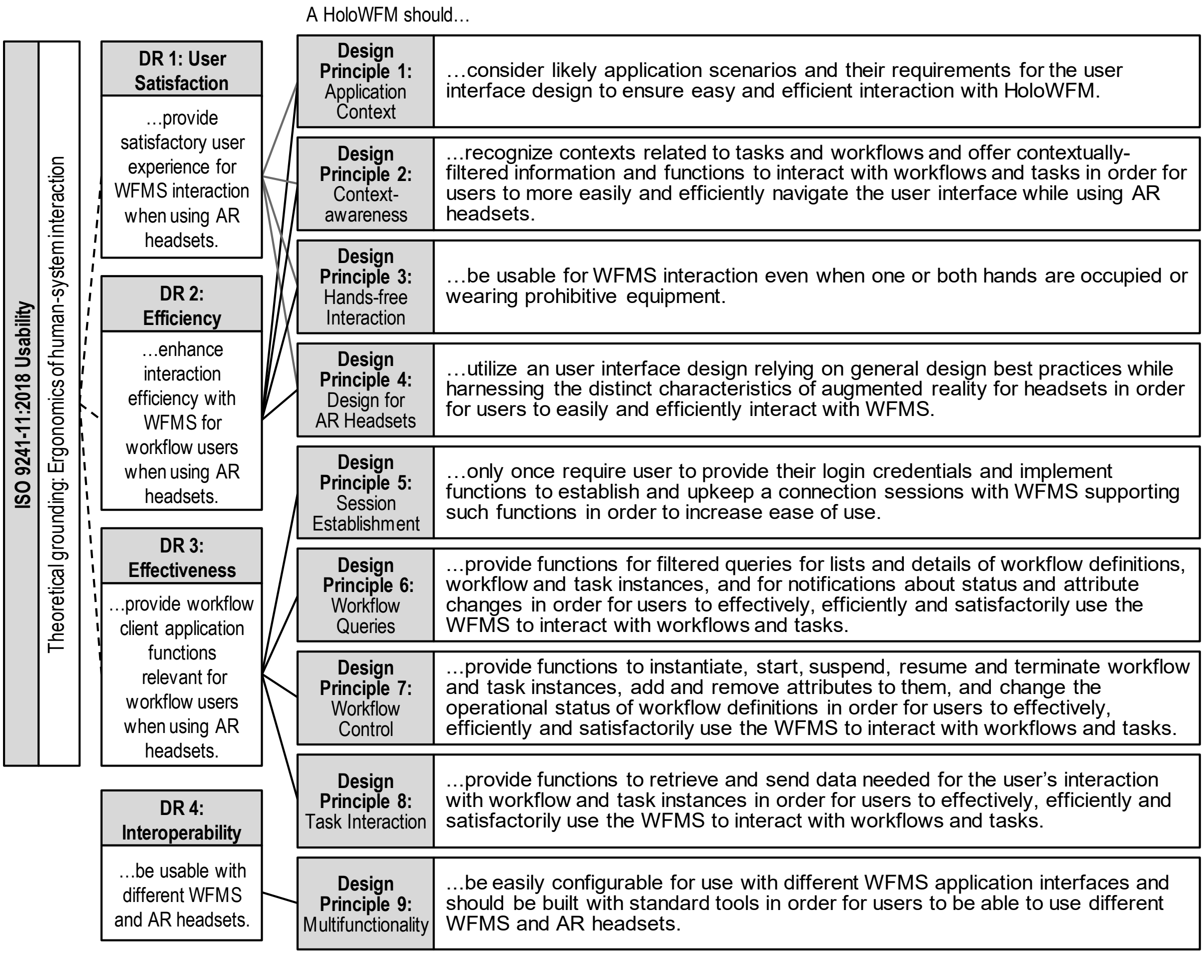
1st order concepts: clustered verbalized statements	2nd order themes
• AR can generally be utilized as an interaction format for all tools and human interfaces to the workflow engine, i.e., process definition tools (interface 1), administration & monitoring tools (interface 5), and especially workflow client applications (interface 2).	1) Applicability for workflow management system interfaces
• The user experience should be a focus of HoloWFM since adaption by employees is very important. • Many AR systems have poor usability and are thus hard to use. • HoloWFM should focus on use cases where conventional devices cannot be utilized well.	2) User experience & usability
• HoloWFM must be useful and offer the same functions as non-headset-based workflow client applications. • HoloWFM must be completely interoperable with existing workflow management systems as if it were a “normal” workflow client application.	3) Effectiveness & interoperability
• Scenarios and processes where users perform some manual labor are generally well-suited. • Industrial processes are generally well suited for HoloWFM, including assembly, service, maintenance, and warehouse picking. • Utilizing real 3D experiences during collaborative planning and design is a well-suited application scenario.	4) Application scenarios
• HoloWFM should offer context-aware functions to fully utilize sensors of headset-based ARSs.	5) Context-awareness
• Application scenarios where only one or no hands can be utilized are well suited to fully realize the potential of HoloWFM.	6) Single-hand & hands-free interaction
• AR has great potential for user experience but needs special user interface design. • Using web browsers in headset-based ARSs as workflow management system front ends is very user-unfriendly. • HoloWFM should be designed as an AR-native workflow client application. • Spatial AR [128] is not well suited for many application scenarios, especially in the field.	7) Design for headset-based ARSs

Table 8. Clustered statements of participants of the moderated focus groups.

To systematize the statements by the participants, the methodology of Gioia et al. [86] was utilized to distill first-order concepts and second-order themes from the verbalized statements of the subjects. Thus, the statements of the subjects (concepts) were clustered, and seven important themes for HoloWFM were derived, as shown in Table 2. The seven second-order themes serve as an empirical basis for developing DRs and DPs for HoloWFM.

4.3.3 Description of Design Theory

After evaluating the distilled concepts and themes from the MFGs, a total of four DRs for HoloWFM were defined, which are addressed by nine DPs. This step was both based on the empirical findings of the MFGs and on state-of-practice concepts and literature. The DT developed in the first design cycle is depicted in Figure 24.



Note. Coloring just for clarity.

Figure 24. Tentative design requirements and design principles for HoloWFM.

The first requirement, "usability" *(*theme 2*),* was divided into its components according to ISO 9241-11:2018 [39]: user satisfaction (**DR 1**), efficiency (**DR 2**), and effectiveness (**DR 3**). This ISO also represents the underlying theoretical framework of the DT: *usability theory*. To address interoperability (theme 3), **DR 4** was defined. DPs 1-4 address DR 1 and DR 2, respectively, and must, therefore, be implemented considering both requirements. **DP 1** was defined to ensure that HoloWFM is designed for relevant scenarios, as suggested by the MFGs (theme 4) and discussed in the literature (e.g., [23, 129]). To increase the artifact's usability in relevant scenarios, **DP 2** and **DP 3** were defined. Taking up the statements of the MFGs (theme 5), the sensors of the headset-based ARS should be utilized to implement context-aware filtering of tasks and workflows and present appropriate interaction options to the user (**DP 2**) [130]. To address scenarios where conventional devices are unusable or poorly suited, HoloWFM should be usable with one and without hands (**DP 3**) (theme 6). While general design guidelines for UIs and UX apply, AR has distinct features that should be used to improve UI and UX [131]. Hence, HoloWFM should be natively designed for headset-based ARS (**DP 4**) (theme 7). To address DR 3 (theme 1), the **DPs 5-8** were defined, whose articulations are based on the management and control capability requirements of a WFMS front end as defined by the Workflow Management Coalition ([15], p.31-35), but were specified due to their relevance for headset-based ARSs. To address

DR 4, **DP 9** was defined to specify and constrain the system architecture and development toolset for HoloWFM.

4.3.4 Description of UI Design

In the second design cycle, the development was focused on a general design direction rather than on implementation details, following the utilized DSR method by Vaishnavi and Kuechler [28]. The UI design orients itself in state-of-practice concepts in contemporary literature (e.g., [131]), but the mixture of influences on the HoloWFM UI design presented here was too informal and complex to document formally. The HoloWFM UI consists of four UI components: a main menu (MM) (Figure 25), a heads-up display (HUD), a quick-access menu (QM), and a context-aware mode (CM) (Figure 26). The figures below show the UI design and the associated DPs. To illustrate the UI, a fictional radio tower inspection workflow as an application scenario was chosen. In this, an engineer has already powered down the radio tower and climbed it and now has to check a data logging unit before finally powering the tower back up.

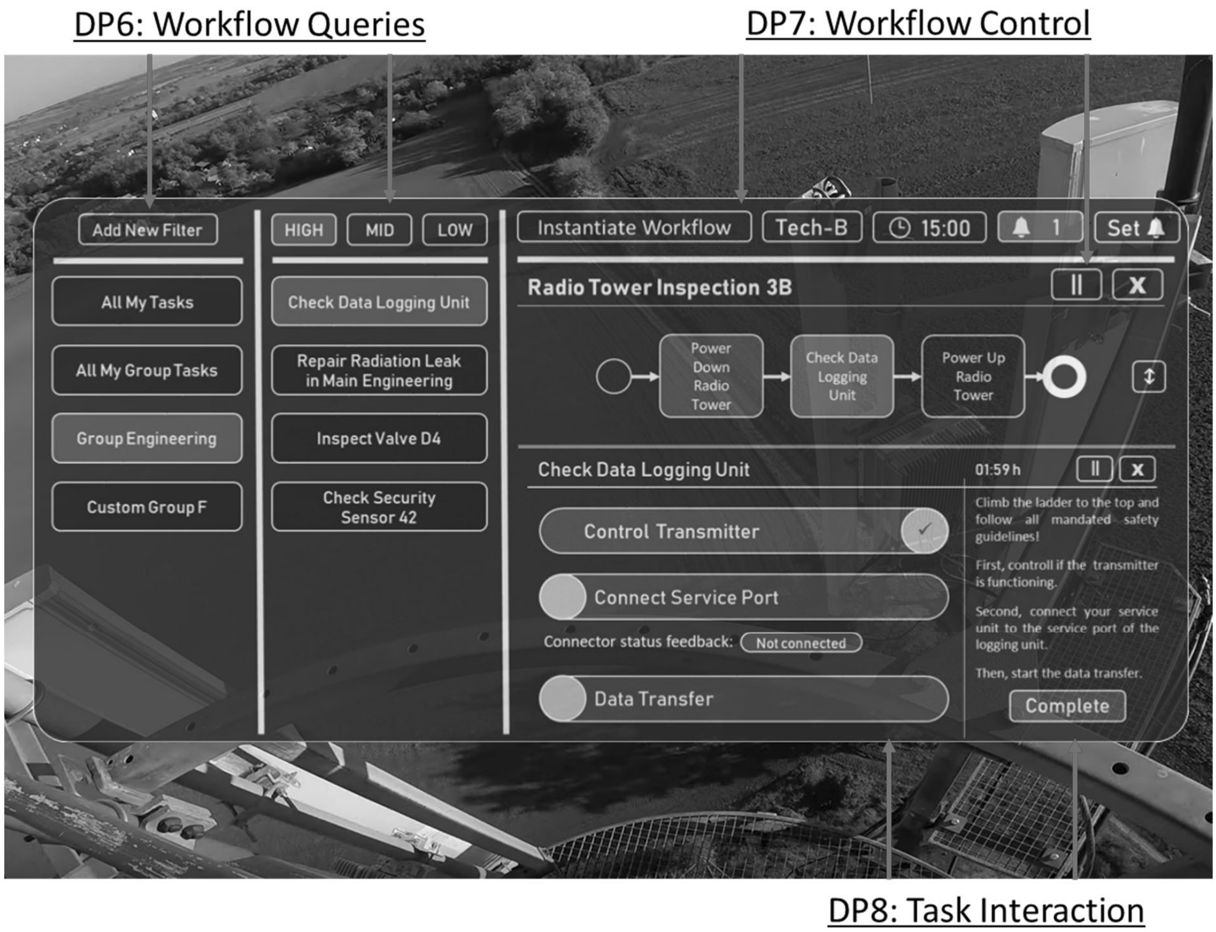


Figure 25. The main menu component of the user interface design of HoloWFM.

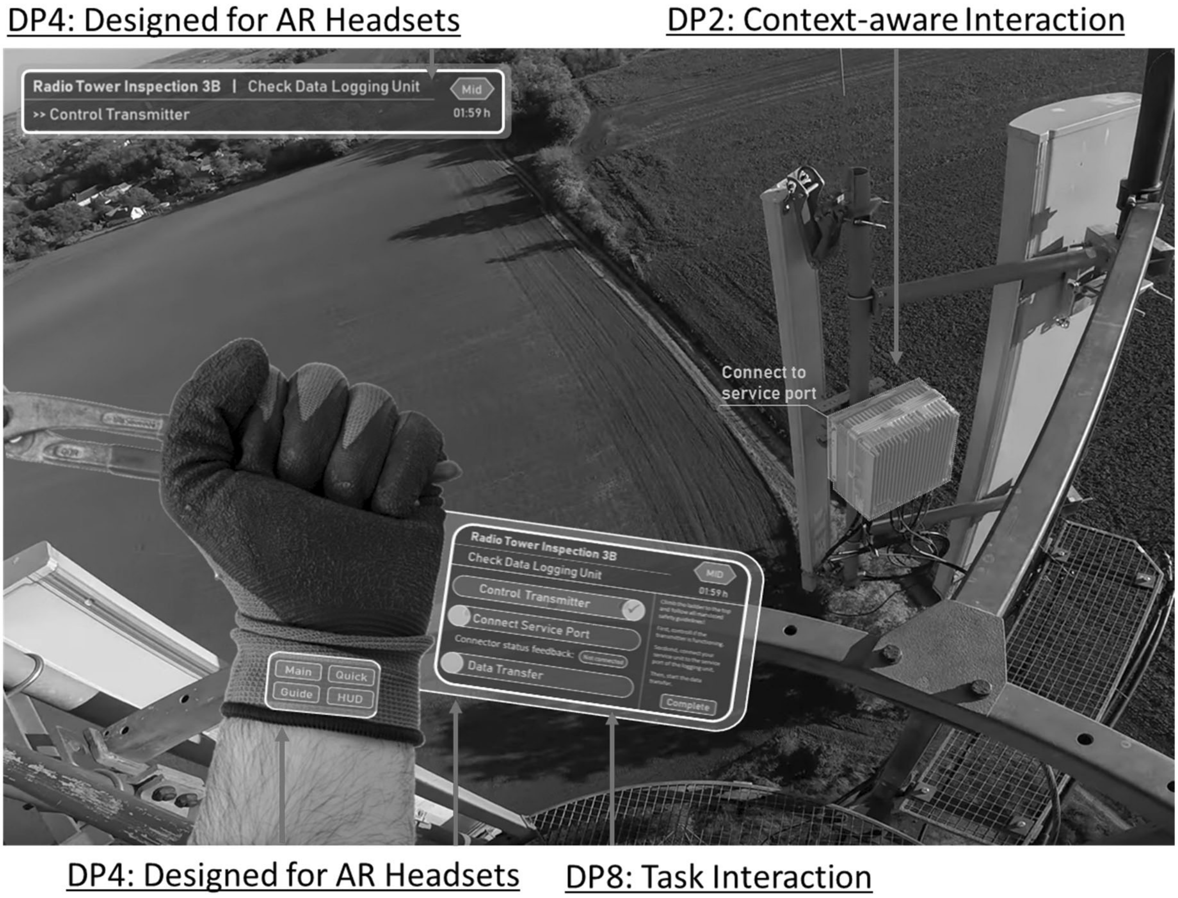


Figure 26. The quick-access menu and heads-up display of the user interface design of HoloWFM.

The HUD addresses DP 4 and presents key information: the currently active task and subtask, the parent workflow, time remaining, and priority. The QM is associated with DPs 3-4 and DP 8 and is anchored to the hand. It is “minimized” by default to minimize interference with the user’s activities. The QM displays more detailed information about the currently active task than the HUD while minimizing the user’s interaction with HoloWFM. In the example, subtasks are marked as completed with a slider. The MM corresponds to DP 3 and DPs 6-8. It fills the entire field of view and displays tasks assigned to the user, additional information, and filters. The CM addresses DP 2 as it visually highlights objects related to currently active tasks and workflows to guide the user. The visibility of the UI is toggled on the wrist.

4.3.5 Updated Taxonomy to Include HoloWFM

The taxonomy was developed in the first design cycle without considering HoloWFMs characteristics since OEC 3 from the taxonomy development method by Nickerson et al. prescribes not to include hypothetical characteristics without real objects exhibiting them. Therefore, the taxonomy was missing some characteristics necessary to describe HoloWFM. Hence, the taxonomy was extended. These extensions correspond primarily to the workflow management and control capabilities as defined within the WFMS RA by the Workflow Management Coalition [15], which was a fundamental part of the HoloWFM DT development process, as described above.

As HoloWFM is designed as a WFMS front end (DPs 5-8), the taxonomy’s dimension of *Workflow Processing* was extended with the characteristic *Modelled Workflow & Explicit Workflow Engine*. Stemming from DP 6 (*Workflow Queries*), the taxonomy’s dimension of *Workflow Management* was extended with the characteristics *Filtered List of Workflow Definitions*, *View Workflow Definition Details*, *Filtered List of Workflow Instances*, *View Workflow Instance Details*, *View Task Instance Details*, and *Notification for Status /Attribute Changes*. Stemming from DP 7 (*Workflow Control*): the dimension was further extended with the characteristics *Start Workflow Instance*, *Suspend/Resume*

Workflow Instance, *Add/Remove Workflow Instance Attribute*, and *Change Operational Status of Workflow Definition*. The updated taxonomy is depicted in Figure 27 in the next Chapter 4.3.6.

4.3.6 HoloWFM Specification with the Developed Taxonomy

With the taxonomy thus updated, HoloWFM can be characterized according to the developed DRs and DPs. This supplements the characterization of HoloWFM with the DT by adding another perspective and describing attributes, rather than requirements and principles, of a HoloWFM. In Figure 27, the updated taxonomy is depicted with the characteristics of HoloWFM marked in green.

Dimension		Characteristics				
Device	Type	Wearable	Head-mounted			
		One-hand Handheld	Two-hand Handheld	Stationary Device		
	Architecture	Single Device	Connected Devices	Integrated Devices		
	User System*	Single-user	Multi-user			
	Output	Projector	Optical See-through	Video See-through		
		Stationary Loudspeaker	Mobile Loudspeaker	Haptic Output		
Tracking System	ARS Position Tracking	Image Targets	Relative to Visual Feature-tracked Objects	Spatial Map		
		Position Tracking via Networked External Optical Sensors	Inertial and Orientation			
		GPS Position Tracking	RFID Position Tracking	None		
	Object Tracking	Visual Marker-based	Visual Feature-based Object Tracking			
		Object Tracking via Networked External Optical Sensors	GPS Object Tracking	RFID Object Tracking	Magnetic	None
	User Interaction Tracking	Hand Gestures	Eye-tracking	Body Pose		
		Mechanical & Touch	Speech	Pointer	None	
Synthetic Content	Representation	Text	Image	Video		
		2D Form	3D Form	Animation	Acoustic	Haptic Representation
	Visual Alignment	Fixed	Proximity	Non-transparent Overlay	Transparent Overlay	
	User Interaction	None	Selection	Manipulation		
	Content Control	Manual	Automatic	Hybrid		
Workflow	Workflow Processing*	Implicit Workflow	Implicit Workflow Task			
		Modelled Workflow & Implicit Workflow Engine				
		Modelled Workflow & Explicit Workflow Engine				
	Workflow Management	None	Change Operational Status of Workflow Definition			
		Filtered List of Workflow Definitions	View Workflow Definition Details			
		Instantiate Workflow	Navigate to Next or Previous Workflow Task Instance			
		Start Workflow Instance	Suspend / Resume Workflow Instance	Terminate Workflow Instance		
		Filtered List of Workflow Instances	View Workflow Instance Details			
		Add/Remove Workflow Instance Attribute	Change Workflow Instance Path			
		Filtered Lists of Workflow Task Instances	View Workflow Task Instance Details			
		Switch Between Workflow Task Instances	Notification for Status / Attribute Changes			
	Workflow Task Support	Process Prescription	Visualise Non-visible Real Objects	Real-time Data		
		Automatic Deviation Detection	Instruction	Demonstration		
		Routing	Telephone	Remote Assistance	Teleoperation	
		Documentation	Data Entry	Data Scanning		
		Process Modelling	Synthetic Object Modelling			
		Auxiliary Information	Workflow Training			

Figure 27. Updated Taxonomy of ARSs supporting workflow execution. HoloWFM's necessary characteristics are marked in green, and unspecified dimensions are marked in yellow.

For the dimensions *ARS Position Tracking* and *Object Tracking*, HoloWFM does not prescribe specific solutions but must incorporate some approach in order to fulfill DP 2 for context awareness. To indicate this, the dimensions *ARS Position Tracking* and *Object Tracking* are characterized by *None* in yellow.

Other characteristics are possible but not necessary, e.g., mobile loudspeakers on an AR headset could be utilized to provide acoustic instructions, or helpful images could provide workflow task support. However, while possible, these characteristics are not necessarily present in all HoloWFM instantiations or provided by all WFMSs. As such, these characteristics are not marked.

4.4 Evaluation

4.4.1 Reconvened Moderated Focus Groups

To evaluate whether the developed DT and UI design represented the thoughts of the participants of the two MFGs and to ascertain its general quality, two reconvened moderated focus groups (RMFGs) were conducted. RMFGs reunite the participants of previous sessions to discuss topics, concepts, theories, or issues in greater depth or to evaluate them under consideration of new information, or both [85]. Consequently, the groups from the development phase were reunited to check the DT and UI design.

The procedure of the RMFGs consisted of four steps: 1) reintroduction to the topic, 2) discussion of the DT and UI design, 3) protocolling, and 4) the evaluation of protocols through manual issue clustering. Analogously to the MFGs (cf. Chapter 4.3.2), the systematization was based again on Gioia et al. [86] and distilled clustered verbalized statements and derived three major themes, displayed in Table 9.

1st order concepts: clustered verbalized statements	2nd order themes
• *Perceived usefulness* and *ease of use* of the Technology Acceptance Model [78] (TAM) are established measures of the quality of an artifact. • Usability [39] not only includes subjective but objective measurements, i.e., efficiency and effectiveness. • Overall, usability is the more holistic choice and should be kept rather than the TAM.	1) Technology Acceptance Model or ISO 9241-11:2018
• In application scenarios, which restrict the use of hands, e.g., industrial maintenance, headset-based ARSs generally offer higher usability than handheld devices, especially because of novel single-hand and hands-free modes of interaction, e.g., eye tracking. • Group 1: Headset-based ARSs have been evaluated positively in the literature regarding task efficiency (cf. Section 1). • Group 2: HoloWFM's benefit must be discussed in a realistic context of already using a headset-based ARS for workflow task support. Then, using additional devices for workflow management and control is inefficient. • Context-aware selection of information and interaction options for tasks and workflows can be a major strength of HoloWFM.	2) Benefit of HoloWFM for real-world practice
• AR applications in the literature are usually hard-coded for a specific application and workflow. • How can AR support be integrated to support multiple different workflows? • For HoloWFM, AR support should be part of the workflow definition. • HoloWFM should enable a seamless integration of AR content from different workflows and workflow management functions into a unified AR user experience.	3) Integration of augmented reality support for various workflows

Table 9. Clustered statements of the reconvened moderated focus groups.

The evaluation with the RMFGs confirmed the choices for DRs and DPs of the developed DT and was overall positive. The first theme included an interesting discussion in both groups about the strengths and weaknesses of the concept of perceived usefulness of the Technology Acceptance Model [78] (TAM) compared with the concept of usability, defined in ISO 9241-11:2018. In the end, the choice of usability as a theoretical framework for the DT was confirmed, however. The discussions regarding theme 2 reaffirmed the relevance of a HoloWFM in specific application scenarios, as initially envisioned. Theme 3 featured an insightful debate about the end-user experience. The groups discussed how the AR UI of HoloWFM and the AR-based workflow task support should be integrated into a unified experience. This was part of the initial motivation, as discussed in Chapter 1. However, during this discussion, it became clear that less-abstract design knowledge was definitely necessary to properly support IS researchers, IS designers, and IS developers during the design, development, and instantiation of a HoloWFM as it was not a priori clear how such unified user experience could be realized on a technical level. Hence, the evaluation via the RMFGs motivated the third design cycle.

4.4.2 Compliance Check with Design Theory Framework

In addition to the empirical evaluation via the RMFGs, the quality of the DT was formally verified with the framework by Jones and Gregor [79]. This framework defines six obligatory and two optional components every DT should include. The HoloWFM DT complies with this framework completely, as demonstrated in Table 10. The eighth component – principals of implementation – are not yes included as they did not yet exist in the second design cycle but were developed in the third design cycle.

Component	Description
Purpose and scope	The goals of a WFMS front end for headset-based ARSs are: providing a satisfactory user experience for interaction with WFMSs (DR 1), improving efficiency for WFMS interaction (DR 2), providing comprehensive WFMS front end functions for headset-based ARSs (DR 3), and ensuring interoperability with other WFMSs and headset-based ARSs (DR 4).
Constructs	WFMS, Workflow, AR, headset-based ARS, front end, UI, UX, IS architecture
Principles of form and function	DP 1: application context, DP 2: context-awareness, DP 3: hands-free interaction, DP 4: designed for headset-based ARSs, DP 5: session establishment, DP 6: workflow queries, DP 7: workflow control, DP 8: task interaction, DP 9: multifunctionality
Artifact mutability	HoloWFM can be used with different headset-based ARSs and WFMSs. The UI design and functionality can be adapted for different user tastes and can be enhanced based on specific practical and theoretical requirements.
Testable propositions	A WFMS front end for headset-based ARSs offers higher user satisfaction, efficiency, and the same effectiveness in scenarios where AR-based workflow task support is provided via headset-based ARSs than alternative approaches using additional devices.
Justificatory knowledge	A three-step literature analysis and two MFGs justify the derivation of DRs and DPs. RMFGs groups justified that a WFMS front end for headset-based ARSs generally delivers higher user satisfaction, efficiency, and the same effectiveness in scenarios where AR-based workflow task support is provided via headset-based ARSs than alternative approaches using additional devices, especially since headset-based ARSs offer novel possibilities for UI and UX design, and one-hand and hands-free interaction modes.
Expository instantiation	Development of a prototypical UI design encompassing four UI components: a heads-up display, a quick-access menu, a main menu, and a context-aware mode.

Table 10. Components of the design theory for HoloWFM.

4.5 Conclusion

Summary of the Second Design Cycle

In the second design cycle, a DT and UI design for HoloWFM were developed, primarily based on the inputs of two MFGs, but also state-of-practice literature. The DT consists of four DRs and nine DPs, and the UI contains four components. The participants of the MFGs were then reunited to evaluate the results, which yielded overall positive feedback. The DT was also formally verified with the framework by Jones and Gregor [79]. The second design cycle, thus, gave a first tentative answer to the third research question (RQ 3) for the design requirements, design principles, and design features of a HoloWFM. These components of a DT are further developed in the next design cycle.

The taxonomy of the first design cycle was expanded with new characteristics so that HoloWFM can be characterized with it. Thus, the answer to the first research question (RQ 1) was updated, and the final taxonomy consists of 14 dimensions and 94 characteristics.

Limitations of the Second Design Cycle

For an adequate interpretation of the results, the following limitations should be considered. First, an inherent weakness of the conceptualization of DTs is the subjectivity of underlying design decisions, e.g., the selection and naming of DRs and DPs. Other designers could make different decisions, thus reaching a different DT. However, not all design decisions must or can be grounded in theory, and a degree of creativity is unavoidable and essential in the DSR process [132, 133]. Nonetheless, the DT was underpinned methodologically with the methodological framework by Möller et al. [82] for supportive approaches to DP development and by Fu et al. [58] for the prescriptive articulation of DPs.

Second, the DT conceptualization and evaluation results depend on the sample, i.e., the choice of other participants for the focus groups could lead to different results. Still, by selecting subject-specific experts and users for the focus groups in the first design cycle, as well as considering the comments by Guest et al. [84] on the required number of groups and the established practices in regard to participant numbers (see Chapter 2.8), it is reasonable to assume that some well-founded insights were gained. Nonetheless, more experts would strengthen the validity of the results.

Reflections on the Results of the Second Design Cycle

Based on the evaluation results, a second useful tool for the high-level design of a HoloWFM has been developed, complementing the novel taxonomy. A detailed characterization of a HoloWFM, the requirements for a HoloWFM design, and general principles of design addressing these can aid IS researchers, IS designers, and IS developers during the design of a HoloWFM.

In terms of the content of the DT, it is noteworthy that the DPs do not only consist of functions defined in the WFMS RA by the Workflow Management Coalition [15] and supporting technical functions but context awareness and multifunctionality for multiple WFMSs also play an important role. Both MFGs explicitly emphasized this, and context awareness was again emphasized in the RMFGs of the evaluation phase. This means that in order to address its DRs successfully, a HoloWFM cannot just replicate the functions of a web-based WFMS front ends for a specific WFMS. Instead, a HoloWFM is envisioned as a rather novel type of IS artifact, akin to a "universal WFMS front end" that also must utilize the technical possibilities of an AR headset.

Taking up theme three from the evaluation phase, it is clear that further low-level guidance is needed to properly support the target audience during the design but also the development and instantiation of the novel type of IS artifact called HoloWFM. These reflections prompted the third design cycle, which aimed at developing such less-abstract guidance.

5 Design Cycle 3: Reference Architecture

5.1 Awareness of Problem

The first and second design cycles yielded two tools for the design of a HoloWFM on a high level of abstraction. Motivated by the evaluation results in the second design cycle, the third HoloWFM design cycle was initiated with the knowledge that in the state of the art, no less-abstract formalized design knowledge to support the design, development, or instantiation of a HoloWFM can exist – otherwise, it would have been identified in the literature reviews in the first or second cycle. An adequate tool to deliver such operationalizable, actionable, less-abstract design knowledge is an RA. As such, the *identified problem* for the third HoloWFM design cycle was the lack of a HoloWFM RA on a low level of abstraction, which would support IS researchers, IS designers, and IS developers during the design, development, and instantiation of a HoloWFM. Consequently, in the first step of the third design cycle, *a new research effort was proposed* to create such a HoloWFM RA.

5.2 Suggestion

The envisioned HoloWFM RA should contain architecture models in the standard notation UML in order to be comprehensible by IS developers. The HoloWFM RA should also be based on the developed HoloWFM DT. To systematically derive UML diagrams from the DPs, the third design cycle should extend the DT with design features (DFs). To document the RA properly, the standard for defining a RA description (RAD) provided by the ISO 42010:2011(E) *Systems and software engineering - Architecture description* [36] should be utilized as a framework. Thus, the *vision* for the third design cycle was an ISO 42010:2011-compliant HoloWFM RAD.

5.3 Development

To develop a reference for a HoloWFM system to provide less-abstract guidance to IS researchers, IS designers, and IS developers when designing, developing, and instantiating a HoloWFM, the developed DT served as a foundation. To address the comments by the participants of the RMFG during the evaluation phase of the second design cycle, a new design principle (DP 10) was defined for the *Seamless Integration* of AR task support and the HoloWFM application. This DP will enhance the user satisfaction (DR 1) and efficiency (DR 2) of a HoloWFM.

The thus updated DT was extended by DFs to document one set of technical-oriented features of a possible design. Even though not a required part of a DT (cf. [56]), DFs can be utilized to document how DPs could be implemented in a specific instance (e.g., [59, 60]). The DFs then serve as a foundation to systematically develop UML diagrams and textual descriptions for the RA, in line with the supportive approach by Möller et al. [82], followed in the first design cycle. The UML diagrams derived from the DFs describe the system architecture and behavior on an even less-abstract level. Thus, the DFs serve to bridge the “abstraction gap” between formalized, highly abstract design knowledge in the DT and less abstract, actionable design knowledge in the RA.

The DFs and RA were based on the design knowledge contained in the 142 analyzed ARSs from the first design cycle as well as state-of-practice concepts from software development. The multitude of complex influences from these knowledge repositories was too complex and informal to be truthfully documented systematically. After developing an initial version of the RAD, it was published at the 31st European Conference on Information Systems and reworked, inspired by the received reviews during the conference's peer-review procedure and the discussions at the conference.

The *novel artifact* of the third HoloWFM design cycle – a HoloWFM RAD – is presented in the latest version in the next Chapter. Its components and structure follow the prescribed components of ISO 42010:2011 (cf. Chapter 2.4).

5.3.1 Reference Architecture Description compliant with ISO 42010:2011

5.3.1.1 Identification and Overview Information

The purpose of the "HoloWFM reference architecture" is to support HoloWFM developers, i.e., IT and AR architects and developers, in designing and building a HoloWFM. A HoloWFM aims to enable end-users to manage and control workflows, e.g., to generate filtered lists for specific workflows and workflow tasks, to control the status of workflows, or to interact with the user tasks by filling out forms and checkboxes or reading information. These management and control functions are provided for end users during the usage of AR headsets, and therefore the UI of HoloWFM is entirely presented with AR elements. To enhance the user experience, efficiency, and effectiveness of HoloWFM, it is designed to be context-aware, i.e., it reacts to contextual environmental information, e.g., a user's location or when a certain object is in the headset camera's field-of-view. To process this context information, *context reasoning workflows* are defined by administrators.

5.3.1.2 Stakeholders and Stakeholder Concerns

Two stakeholders are of preeminent importance. First and directly, HoloWFM developers, i.e., IS researchers, IS designers, and IS developers, especially specializing in the development of ARS, are concerned with the RAD, as it should support them in designing, developing, and deploying a HoloWFM instantiation in real organizations.

The second important stakeholders are HoloWFM end-users. Their concerns refer to the efficiency, effectiveness, and usability of HoloWFM, as qualitative studies during the development of this RAD revealed. These concerns are systematically addressed in the DT, esp. the DRs therein. As such, these stakeholders do not warrant their own RA viewpoint.

5.3.1.3 Reference Architecture Viewpoint "HoloWFM Developer" Definition

Consequently, the herein-considered RA viewpoint is that of the *HoloWFM developer*. This viewpoint is concerned with guidance provided by the RA during the actual design and development of a HoloWFM instantiation for an organization. Abstract design knowledge is helpful as it can apply to many different organizations. Taxonomy-based descriptions and DTs are, therefore, appropriate in this viewpoint. Tangible architectural knowledge, however, is also important to shorten and ease development cycles (cf. Chapter 2.4). Hence, UML diagrams in lower levels of abstractions are appropriate for the *HoloWFM developer's* viewpoint.

5.3.1.4 Reference Architecture View "HoloWFM Developer"

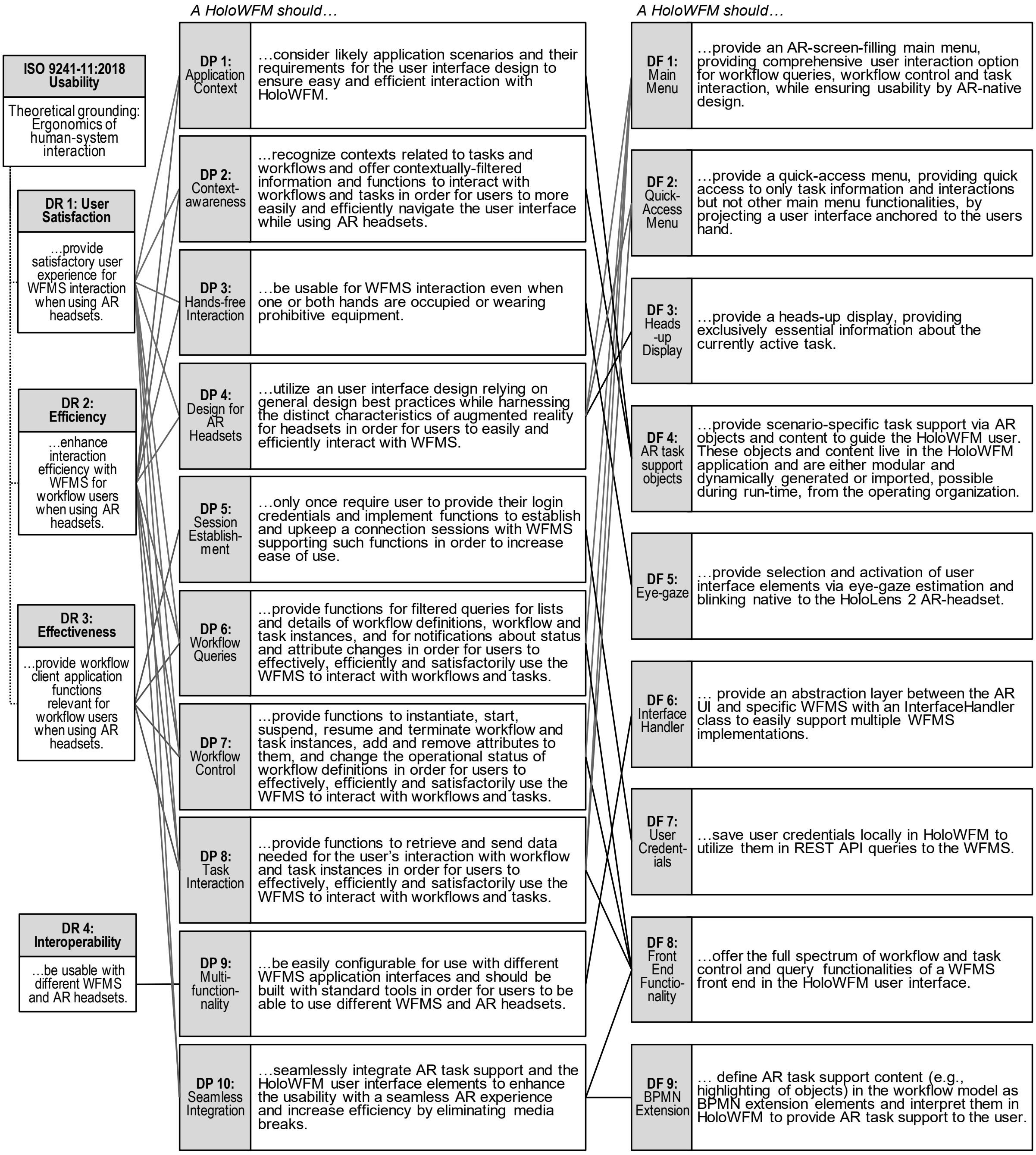
5.3.1.4.1 Reference Characterization of HoloWFM According to the Developed Taxonomy of ARSs Supporting Workflow Execution

The formalized design knowledge contained in the characterization of HoloWFM with the novel taxonomy of this dissertation can provide high-level guidance to HoloWFM developers (Figure 28).

	Dimension	Characteristics				
Device	Type	Wearable	Head-mounted			
		One-hand Handheld	Two-hand Handheld	Stationary Device		
	Architecture	Single Device	Connected Devices	Integrated Devices		
	User System*	Single-user	Multi-user			
	Output	Projector	Optical See-through	Video See-through		
		Stationary Loudspeaker	Mobile Loudspeaker	Haptic Output		
Tracking System	ARS Position Tracking	Image Targets	Relative to Visual Feature-tracked Objects	Spatial Map		
		Position Tracking via Networked External Optical Sensors	Inertial and Orientation			
		GPS Position Tracking	RFID Position Tracking	None		
	Object Tracking	Visual Marker-based	Visual Feature-based Object Tracking			
		Object Tracking via Networked External Optical Sensors	GPS Object Tracking	RFID Object Tracking	Magnetic	None
	User Interaction Tracking	Hand Gestures	Eye-tracking	Body Pose		
		Mechanical & Touch	Speech	Pointer	None	
Synthetic Content	Representation	Text	Image	Video		
		2D Form	3D Form	Animation	Acoustic	Haptic Representation
	Visual Alignment	Fixed	Proximity	Non-transparent Overlay	Transparent Overlay	
	User Interaction	None	Selection	Manipulation		
	Content Control	Manual	Automatic	Hybrid		
Workflow	Workflow Processing*	Implicit Workflow	Implicit Workflow Task			
		Modelled Workflow & Implicit Workflow Engine				
		Modelled Workflow & Explicit Workflow Engine				
	Workflow Management	None	Change Operational Status of Workflow Definition			
		Filtered List of Workflow Definitions	View Workflow Definition Details			
		Instantiate Workflow	Navigate to Next or Previous Workflow Task Instance			
		Start Workflow Instance	Suspend / Resume Workflow Instance	Terminate Workflow Instance		
		Filtered List of Workflow Instances	View Workflow Instance Details			
		Add/Remove Workflow Instance Attribute	Change Workflow Instance Path			
		Filtered Lists of Workflow Task Instances	View Workflow Task Instance Details			
		Switch Between Workflow Task Instances	Notification for Status / Attribute Changes			
	Workflow Task Support	Process Prescription	Visualise Non-visible Real Objects	Real-time Data		
		Automatic Deviation Detection	Instruction	Demonstration		
		Routing	Telephone	Remote Assistance	Teleoperation	
		Documentation	Data Entry	Data Scanning		
		Process Modelling	Synthetic Object Modelling			
		Auxiliary Information	Workflow Training			

Figure 28. Reference HoloWFM characterization using the novel taxonomy of this dissertation.

5.3.1.4.2 Reference Extended Design Theory for HoloWFM



Note. Coloring just for clarity.

Figure 29. Extended design theory.

The DT shown above was extended with more connections between DRs and DPs, following the feedback from its original publication at the 30th ECIS (cf. Chapter 4.3.3). The underlying theoretical framework of the DT is *usability theory*, as formulated in ISO 9241-11:2018 [39]. According to the ISO, usability is constituted by three components, which are the first three DRs of the DT: user satisfaction (**DR 1**), efficiency (**DR 2**), and effectiveness (**DR 3**). Additionally, **DR 4** prescribes the interoperability of a HoloWFM with different WFMSs and AR headsets. DR 1 and DR 2 are both addressed by DPs 1-4, 6-8, and 10. DR 3 is addressed by DPs 5-8. DR 4 is addressed by DP 9.

A total of ten DPs were defined to address the four DRs. **DP 1** was defined to ensure that HoloWFM is designed for relevant scenarios, e.g., different UI designs. **DP 2** enables a HoloWFM to be context-aware using the sensors of the headset-based ARS. Thus the end-user can be guided better, e.g., by context-aware filtering of tasks and workflows, by presenting contextually fitting AR-based task support content, or by providing filtered workflow interaction options like instantiating a specific workflow. To address scenarios where conventional devices are unusable or poorly suited, HoloWFM should be usable with one and without hands (**DP 3**). While general design guidelines for UIs and UX apply, AR has distinct features that should be used to improve UI and UX. Hence, HoloWFM should be natively designed for headset-based ARS (**DP 4**). To address DR 3 for effective WFMS interactions, the articulations of **DP 5-8** are based on the management and control capability requirements of a WFMS front end as defined by the Workflow Management Coalition ([15], p.31-35) but were specified due to their relevance for headset-based ARSs. To address DR 4, **DP 9** was defined to specify and constrain the system architecture and development toolset for HoloWFM. The **DP 10** addresses both user satisfaction and efficiency by ensuring that the task support via AR content and the AR UI of HoloWFM are integrated such that no media breaks occur, i.e., the same application provides the HoloWFM UI and task support. In contrast, an alternative approach could start or send a message to a second application in the AR headset, which – after the user switches applications – provides the appropriate task support.

A total of nine DFs was defined to operationalize the ten DPs. These represent one set of DFs that can address the DPs and should be adopted to the specific application scenario of a HoloWFM instantiation. E.g., this set of DFs operationalizes the context-awareness (DP 2) via DF 4 for context-aware AR task support objects. In the software prototype implementation (see Chapter 5.4.2), this was demonstrated by presenting AR task support objects only for a specific task (see Figure 66).

The defined DFs for the HoloWFM DT are as follows. To implement DP 4 for an AR headset-native design and provide workflow management and control functionalities (DP 6-8), three UI components are proposed: a *main menu* (**DF 1**), *quick-access menu* (**DF 2**), and *heads-up display* (**DF 3**). The consideration of the relevant application context (DP 1) is inherently realized in *AR task support objects* (**DF 4**), which are also context-aware (DP 2). As the Microsoft HoloLens offers native *Eye-gazing* (**DF 5**) features, it is reasonable to assume that these features will be present in future headset-based ARSs. This solution is defined to operationalize DP 3 for one-handed and hands-free modes of interaction. To maximize interoperability with different WFMS and AR headsets, an *Interface Handler* (**DF 6**) is utilized as an abstraction layer for WFMS functions. To enable session establishment (DP 5), the *User Credentials* (**DF 7**) can be saved in HoloWFM. Since not all UI elements in DFs 1-3 enable all functionalities, **DF 8** is explicitly defined to ensure full *WFMS Front End Functionality*. In addition to DF 8, a *BPMN Extension* (**DF 9**) is utilized to realize the seamless integration of AR UI and AR task support. In particular, workflow elements link to AR task support content via BPMN extension elements. The AR task support objects themselves are saved in the HoloWFM application.

5.3.1.4.3 Reference UML Use Case Diagram

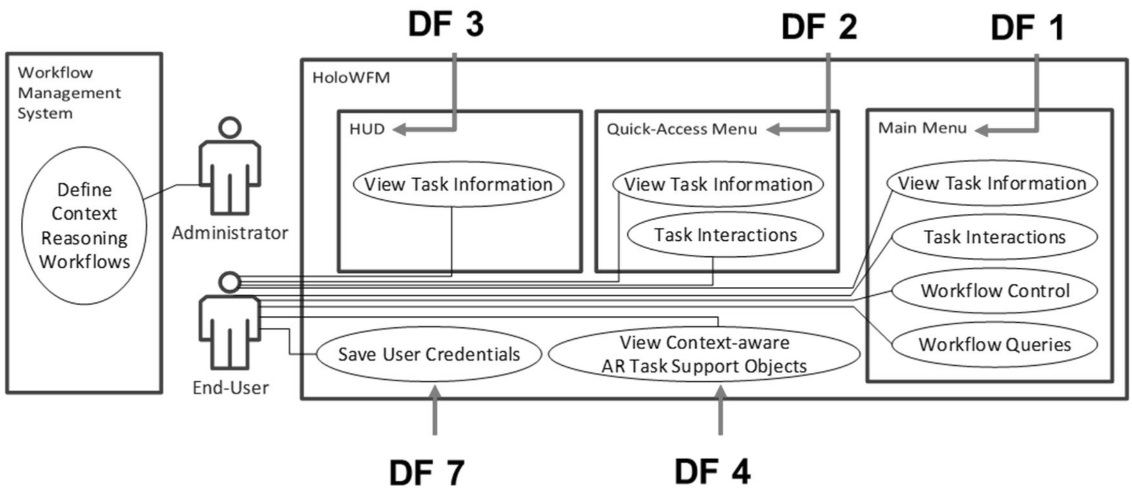


Figure 30. Reference UML use case diagram with corresponding design features.

The use case diagram depicted in Figure 30 visualizes how two roles, *administrators* and *end users*, can interact with HoloWFM. This diagram provides HoloWFM developers with a formalized notation of their possible actions, which refer to the DFs and subsequently also to the DPs. This UML use case diagram, thus, provides a first, quickly comprehensible overview of the UI functions that need to be implemented eventually. DFs 5 and 6 do not apply to the use case diagram. *Administrators* also define context reasoning workflows, i.e., workflows that calculate how to process identified contextual environmental information. Interactions of the *end user* with the organization's workflows aren't depicted.

5.3.1.4.4 Reference User Interface Design

Below, the reference UI design and the corresponding DFs are depicted in Figure 31 and Figure 32. The DFs 5-7 and 9 don't apply to the UI design. In Figure 31, the main menu offers two levels to filter tasks on the left and a full, more detailed view of the currently selected user task on the right. In this menu, the user can also switch tasks or workflows and access advanced management and control functions. In Figure 32, the heads-up display is depicted in the upper left corner, visualizing some minimalistic information about the currently active task. Attached to the wrist and hand is the quick-access menu, which provides users with task interactions and access to the main menu. The context-aware recognition and highlighting of an object identified as relevant for the action "connect to service port" (visible in the quick-access menu) is shown on the right.

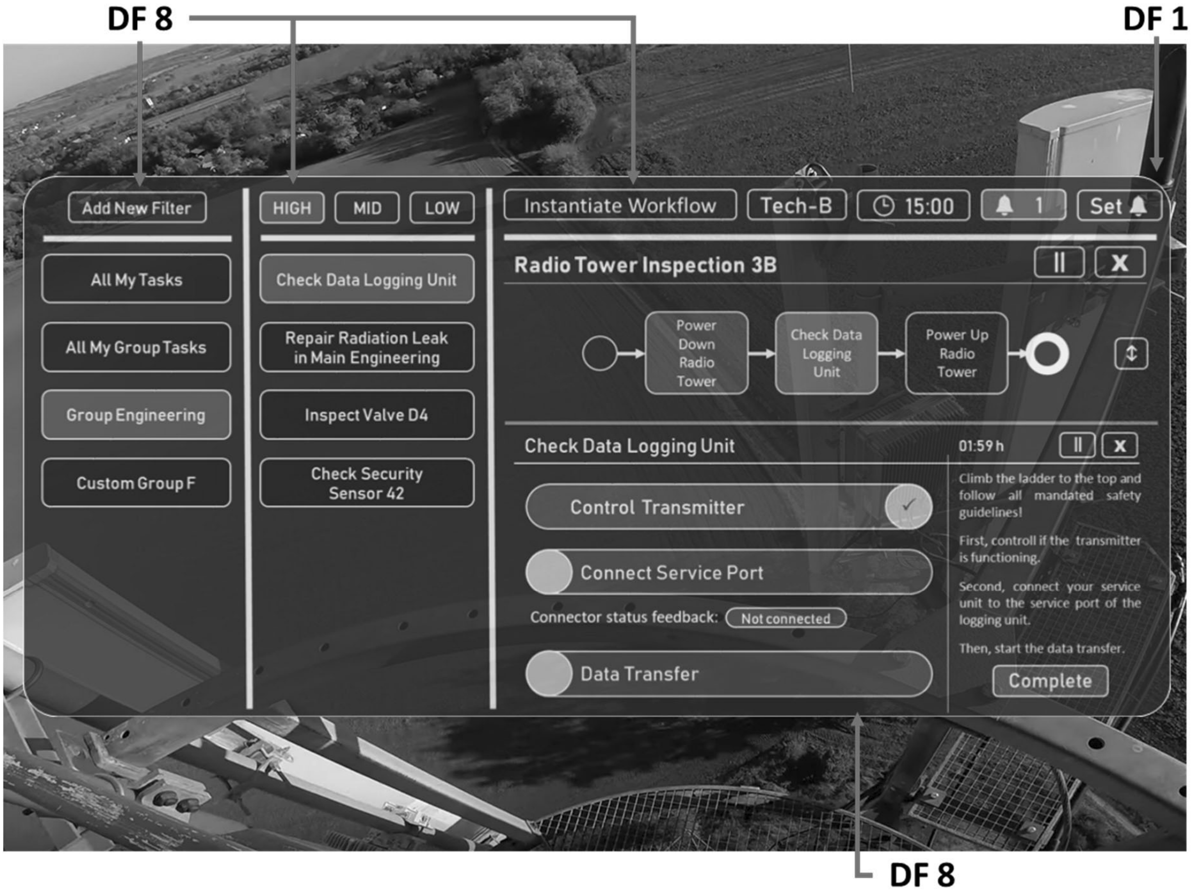


Figure 31. Reference HoloWFM user interface design for the main menu.

Figure 32. Reference HoloWFM user interface design for heads-up display, quick-access menu, and context-aware mode.

5.3.1.4.5 Reference UML Component Diagram

The component diagram and corresponding DFs are depicted in Figure 33. It contains three systems: 1) a WFMS, 2) a database system, and 3) the HoloWFM system.

The database system contains three databases for a) *Raw Context Variables* directly from the sensors. e.g., a temperature data point of 42° Celsius ("42"), b) *context states*, which are calculated from the raw context variables, e.g., "hot" or "cold" (cf. DP 2), and c) *Context-local Tasks, Workflow Instances, and Workflow Definitions*. The organization's data that may be contained in the database system, e.g., for workflows, is not depicted to increase clarity. The *Raw Context Variables* originate from sources outside of the HoloWFM system architecture. The internal sensors of the AR headset might be used, but this is not part of the HoloWFM RA. Other external sources might also be utilized, e.g., hardware sensors (e.g., IoT devices), software sensors (e.g., database requests or API calls), or systems, e.g., AI-based reasoning services.

The WFMS contains four sets of workflows. First, reading from the database's *Raw Context Variables* are the *Context State Reasoning Workflows*, which calculate context states from the raw data and write these to the *Context States* database accordingly.

Second, reading from the context states are the *AR-supported Organization's Workflows*, i.e., the workflows of the organization, that are supported with AR and are managed and controlled via HoloWFM. These workflows utilize BPMN extension elements in their task to link to corresponding *AR Task Support Objects*, e.g., synthetic object highlights, synthetic arrows, etc. These can be implemented in *Unity,* for example. As such, the AR content for the end-users is controlled via the *AR-supported Organization's Workflows*. These, in turn, can change depending on read context states.

Third, *Context-locality Reasoning Workflows* read from the *Raw Context Variables*. For each workflow definition, workflow instance, and workflow task, a context condition can be defined. This condition is a logical expression involving one or multiple context states and logical operators, and if resolving to *true*, a workflow definition, workflow instance, or task is marked as *context-local* in the corresponding database. This attribute allows the end-users to easily filter for currently relevant tasks to execute, workflow instances to inspect, and workflow definitions to instantiate. E.g., a workflow definition may be contextually local if a certain end-user (e.g., user role: technician) is in a certain location (e.g., cafeteria) at a certain time (e.g., after 18 o'clock), and a certain object is present (e.g., coffee machine) as well. In this example, a technician can then easily filter the set of all available workflow definitions to instantiate down to the currently relevant "coffee machine maintenance workflow," as the technician is in the cafeteria and it's after closing hours. The terminology *context-local* leans on the idea that a user and a task, workflow instance, or workflow definition are at the same place as an end-user in a "multi-dimensional context state vector space."

Fourth, *Context State Detection Messenger Workflows*, are triggered by the *Visual Object Detection* module of the HoloWFM application. E.g., when a certain object is within the field-of-view of the headset camera, the context state "objectVisible" could be set to 1 in the *Context States* database. The visual detection module might be natively implemented in the utilized IDE, e.g., *Unity*. The organization's workflows also interact with the *WFMS-specific Implementation* module of HoloWFM, which can trigger changes in workflow definitions and instances and read data from these for display in the AR-based UI of HoloWFM. The *WMFS-specific Implementation* contains all the methods, data formats, and communication protocols necessary to communicate with specific WFMSs, e.g., *Camunda*.

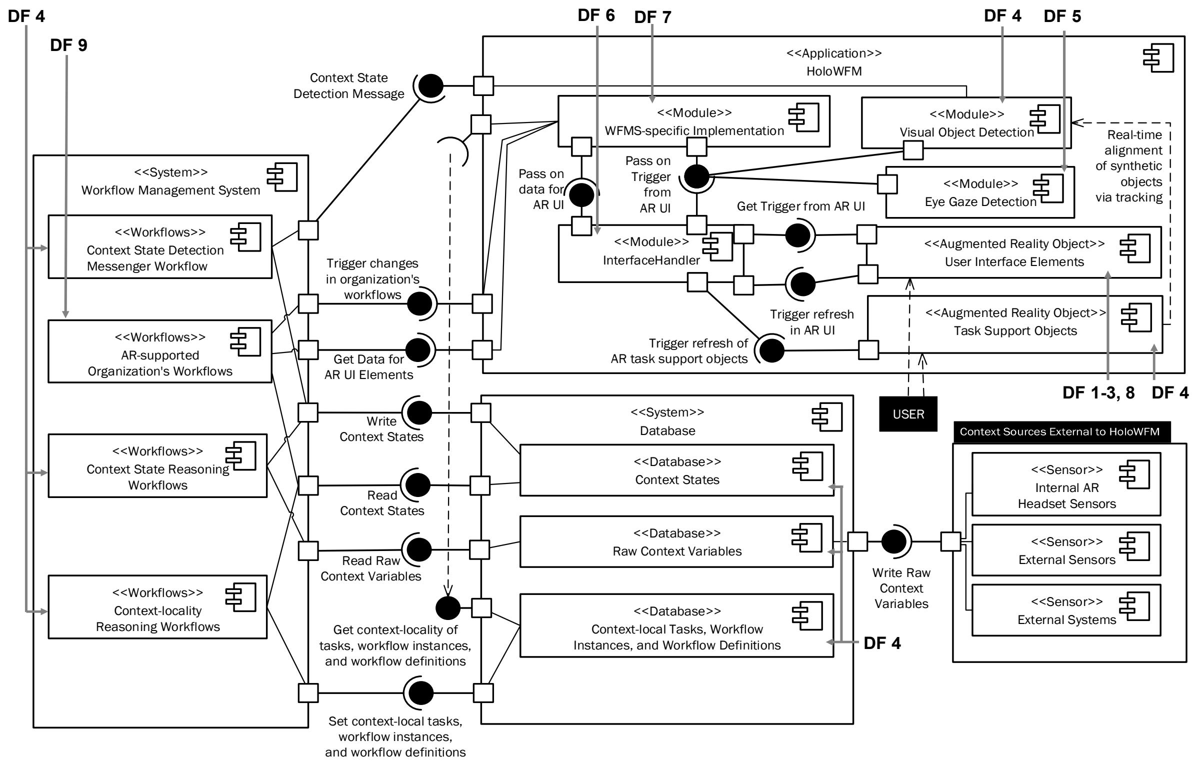


Figure 33. Reference UML component diagram with corresponding design features indicated.

Abstracting from these implementations is the *InterfaceHandler* module. Leaning on the Model-View-Controller software architectural pattern, the *InterfaceHandler* sends triggers from and receives data for the AR UI from the *WFMS-specific Implementations* and receives, and vice versa, sends them to the *User Interface Elements*. It also triggers refreshes of *AR Task Support Objects*, which are not part of the UI but, e.g., highlight task-relevant objects directly. These objects are also tracked with the visual object detection module to align AR objects in real-time. The *InterfaceHandler* thus integrates the user experience of AR task support objects and HoloWFM UI, addressing DP 10 raised at the end of the first design cycle. Finally, the end-user's points of contact with HoloWFM are the AR-based *User Interface Elements* and synthetic *Task Support Objects*. A rough comparison between the HoloWFM architecture and the Model-View-Controller software architectural pattern for illustrative purposes is depicted in Figure 34.

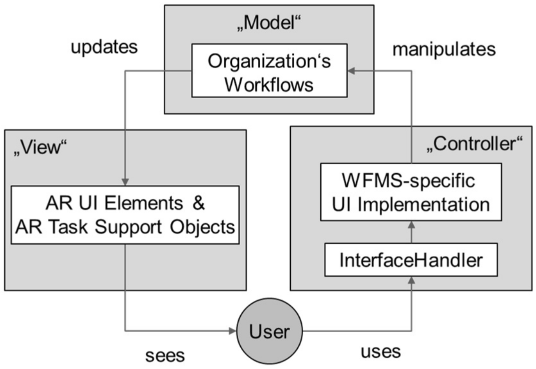


Figure 34. Rough mapping of the HoloWFM architecture onto the Model-View-Controller pattern.

5.3.1.4.6 Reference UML Sequence Diagram

The UML sequence diagram in Figure 35 depicts the flow of information and actions between the HoloWFM end-user and components during usage logically and chronologically. The level of abstraction in the UML sequence diagram is roughly equivalent to the UML component diagram depicted in Figure **33**. The corresponding DFs are also indicated in Figure 35.

The main action starts with the end-user's lifeline. First, the user selects the WFMS to connect to, which defines the subsequent login sequence, e.g., password/username or token. In the *loop* fragment, the end-user first interacts with the AR UI either via holographic touch or eye gaze (first *alt* fragment). This interaction is processed in HoloWFM by the *InterfaceHandler*. The end-user can use some AR UI elements locally, i.e., without requiring further communication with the WFMS, e.g., opening and closing the quick-access menu or inspecting a user task.

The end-user may, however, perform some actions requiring some interaction with the WFMS (second *alt* box), which are then forwarded to the WFMS-specific UI implementation to trigger some WFMS communication. These actions or method executions, respectively, are further detailed in Figure 39 in the interface *IuserInterfaceFunctionsForwardedToWFMS*.

If the end-user's action also affects an organization's workflow (first *opt* fragment), the WFMS-specific UI implementation will communicate this to the WFMS. Such workflow action may be, e.g., the completion of a user task or the activation of a checkbox in a user task.

Depending on the specific workflow, a task therein may read context states from the database (second *opt* fragment). This may be, e.g., a request for the current state of a machine or the user's location.

If a context state is relevant to the workflow (third *opt* fragment) and has the right value, the workflow can change based on the context state. This may be, e.g., a gateway redirecting the workflow to another path or a change of the AR task support content if a machine is on or the user is in a certain location. It is important to emphasize that the AR task support objects for the workflow end-users are controlled via the organization's workflows. Therefore, changes in the context states propagate to the AR content via changes in the organization's workflows.

Independently from the above three optional sequences and still within the first *alt* fragment, the WFMS-specific UI implementation in HoloWFM requests task, workflow instance, and/or workflow definition data from the WFMS. This sequence is performed to at least address the user's action, which necessitates a communication sequence with the WFMS in the first place.

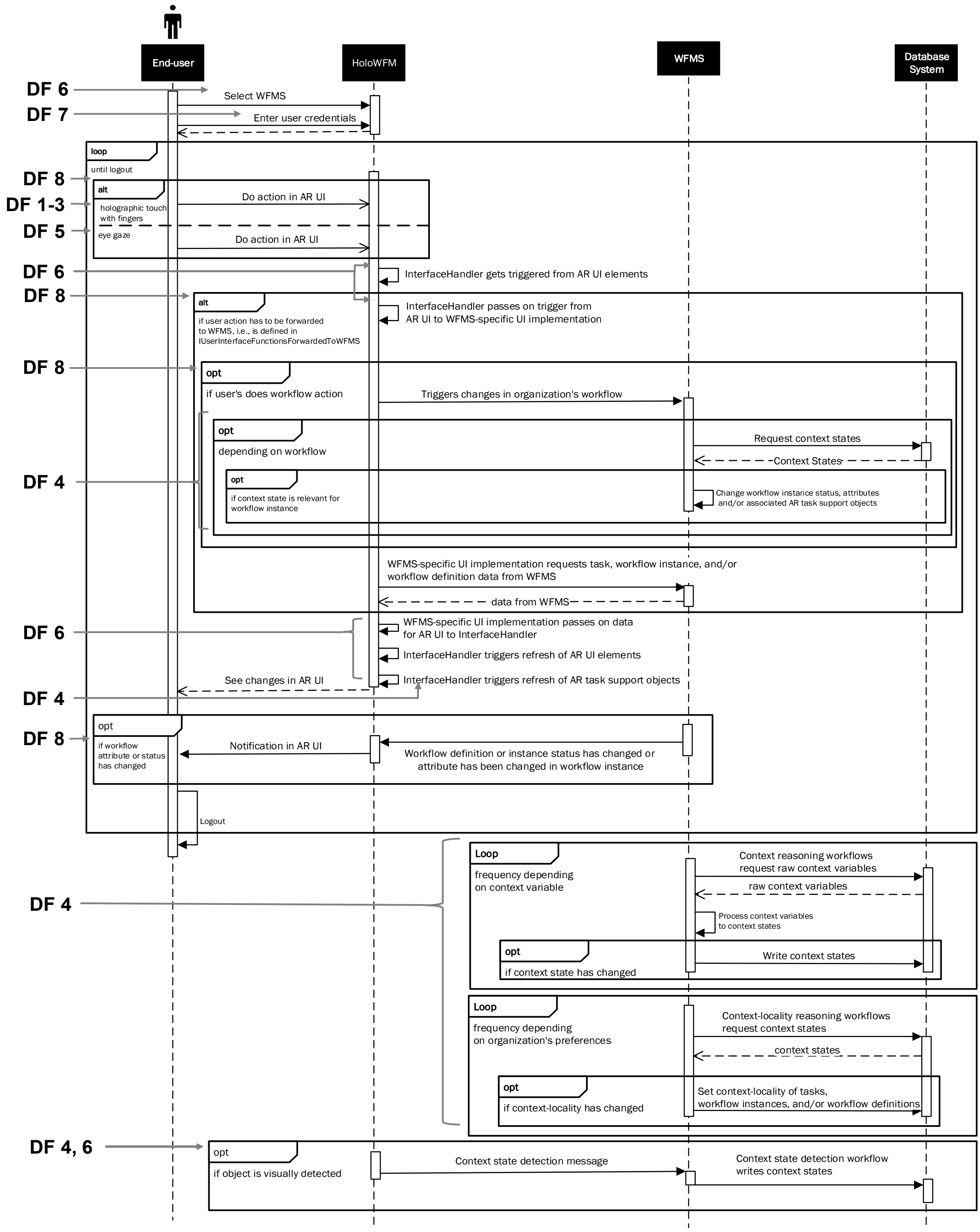


Figure 35. Reference UML sequence diagram with corresponding design features.

After receiving the data, the sequence flow continues outside the first *alt* fragment. Irregardless of whether the user's initial action necessitated communication with the WFMS, the WFMS-specific UI implementation passes on the necessary data to the *InterfaceHandler*, which in turn uses this data to refresh the AR UI elements and AR task support objects. In this way, the end-user finally sees the changes in the AR UI corresponding to the end-user's initial actions.

The fourth *opt* fragment (last within the *loop* fragment) depicts the event that a status of a workflow definition or instance has changed or an attribute of a workflow instance has changed. Then, a notification may appear in the AR UI for the end-user.

Three sequence groups exist without end-user interaction. First, the second *loop* fragment runs to read and check for updates of the context variables and changes the context states if necessary (*opt* fragment within). Similarly, the third *loop* fragment runs to check whether changes in context states require changing the context-locality status of tasks, workflow instances, or workflow definitions. Also, if the sensors of HoloWFM recognize a known object (last *opt* fragment), a context state detection message is sent to the WFMS, which will initiate a context detection workflow to note the recognition of the object in the context state database.

5.3.1.4.7 Reference Simplified UML Class Diagram

Figure 36 shows a simplified UML class diagram for HoloWFM, with the corresponding DFs, but no methods or attributes for the classes to enhance comprehensibility. This version is meant to provide a quick overview of the class structure for HoloWFM. An extended and enlarged version is available in Chapter 5.3.1.4.8.

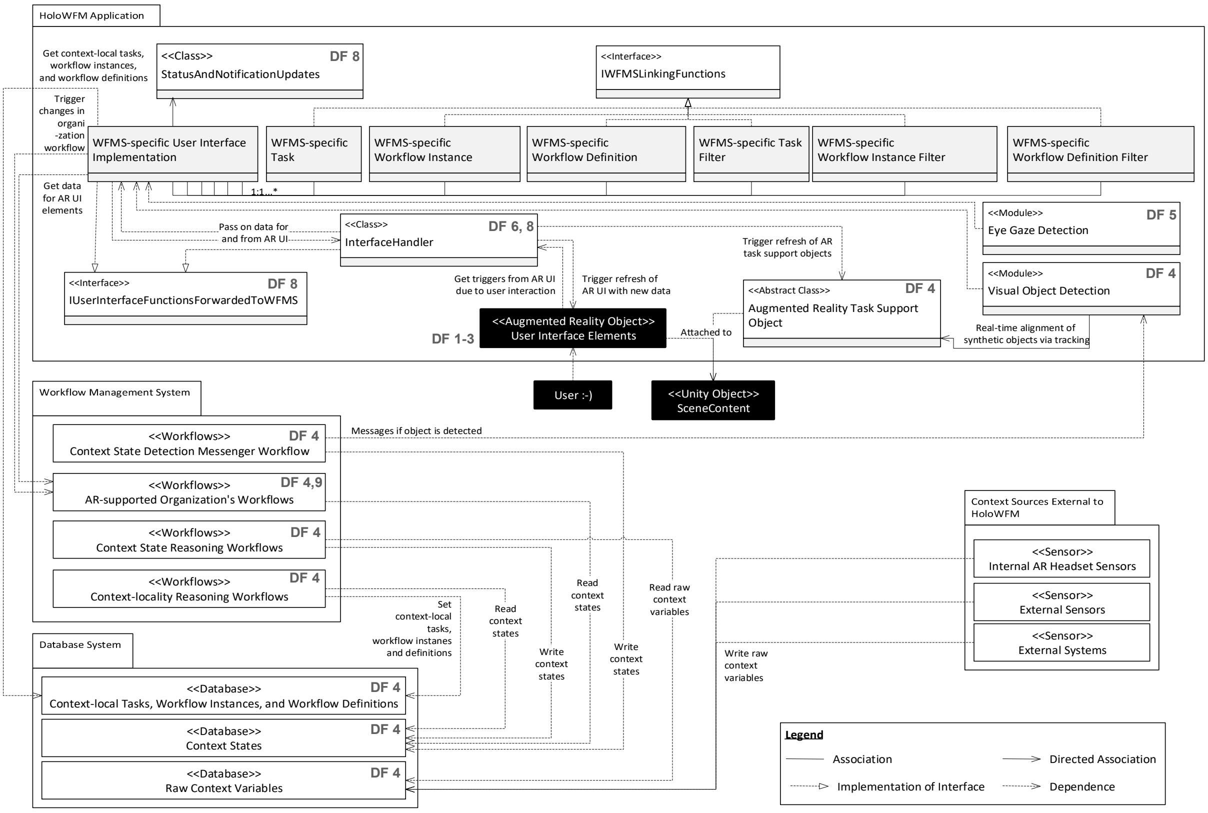


Figure 36. Reference simplified UML class diagram.

The layout is similar to the reference UML component diagram to ease comprehension. As such, the description of the UML components still applies. On the class level of abstraction, some previously occluded details are now visible, however.

The class *InterfaceHandler* and the *WFMS-specific User Interface implementation* both must implement a series of UI functions, which are defined in the interface *IUserInterfaceFunctionsForwardedToWFMS* (see Figure 39). As the name of the interface implies, these functions are available to the HoloWFMs end-user in the AR *User Interface Elements* and are passed on from the *InterfaceHandler* to the *WFMS-specific User Interface implementation*, which finally interacts with the WFMS to execute these functions. Hence, both the *InterfaceHandler* and the *WFMS-specific User Interface implementation* must implement the same functions defined in the corresponding interface.

The *WFMS-specific implementation* also contains six WFMS-specific implementations for tasks, workflow instances, workflow definitions, and respective filters. These must implement a common defined interface, which prescribes some attributes every WFMS-specific implementation must fulfill in order to be compatible with HoloWFM. These attributes serve to connect the entities present in HoloWFM with the entities in the WFMS.

5.3.1.4.8 Reference UML Class Diagram

While the simplified reference UML class diagram is useful for a quick overview and to understand the interrelationships between classes, the extended version offers more utility for software development. As such, this version features the attributes and methods of the classes and interfaces and is depicted in full in Figure 47 at the end of this chapter.

HoloWFM Application

In the upper package, four entities in the HoloWFM application are expanded with attributes and methods.

First, the interface *IWFMSLinkingFunctions* (Figure 37) has two attributes and two methods. The attribute *holoWFMUniqueID* is a string that identifies the task, workflow instance, or workflow definition uniquely in HoloWFM. The attribute *wfmsLink* is of unclear data type and therefore prescribed as an object type. The attribute serves to link the internal representation of a task, workflow instance, or workflow definition in HoloWFM with the corresponding entity in the WFMS. An instance of a *wfmsLink* may thus be, e.g., an URL for a REST API, as is the case for the WFMS *Camunda*. The defined methods of the interface are the getter and setter methods *getWfmsLink()* and *setWfmsLink()*.

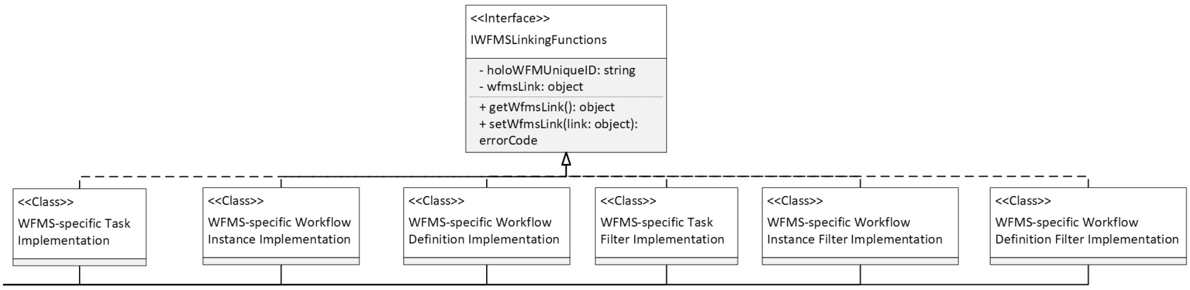


Figure 37. Interface *IWFMSLinkingFunctions*.

Second, the abstract class *Augmented Reality Task Support Object* (Figure 38) prescribes the implementation of only the private attribute *uniqueARTaskSupportObjectId,* which is a string containing a globally unique ID to link the AR task support object to tasks via a BPMN extension.

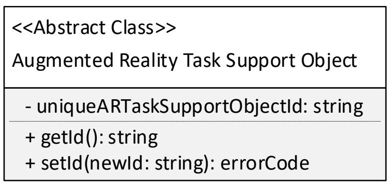


Figure 38. Abstract class *Augmented Reality Task Support Object*.

Third, the interface *IUserInterfaceFunctionsForwardedToWFMS* (Figure 39) has a total of thirty-one methods and is implemented by both the classes *WFMS-specific User Interface Implementation* and *InterfaceHandler*. The methods contained in this interface are operated by the HoloWFM end-user via the *InterfaceHandler* that communicates with the AR UI elements. Then, the appropriate WFMS-specific implementation of a method is selected by the *InterfaceHandler*, and the method call and its parameters are forwarded to the *WFMS-specific User Interface Implementation* for further processing and communication with the WFMS. To get tasks, workflow instances, and workflow definitions from the WFMS, methods to get all entities are available, e.g., *getAllTasks()*. Some WFMS-specific filters can also be applied to reduce the number of returns, e.g., *getFilteredTasks()*. A special kind of filter is context-locality. As such, a special method is defined to only get tasks, workflow instances, and workflow definitions marked as context-local in the database (see below), e.g., *getContextLocalTasks()*.

Tasks can – in general – be *instantiated*, *started*, *completed*, *suspended*, *resumed*, or *terminated*, depending on the WFMS, e.g., *instantiateTask()*. The operational status of a workflow definition can be toggled via *setWorkflowDefinitionCanBeInstantiated()*. If set to true, a workflow definition can be *instantiated,* and the workflow instance can be *started*, *suspended*, *resumed*, and *terminated*, depending on the specific WFMS.

To facilitate filtering of tasks, workflow instances, and workflow definitions, add data to process logs, or other purposes, attributes can be added or removed to and from tasks, workflow instances, and workflow definitions, e.g., via *addAttributeToTask()*.

The UI of user tasks can be displayed in the main menu, quick-access menu, and HUD, and lists of tasks, workflow instances, and workflow definitions are available. To provide the end-user with additional information about these, e.g., completion date of tasks, variables present in workflow instances, etc., methods are available to get further details for tasks, workflow instances, and workflow definitions, e.g., *getTaskDetails()*. Finally, unread status updates or notifications can be downloaded from the WFMS via *getStatusAndNotificationUpdates()*.

```
<<Interface>>
IUserInterfaceFunctionsForwardedToWFMS
---
+ getAllTasks(): Task[0..*]
+ getAllWorkflowInstances(workflowDefId: string): WorkflowInstance[0..*]
+ getAllWorkflowDefinitions():WorkflowDefinition[0..*]
+ getFilteredTasks(filter: TaskFilter): Task[0..*]
+ getFilteredWorkflowInstances(wiFilter: WorkflowInstanceFilter): WorkflowInstance[0..*]
+ getFilteredWorkflowDefinitions(wdFilter: WorkflowDefinitionFilter): WorkflowDefinition[0..*]
+ getContextLocalTasks(): Task[0..*]
+ getContextLocalWorkflowInstances(): WorkflowInstance[0..*]
+ getContextLocalWorkflowDefinitions(): WorkflowDefinition[0..*]
+ instantiateTask(taskId: string): errorCode
+ startTask(taskId: string): errorCode
+ completeTask(taskId: string): errorCode
+ suspendTask(taskId: string): errorCode
+ resumeTask(taskId: string): errorCode
+ terminateTask(taskId: string): errorCode
+ setWorkflowDefinitionCanBeInstantiated(workflowDefId: string, isInstantiatable: boolean): errorCode
+ instantiateWorkflowDefinition(workflowDefId: string) errorCode
+ startWorkflowInstance(workflowInstId: string): errorCode
+ suspendWorkflowInstance(workflowInstId:string): errorCode
+ resumeWorkflowInstance(workflowInstId:string): errorCode
+ terminateWorkflowInstance(wfInstId:string): errorCode
+ addAttributeToTask(atributeName: string, attributeValue: object, taskId: string): errorCode
+ addAttributeToWorkflowInstance(attributeName: string, attributeValue: object, workflowInstId: string): errorCode
+ addAttributeToWorkflowDefinition(attributeName: string, attributeValue: object, workflowDefId: string): errorCode
+ removeAttributeFromTask(attributeName: string, taskId: string): errorCode
+ removeAttributeFromWorkflowInstance(attributeName: string, workflowInstId: string): errorCode
+ removeAttributeFromWorkflowDefinition(attributeName: string, workflowDefId: string): errorCode
+ getTaskDetails(taskId: string): object
+ getWorkflowInstanceDetails(workflowInstId: string): object
+ getWorkflowDefinitionDetails(workflowDefId: string): object
+ getStatusAndNotificationUpdates(): StatusAndNotificationUpdates
```

Figure 39. Interface *IUserInterfaceFunctionsForwardedToWFMS*.

Fourth, the class *InterfaceHandler* (Figure 40) contains a total of four attributes and fifteen methods. It implements the methods contained in the interface *IUserInterfaceFunctionsForwardedToWFMS.* The attribute *wfmsSelection* is a string representing the WFMS the HoloWFM user is currently utilizing, e.g., "Camunda." Based on this selection, WFMS-specific implementations are selected by the *InterfaceHandler* to process and forward the AR UI functions. As such, instances of the class *WFMS-specific User Interface Implementation* are contained in the attribute array *implWFMS*. The attribute *activeTaskId* marks the task currently operated by the end-user, which is used in various methods. The boolean attribute *connected* is used to indicate the connection status to some methods and the end-user.

The first action taken by the end-user is to choose the WFMS to connect to via *selectWFMS()*, which modifies the attribute *wfmsSelection*. Afterward, the login is facilitated by the method *enterUserCredentials()*, which expects an object. This allows various methods of login, e.g., username/password, tokens, etc. Then, the *establishConnection()* method connects to the WFMS. If a RESTful API is used by the WFMS, the *upkeepConnection()* method will just regularly ping the WFMS to check if it can be reached.

Three methods are available to update the lists of tasks, workflow instances, and workflow definitions, e.g., *refreshMainMenuTasklist()*, with entities gotten from the appropriate methods, e.g., *getAllTasks()*. The AR UI components *Heads-up Display* and *Quick-access Menu* do not show lists of workflow instances or workflow definitions (cf. Chapter 5.3.1.4.4). Thus, no *refreshHUD()* or *refreshQAM()* methods are defined for those. For tasks, however, the methods *displayTaskInMainMenu()*, *displayTaskInHUD()*, and *displayTaskInQuickAccessMenu()* are defined as tasks are available in all AR UI components.

To facilitate user interaction, three methods are defined so that the end-user can select tasks, workflow instances, and workflow definitions in the AR UI, and the corresponding identifiers are returned for further processing, e.g., *selectTask()*. Also, the method *displayARTaskSupport()* will load the available AR task support objects and display them for the end-user. Finally, as the changes in the UI of a user task are local in HoloWFM, e.g., selecting a check-box, the method *synchUserTaskARUserInterfaceToWFMS()* will facilitate the recording of changes in the WFMS.

```
<<Class>>
InterfaceHandler
------------------------------------------------------------
- wfmsSelection: string
- implWFMS: wfmsSpecificUserInterfaceImplementation [1..*]
+ activeTaskId: string
+ connected: boolean
------------------------------------------------------------
+ selectWFMS(): string
+ enterUserCredentials(usrCreds: object): errorCode
+ establishConnection(): errorCode
+ upkeepConnection(): errorCode
+ refreshMainMenuTasklist(tasks[]: Task[0..*]): errorCode
+ refreshMainMenuWorkflowInstancesList(wfInsts[]: workflowInstance[0..*]): errorCode
+ refreshMainMenuWorkflowDefinitionsList(wfDefs[]: workflowDefinition[0..*]): errorCode
+ selectTask(): taskId
+ selectWorkflowDefinition(): workflowDefId
+ selectWorkflowInstance(string): workflowInstId
+ displayTaskInMainMenu(taskId: string): errorCode
+ displayTaskInHUD(taskId: string): errorCode
+ displayTaskInQuickAccessMenu(taskId: string): errorCode
+ displayARTaskSupport(taskId: string): errorCode
+ synchUserTaskARUserInterfaceToWFMS(taskId: string): errorCode
```

Figure 40. Class *InterfaceHandler*.

Workflow Management System

In the WFMS (middle package), three entities have been expanded. **First**, the interface *IARSupportedOrganizationWorkflow* (Figure 41) is implemented by a WFMS-specific class and contains one private attribute *arTaskSupportObjectId*, which is an array of BPMN extension elements. These extension elements contain the unique IDs of the AR task support objects. Thus, the synthetic task support objects are linked to the tasks.

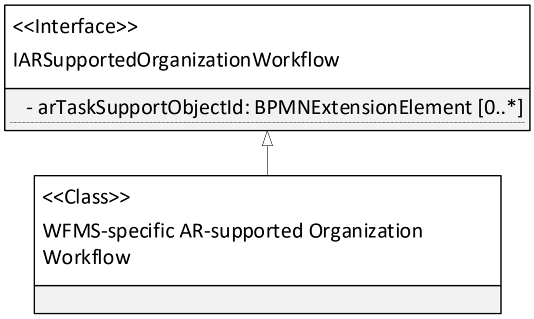


Figure 41. Interface *IARSupportedOrganizationWorkflow* and implementing class.

Second, the interface *IContextReasoningWorkflow* (Figure 42) is implemented by a WFMS-specific class. It prescribes four attributes and one method. The attribute *equationWithContextVariablesResolvesToContextState* is a string that contains an expression of context variables and logical and arithmetic operators on the one side and a context state on the other of an equation. When the workflow is executed via the method *computeEquationAndWriteContextState()*, the equation is computed, and the context state is set to the calculated value.

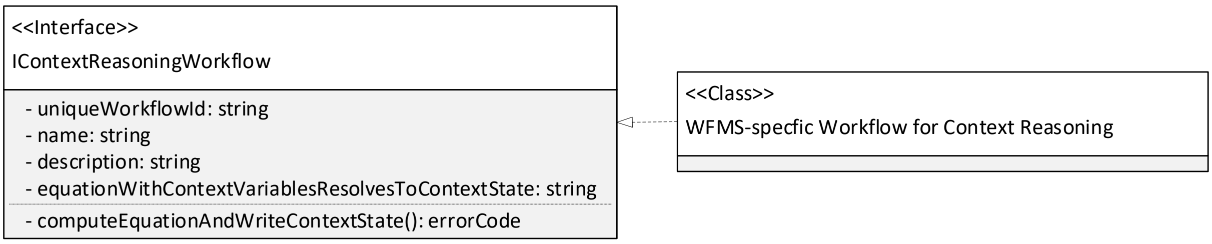


Figure 42. Interface *IContextReasoningWorkflow* and implementing class.

Third, the interface *IContextLocalityReasoningWorkflow* (Figure 43) is implemented by a WFMS-specific class. It contains two important attributes. First, *expressionWithContextStatesResolvesToTrue* is an expression containing context states and logical and arithmetic operators to calculate a boolean value. As the identifiers of tasks, workflow instances, and workflow definitions are globally unique, the attribute *targetTaskOrWorkflowInstanceOrWorkflowDefinitionId* is defined to contain the respective ID. The method *computeExpressionAndUpdateContextlocalityTable()* resolves the expression and, depending on the outcome and set target ID, will add or remove a task, workflow instance, or workflow definition from the context-locality table.

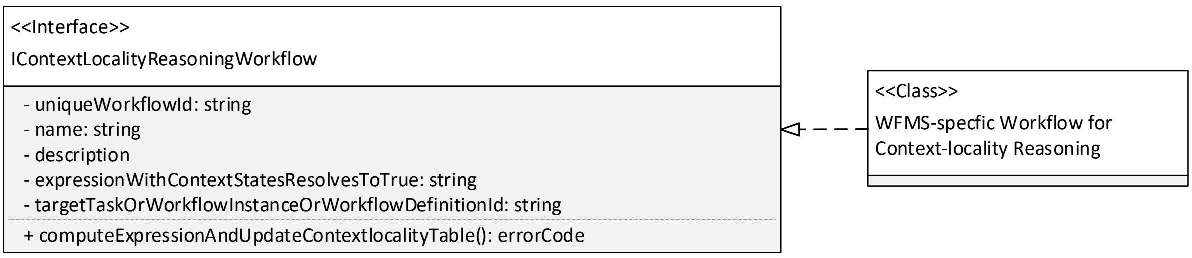


Figure 43. Interface *IContextLocalityReasoningWorkflow* and implementing class.

Database System

The lower package containing the database entities has three entities expanded. **First**, the interface *IContextLocalDatabaseAttributes* (Figure 44) contains three attributes, each an array of identifiers for tasks, workflow instances, and workflow definitions that are context-local. Non-context-local entities are not saved. The interface is implemented by database system-specific tables or classes.

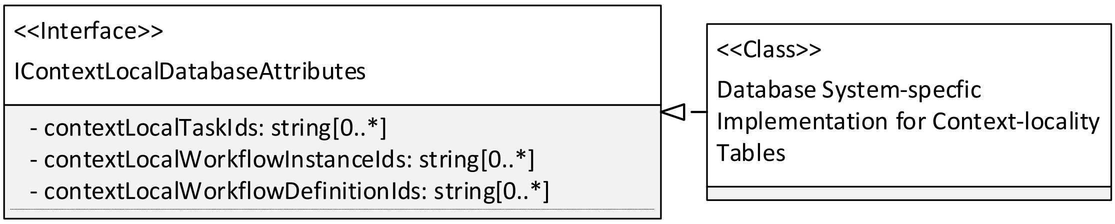


Figure 44. Interface *IContextLocalDatabaseAttributes* and implementing class.

Second and **third**, the interfaces *IContextState* (Figure 45) and *IRawContextVariable* (Figure 46) contain unique identifiers, names, descriptions, and values for context variables and states. These are implemented by database system-specific tables or classes.

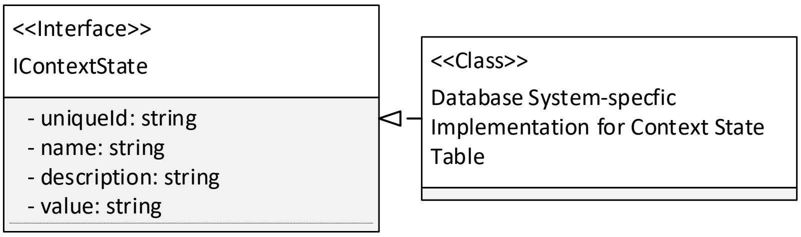


Figure 45. Interface *IContextState* and implementing class.

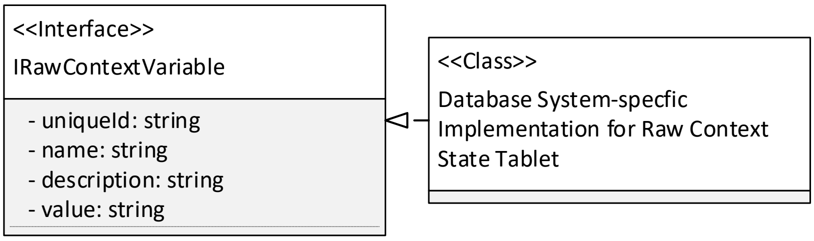


Figure 46. Interface *IRawContextVariable* and implementing class.

On the following page, the complete UML class diagram is depicted.

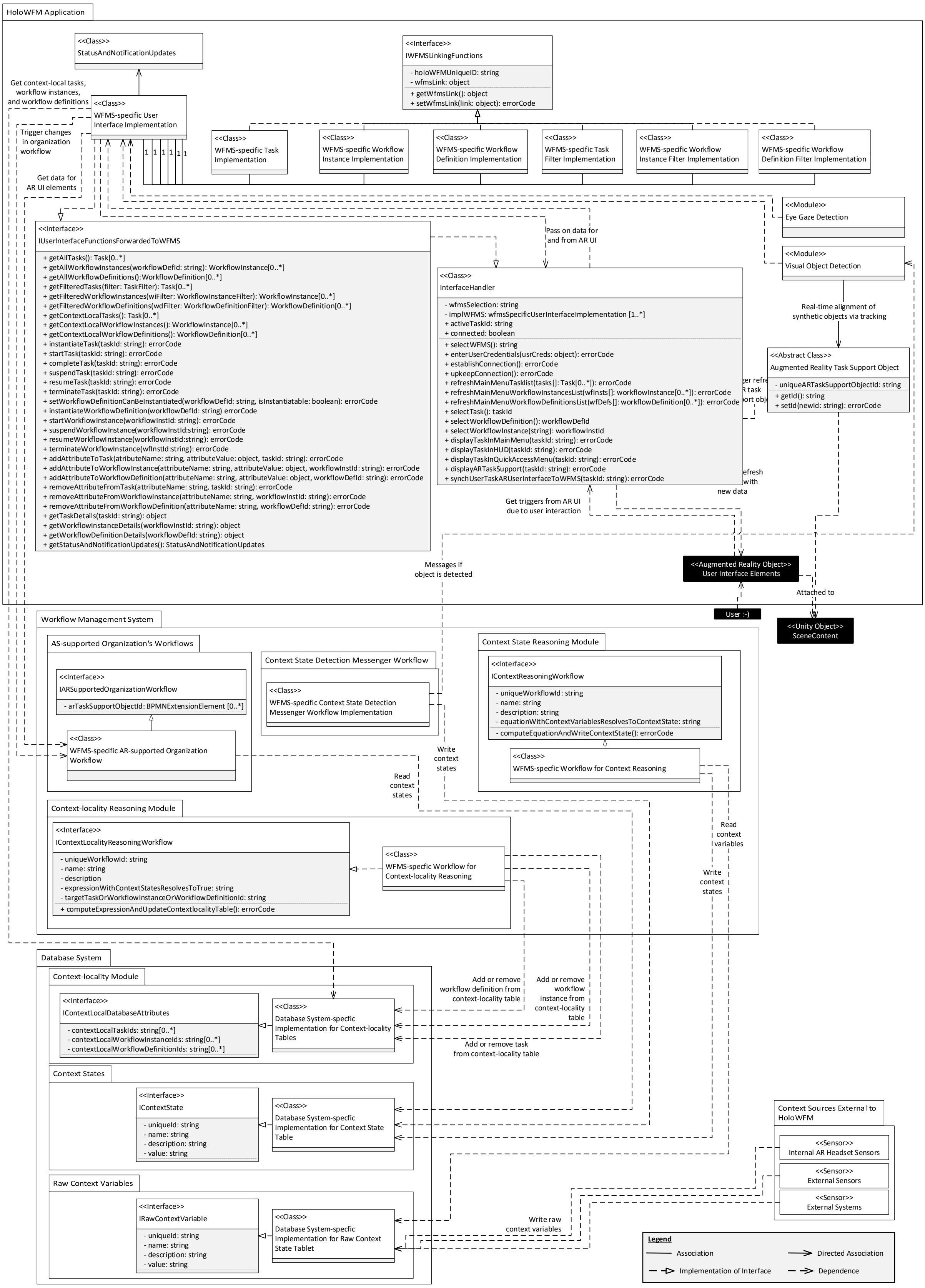


Figure 47. Reference UML class diagram.

5.3.1.5 Reference Architecture Description Correspondences

The names of elements in the UML diagrams are instructive, i.e., the names and relationships do correspond between models. E.g., the *InterfaceHandler* in Figure 33 indicates the same object as in Figure **36** and Figure 47.

5.3.1.6 Rationales for Architectural Decision

Four key design decisions may be of interest. First, regarding the abstraction layer between UI and WFMS constituted by the class *InterfaceHandler* and the interface *IWFMSMethods, i*t was decided not to include WMFS-specific implementations of methods in the *InterfaceHandler*. Instead, this class selects and calls the appropriate *WFMS-specific User Interface Implementation* and passes any parameters to the WMFS-specific implementation of the method. This allows easier maintenance and parallel development for multiple WMFS implementations, as the classes that interface with the *InterfaceHandler* won't need to change when WFMS-specific implementations of the UI change. The alternative would've been to implement a case-based selection in every method that is currently defined in the *InterfaceHandler*. When a method is called, the appropriate WFMS-specific implementation of the method would be selected, based on the currently connected WFMS, i.e., via the attribute *wfmsSelection* in the *InterfaceHandler*. This would, however, make the code in every method very long and, thus, difficult to read and maintain.

Second, it was decided to outsource the storage and processing of the *raw context variables* and *context states* from HoloWFM to the *Database System* and *WFMS*. This was done to support cases where the amount of context variables collected becomes very large, and thus external storage and processing become necessary. In these cases, context-state reasoning workflows might also utilize further IT services, e.g., AI-based reasoning modules, or run in a distributed manner. To enable optimal performance, the context reasoning system was, therefore, entirely outsourced from the HoloWFM application. A potential downside to this architectural decision is that HoloWFM requires network access to the database system to be context-aware. However, in the scenario where HoloWFM does not have network access, the WFMS would also be unreachable, and thus workflow management and control would not be possible. Contemporary WFMSs are not designed to address scenarios where some WFMS front ends might execute workflows "offline" in a distributed manner and synchronize only occasionally to the WFMS. Therefore, HoloWFM also does not cover this scenario. However, this might be an interesting direction for further research for WFMSs. Then, HoloWFM should evolve accordingly.

Third, the context information is stored and processed in a three-staged distributed manner. First, *Raw Context Variables* are gathered, which are then processed via special workflows to *Context States*. The latter are then utilized by *AR-supported Organization's Workflows* or further processed with special workflows to mark tasks, workflow instances, and workflow definitions as context-local. This architecture was utilized to decouple the different stages of the context information lifecycle to enable better scalability, analogous to the considerations in the previous paragraph. Also, this architecture ensures a degree of openness: it enables developers to define the "consumers," i.e., *Context-reasoning Workflows, Context-locality Reasoning Workflows, a*nd *AR-supported Organization's Workflows* to be defined later and use the gathered *Raw Context Variables* and calculated *Context States* in a distributed and independent manner. An alternative approach could define the gathering and processing of *Raw Context Variables* directly in the individual *AR-supported Organization's Workflows*. By reusing the service task used to gather and process the contexts across multiple *AR-supported Organization's Workflows*, a degree of development efficiency could be ensured. However, maintainability would certainly suffer, e.g., when the name or format of a context variable or context state changes, all corresponding organization's workflows would have to be changed. Further, the context information would potentially be processed multiple times by different workflows in parallel, which would reduce computational efficiency.

Fourth, BPMN extension elements (see Figure 60 and the following for an example) were utilized to refer to and pass on parameters to appropriate AR task support objects, which may be stored or dynamically generated in Unity. An alternative approach that was explored was to somehow embed AR task support objects directly in the XML underlying the BPMN model. However, this would massively increase the size of the BPMN models and would make them and the AR objects harder to maintain. Instead, in the chosen approach, the AR task support objects need to be somehow imported into the HoloWFM application, in particular into the *Unity scene*. This import could be done during build-time. However, this would require a new *build* of HoloWFM for each change in AR workflow support. Then, this new build would need to be distributed to all HoloWFM users. As such, parallel distributed work on AR content would be difficult: every time any workflow of any organization is changed in regard to the AR support, a new HoloWFM build would need to be distributed to all HoloWFM users. Very frequent software updates would be the consequence, even for those users whose workflows were not updated. A better approach, therefore, is to dynamically load or preload AR task support objects into HoloWFM during runtime. Thus, no update of the HoloWFM application itself would be needed. The AR task support objects can then be built in a distributed fashion alongside their respective workflows.

5.4 Evaluation

A three-step approach was implemented to evaluate the developed RAD of the third design cycle. First, the derivation of UML diagrams from the DT verified the DT but also transferred the rigor from the DT development to the RA models (Chapter 5.4.1). Second, the RAD was instantiated as a software prototype (Chapter 5.4.2). Third, the RAD was evaluated via an expert survey (Chapter 5.4.3).

5.4.1 Evaluation of Design Theory via Projection as Reference Architecture

The derivation of the UML diagrams and textual descriptions of the RAD from the DT can be interpreted through the lens of the conceptual framework of *projectability* by Goodman [80], as recommended by Baskerville and Pries-Heje [81]. According to this framework, a DT is *actually projected* when it's instantiated. When this *projection* is successful, i.e., no observation in opposition to the DT is made, but not all possible instantiations have been examined, a DT is *projectable*. The more frequently a DT is actually projected, the more entrenched it becomes [80]. Therefore, the projectability of the DT was demonstrated by deriving components of a HoloWFM RAD from it as an actual projection.

Also, as Fu et al. [58] find, the majority of publications containing DPs lack a proper validation of these. By developing the RAD, this common shortcoming was addressed. Further, by far the most common validation principle for DPs is their application for the actual design of an artifact [58]. As such, the approach chosen in this dissertation follows accepted practice.

By systematically linking the elements of the UML diagrams to the well-founded DPs and DRs via the DFs, the quality of the UML diagrams is – to some degree – ensured. In a sense, the rigor during the development of the DRs and DPs is transferred down the abstraction levels to the RAD.

5.4.2 Feasibility of Reference Architecture via Operationalization

To evaluate whether the developed design and derived RAD are *feasible*, this dissertation oriented itself on the framework by Sonnenberg and vom Brocke [67]. In this context, *evaluation activity 3* was performed via a *demonstration with a prototype* [67]. For this, the WFMS *Camunda*, a *MySQL* database, and a *Unity* application running on the *Microsoft HoloLens* were utilized to instantiate a software prototype. To develop the prototype, a solution instance architecture (cf. Chapter 2.4) was derived from the RAD.

In the developed HoloWFM software prototype, the focus was on demonstrating the feasibility of the architecture to ensure utility for potential *HoloWFM developers*, i.e., if the approaches to structure the components, classes, and sequence logic work. Thus, in the prototype, the four key design decisions described in Chapter 5.3.1.6 were implemented, i.e., 1) an *InterfaceHandler* class was implemented that selects the WFMS-specific implementations of methods, 2) the three-component architecture with

HoloWFM, WFMS, and context database was realized, 3) exemplary context information was stored and processed with a database and workflows, and 4) BPMN extensions in user tasks were used to link AR content in Unity to tasks in Camunda. As such, the feasibility of the key design decisions was verified.

Consequently, the full reference UI was not implemented. As described in Chapter 2.6, the implementation of a "polished" UI would not serve any function for the evaluation of the HoloWFM RAD. Indeed, the implementation of a polished AR UI would've only reflected programming and media design expertise. An evaluation with such a polished prototype, thus, would have overly evaluated programming and media design skills and not the underlying RAD.

Below multiple exemplary figures, screenshots, and descriptions from the prototype development and testing are included.

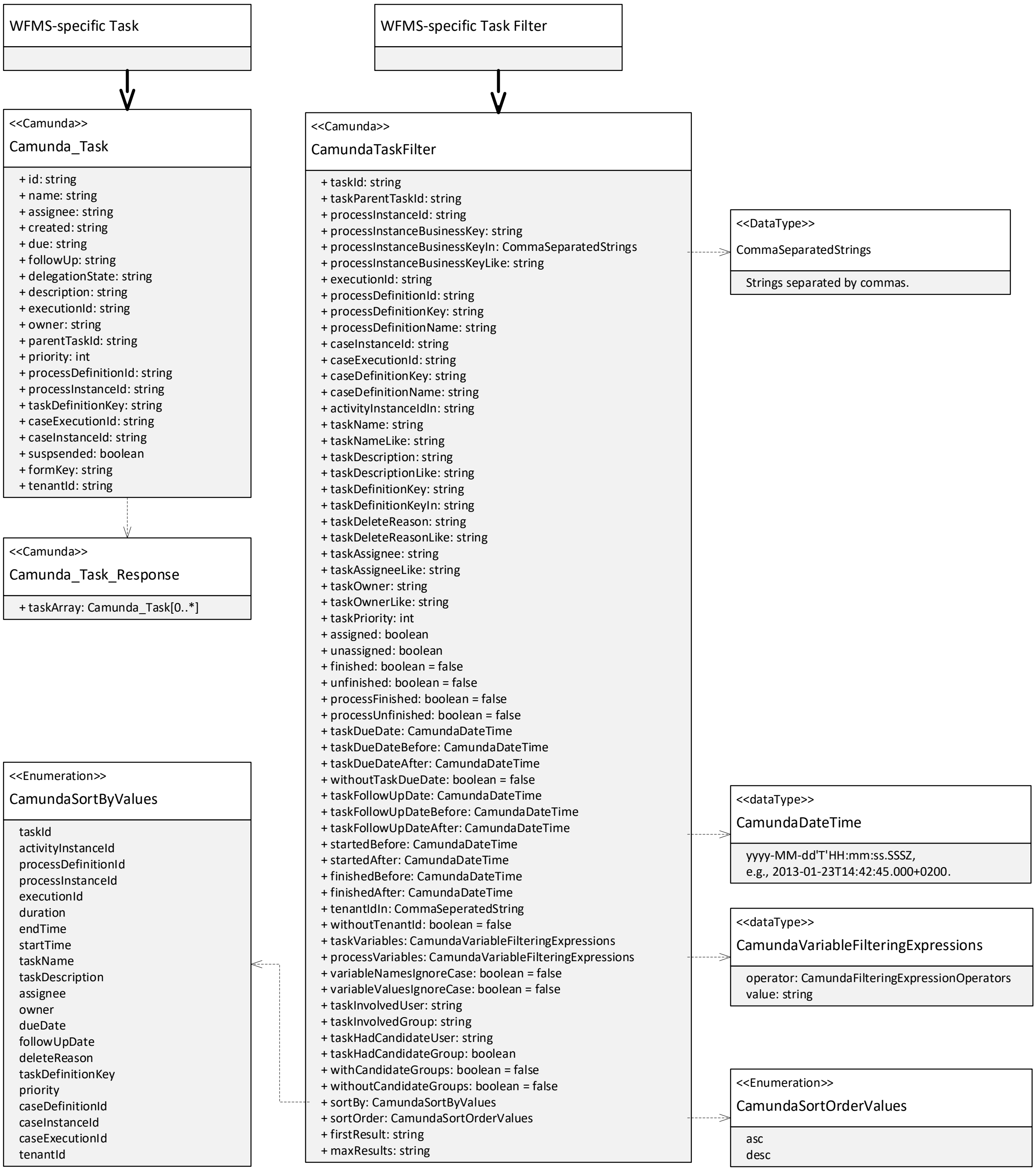


Figure 48. Excerpt of implemented Camunda classes and data types in the prototype, documented as UML class diagram.

Description: Excerpt of implemented Camunda classes and data types in the prototype, documented as UML class diagram. The corresponding classes from the reference class diagrams are depicted above. For clarity, implemented interface attributes and methods not depicted.

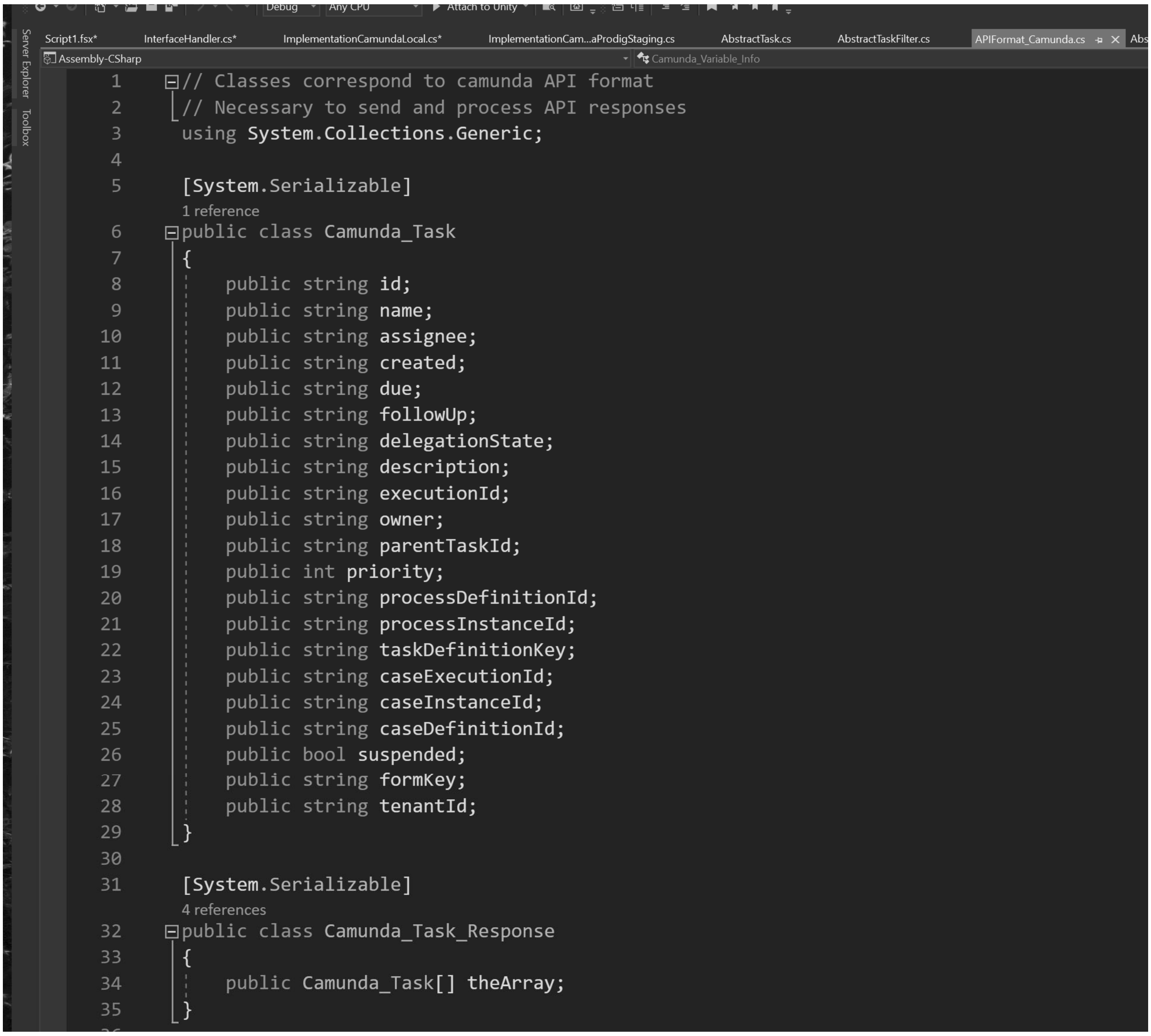


Figure 49. Screenshot of a code excerpt in Microsoft Visual Studio of implemented WFMS-specific class task for Camunda.

```
using TMPro;
using UnityEngine;
using UnityEngine.EventSystems;
using System.Threading.Tasks;
using System.Collections;
using System;

Unity Script (1 asset reference) | 4 references
public class InterfaceHandler : MonoBehaviour
{
    private string _wfmsSelection;
    private string activeTask;
    private ImplementationCamundaLocal ImplCamundaLocal;
    private ImplementationCamundaProdigStaging ImplCamundaProdigStaging;
    private Boolean connected = false;

    0 references
    public void GetTasks()
    {
        switch (_wfmsSelection)
        {
            case "camunda_local":
                Debug.Log("GetTasks with case camunda_local");
                StartCoroutine(ImplCamundaLocal.GetTasks());
                break;
            case "camunda_prodig_staging":
                Debug.Log("GetTasks with case camunda_prodig_staging");
                StartCoroutine(ImplCamundaProdigStaging.GetTasks());
                break;
            default:
                Debug.Log("GetTasks with Default! No Connection!");
                break;
        }
    }
}
```

Figure 50. Screenshot of a code excerpt in Microsoft Visual Studio of the InterfaceHandler implementation, showing the method getTasks().

```
public class ImplementationCamundaLocal : MonoBehaviour
{

    public IEnumerator GetTasks()
    {
        string URL = "https://staging.prodig.uni-halle.de/engine-rest/task/?assignee=amsxn";
        UnityWebRequest www = UnityWebRequest.Get(URL);
        www.SetRequestHeader("Authorization", "Basic YW1zeG46elhSRnQtMzY=");
        yield return www.SendWebRequest();
        if (www.isNetworkError || www.isHttpError){ Debug.Log(www.error); }
        string jsonWrapped = "{ \"theArray\": " + www.downloadHandler.text + "}";
        Camunda_Task_Response _camundaTaskResponse = JsonUtility.FromJson<Camunda_Task_Response>(jsonWrapped);

        for (int i = 0; i < GameObject.Find("ScrollViewContent").transform.childCount; i++)
        {
            Destroy(GameObject.Find("ScrollViewContent").transform.GetChild(i).gameObject);
        }

        for (int i = 0; i < _camundaTaskResponse.theArray.Length; i++)
        {
            Debug.Log("_camundaTaskResponse.theArray[" + i + "]: " + _camundaTaskResponse.theArray[i].id);
            Vector3 _newPosition = GameObject.Find("TemplateButton").transform.position + new Vector3(0, -60 * i, 0);
            GameObject newButton = Instantiate(GameObject.Find("TemplateButton"),
                                                                    _newPosition, Quaternion.identity,
                                                                    GameObject.Find("ScrollViewContent").transform);
            newButton.name = _camundaTaskResponse.theArray[i].id;
            newButton.transform.GetChild(0).gameObject.GetComponent<TextMeshProUGUI>().text = _camundaTaskResponse.theArray[i].name;
        }
    }
```

Figure 51. Screenshot of a code excerpt in Microsoft Visual Studio of the WFMS-specific UI implementation for Camunda, showing an implementation for the method getTasks().

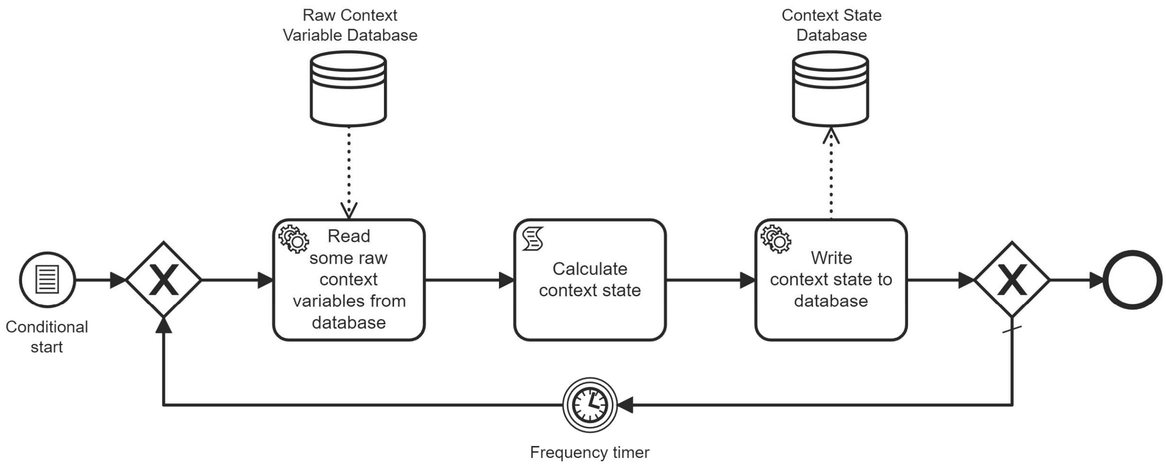


Figure 52. Example *Context State Reasoning Workflow* in BPMN.

Description: Example *Context State Reasoning Workflow.* A service task retrieves some raw context variables from the corresponding database. Then, a script task calculates a context state and finally another service task writes the current context state to the corresponding database.

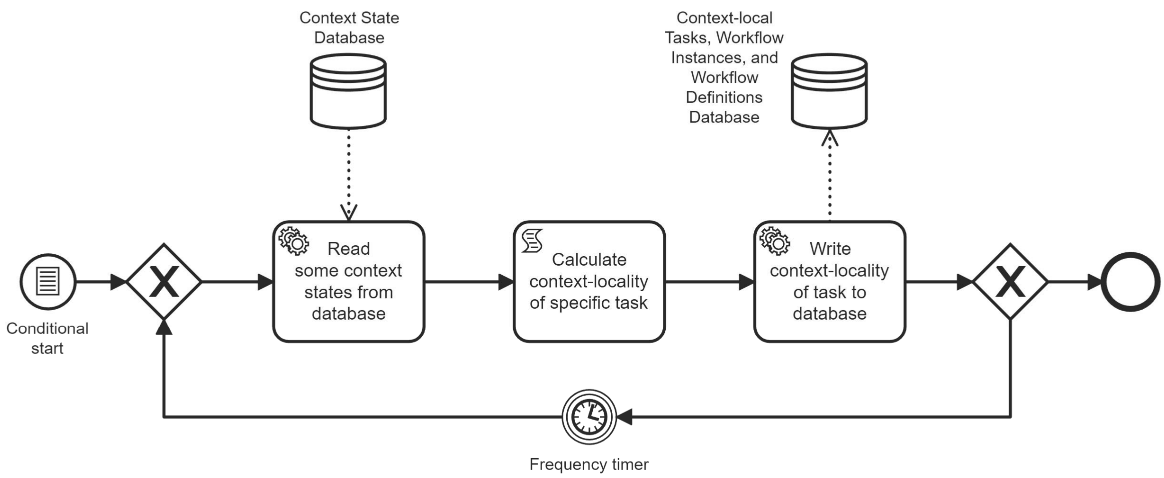


Figure 53. Example *Context-locality Reasoning Workflow* in BPMN.

Description: Example *Context-locality Reasoning Workflow* for a specific task. A service task retrieves some context states from the corresponding database. Then, a script task calculates if the task is context-local and writes the result to the corresponding database.

```
public IEnumerator FilterForNonContextLocalTasks()
{
    private const string ConnectionString = "Server=localhost;Database=myDatabase;Uid=admin;Pwd=admin;";

    MySqlConnection connection = new MySqlConnection(ConnectionString);
    try
    {
        connection.Open();
        MySqlCommand command = connection.CreateCommand();
        command.CommandText = "SELECT ID FROM ContextlocalTasksWorkflowInstancesAndWorkflowDefinitionsDatabase";
        MySqlDataReader reader = command.ExecuteReader();
        List<string> contextLocalTaskIDs = new List<string>();

        while (reader.Read())
        {
            string id = reader.GetString(0);
            contextLocalTaskIDs.Add(id);
        }
        reader.Close();
    }
    catch (MySqlException ex) { Debug.LogError("Database Connection Error: " + ex.Message); }
    finally {connection.Close(); }

    for (int i = 0; i < GameObject.Find("ScrollViewContent").transform.childCount; i++)
    {
        if (contextLocalTaskIDs.contains(GameObject.Find("ScrollViewContent").transform.GetChild(i).name)){
            Destroy(GameObject.Find("ScrollViewContent").transform.GetChild(i).gameObject);
        }
    }

    yield return StartCoroutine(ReorderTaskList());
}
```

Figure 54. Screenshot of a code excerpt in Microsoft Visual Studio of a context-locality filter for tasks.

Description: Screenshot of a code excerpt in Microsoft Visual Studio of a context-locality filter for tasks. First, the IDs of context-local tasks are retrieved from the MySQL database *Context-local Tasks, Workflow Instances, and Workflow Definitions Database* and stored in a list. Then, the IDs in the list and the tasks in the tasklist are compared, and the matching tasks are removed from the tasklist. Finally, another method is started to reorder the tasklist as each task is a gameobject with 3D coordinates in “AR space” and after the prior removal, gaps could exist.

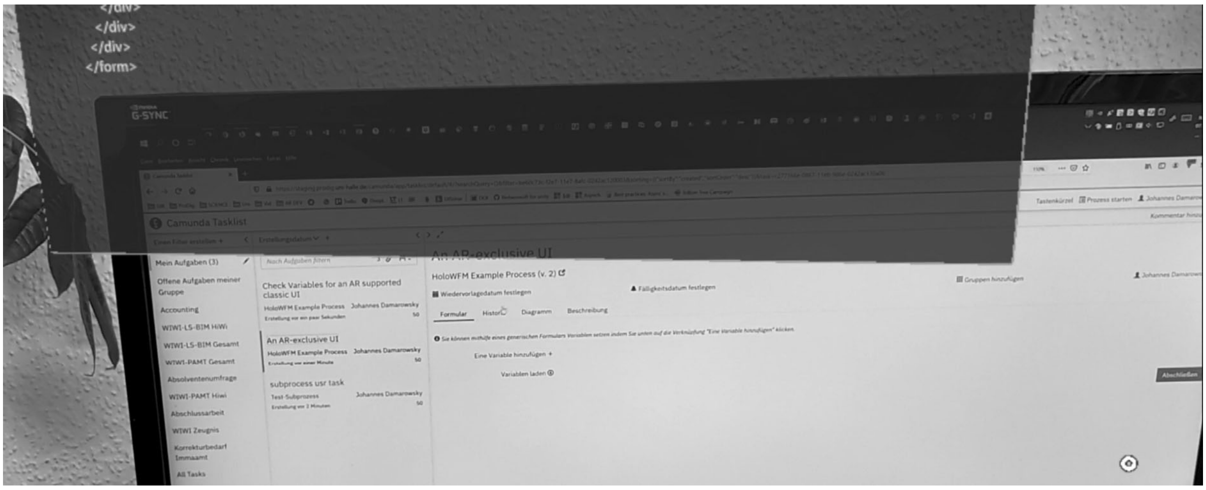


Figure 55. Screenshot from the HoloLens user's point-of-view of the web-based Camunda front end showing the tasklist with three user tasks available.

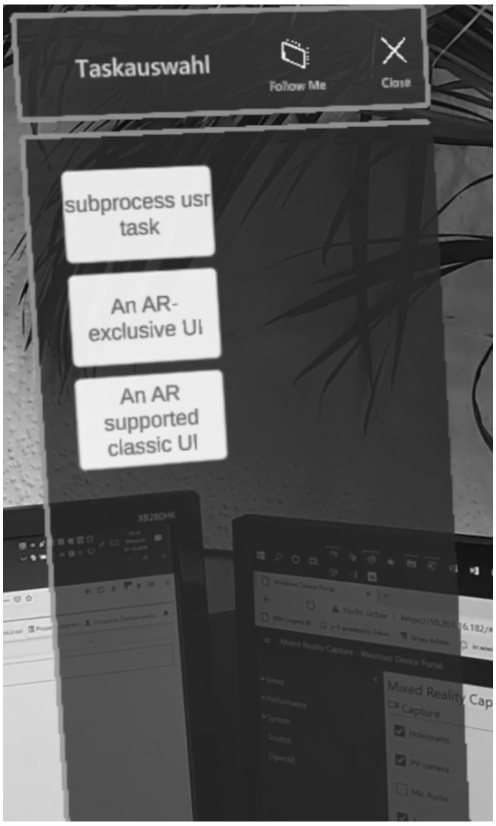


Figure 56. Screenshot from the HoloLens user's point-of-view of the prototype tasklist, showing the same three user tasks as the Camunda tasklist depicted above.

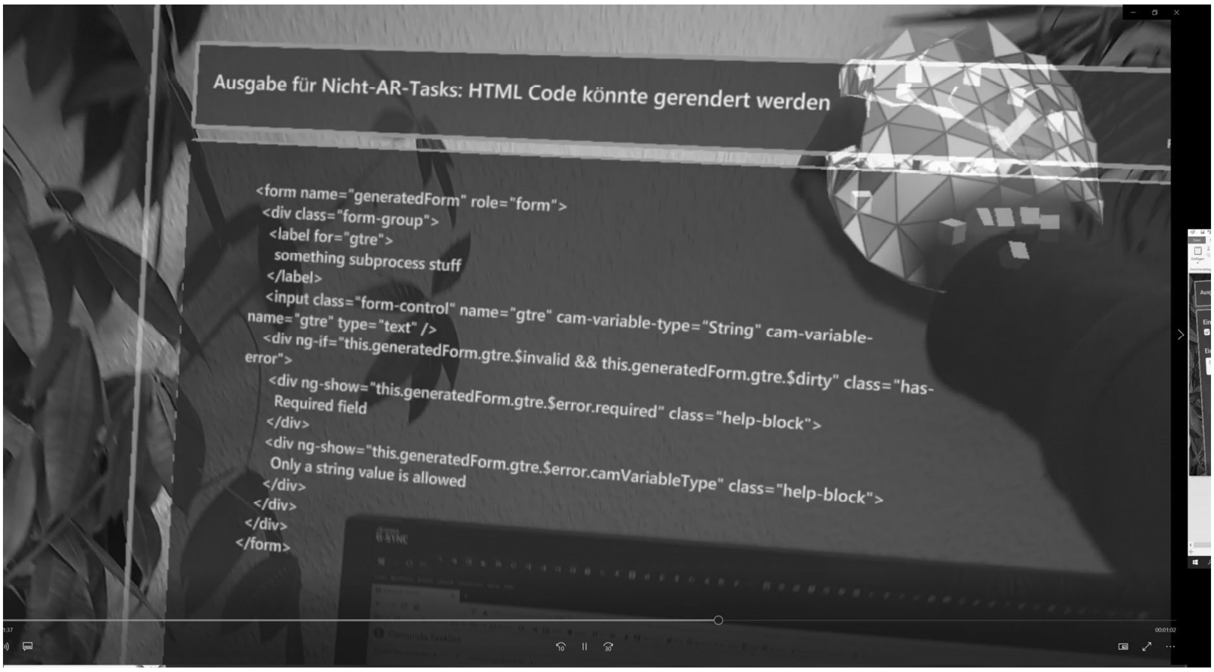


Figure 57. Screenshot from the HoloLens user's point-of-view of the HTML code of a user task UI.

Description: Screenshot from the HoloLens user's point-of-view of the HTML code of a user task UI. The hand is detected and skeleton-tracked via HoloLens-native features to enable interaction with the AR window.

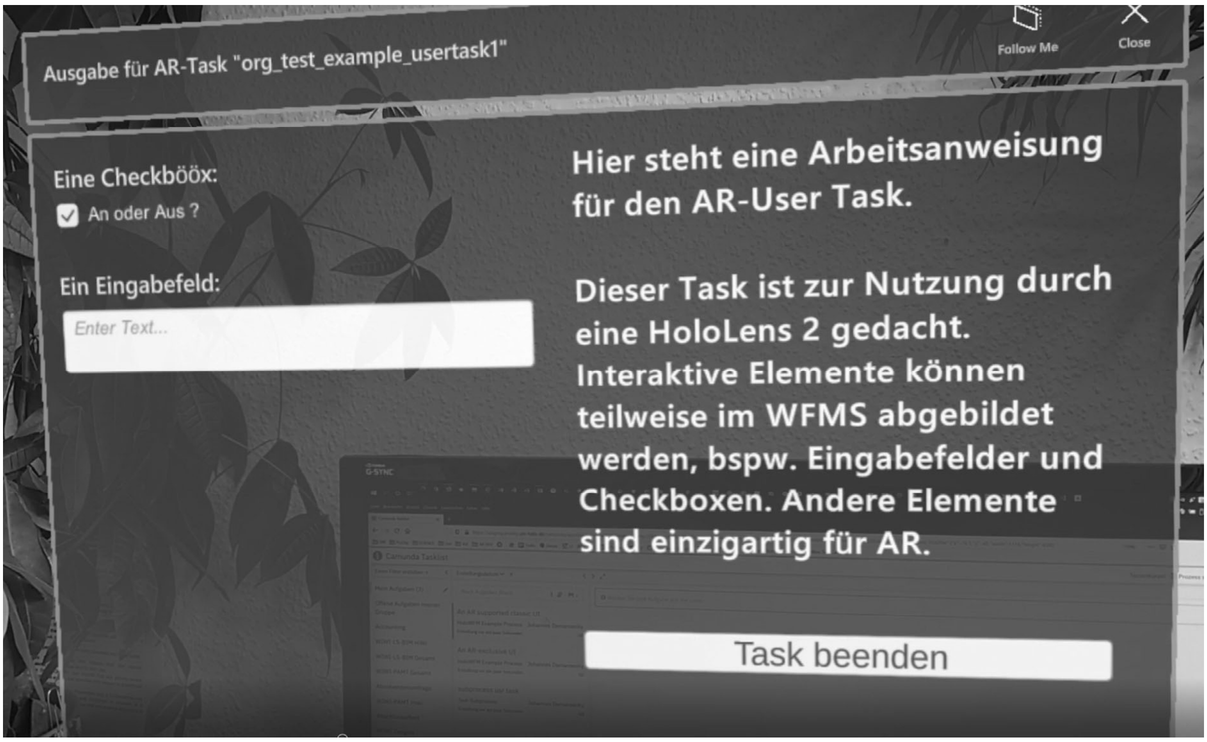


Figure 58. Screenshot from the HoloLens user's point-of-view of an AR UI for a user task with different UI elements. In the background: WFMS Camunda with selected user task.

Figure 59. Screenshot from the HoloLens user's point-of-view of the virtual keyboard used to type in the input field.

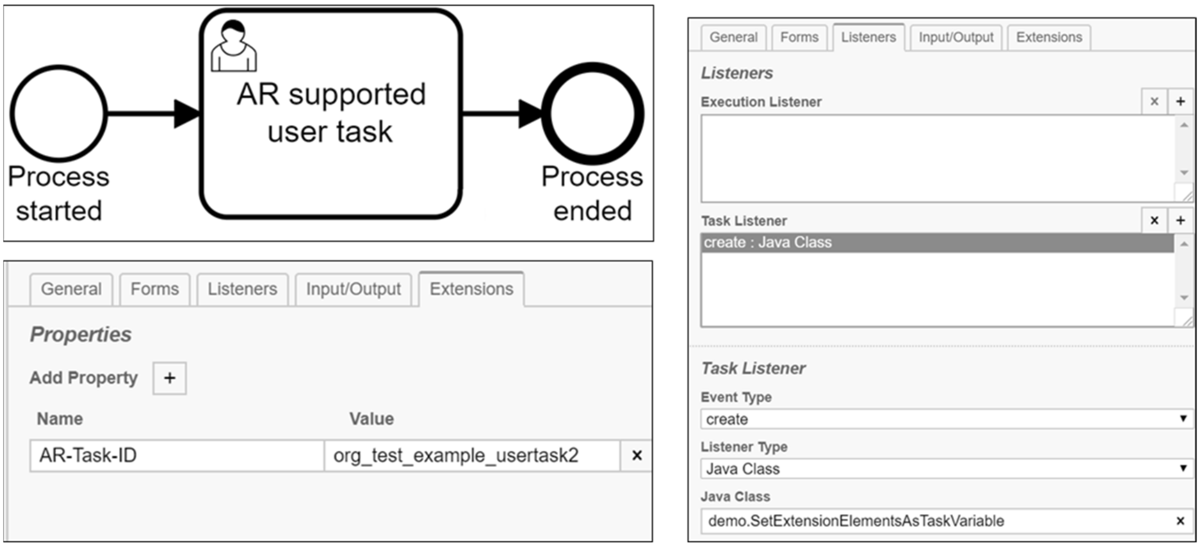


Figure 60. Screenshot of the Camunda Modeler building an example implementation of a BPMN extension for Camunda.

Description: Example implementation of BPMN extension with Camunda. The workflow (upper left) has an additional property (lower left) *AR-Task-ID* with the value *org_text_example_usertask2*. The user task also has a *task listener* for the event *create* that executes the java class *SetExtensionElementsAsTaskVariable()*when the user task is instantiated in the WFMS Camunda.

```xml
<bpmn:userTask id="Activity_ARSupportedUserTask" name="AR-supported User Task">
  <bpmn:extensionElements>
    <camunda:properties>
      <camunda:property name="AR-Task-ID" value="org_test_example_usertask2"/>
    </camunda:properties>
  </bpmn:extensionElements>
  <bpmn:incoming>Flow_0qcoo60</bpmn:incoming>
  <bpmn:outgoing>Flow_0uorx73</bpmn:outgoing>
</bpmn:userTask>
```

Figure 61. Example XML code for a BPMN extension for Camunda for an example user task.

Description: Example XML code for a BPMN extension for Camunda. The BPMN extension elements are part of the OMG BPMN specification [40] and allow subordinated XML structures. In this case, Camunda has defined the *properties* entity, which can hold many *property* entities, each with a name and value.

```java
import org.camunda.bpm.engine.delegate.BpmnError;
import org.camunda.bpm.engine.delegate.DelegateExecution;
import org.camunda.bpm.engine.delegate.JavaDelegate;
import org.camunda.bpm.model.bpmn.instance.BaseElement;
import org.camunda.bpm.model.bpmn.instance.camunda.CamundaProperties;
import org.camunda.bpm.model.bpmn.instance.camunda.CamundaProperty;
import java.util.ArrayList;
import java.util.Collection;

public class SetExtensionElementsAsLocalVariable implements JavaDelegate {

    public void execute(DelegateExecution execution) {
        try{
            // Get base element
            BaseElement elem = execution
                    .getProcessEngineServices()
                        .getRepositoryService()
                            .getBpmnModelInstance(execution.getProcessDefinitionId())
                                .getModelElementById(execution.getCurrentActivityId());

            // Import CamundaProperties to query for them
            CamundaProperties extElem = elem
                    .getExtensionElements()
                        .getElementsQuery()
                            .filterByType(CamundaProperties.class)
                                .singleResult();
            Collection<CamundaProperty> camPropCollection = extElem.getCamundaProperties();

            // Parse CamundaProperties Collection to ArrayList,
            // otherwise Nashorn JavaScript engine can't handel collection type
            ArrayList<CamundaProperty> extElementsArray = new ArrayList<>(camPropCollection);

            // Loop through all extension elements
            for(int i=0 ; i < extElementsArray.size() ; i++){
                System.out.println("extElementsArray.get(i).getCamundaName(): "+extElementsArray.get(i).getCamundaName());
                System.out.println("extElementsArray.get(i).getCamundaValue(): "+extElementsArray.get(i).getCamundaValue());
                System.out.println("elem.getId(): "+elem.getId());
                execution.setVariable(extElementsArray.get(i).getCamundaName(),extElementsArray.get(i).getCamundaValue(),
                "UserTask_1");
                execution.setVariableLocal("localVar","asd");

            }
        } catch (Exception e){
            throw new BpmnError("GeneralProcessError","[getExtensionPropsDelegate.java]:There was an error parsing the
            extension properties.");
        }
    }
}
```

Figure 62. Screenshot of a code excerpt of a Java class for Camunda that creates a Camunda variable out of a BPMN extension element.

Description: Screenshot of a code excerpt of the Java class *SetExtensionElementsAsLocalVariable()* implemented in Camunda that creates a Camunda variable out of a BPMN extension element. This class is executed in the example in Figure 60 when the AR-supported user task is instantiated. This class operationalizes the BPMN extension attribute array *arTaskSupportObjectId*, defined in the interface *IARSupportedOrganizationWorkflows.*

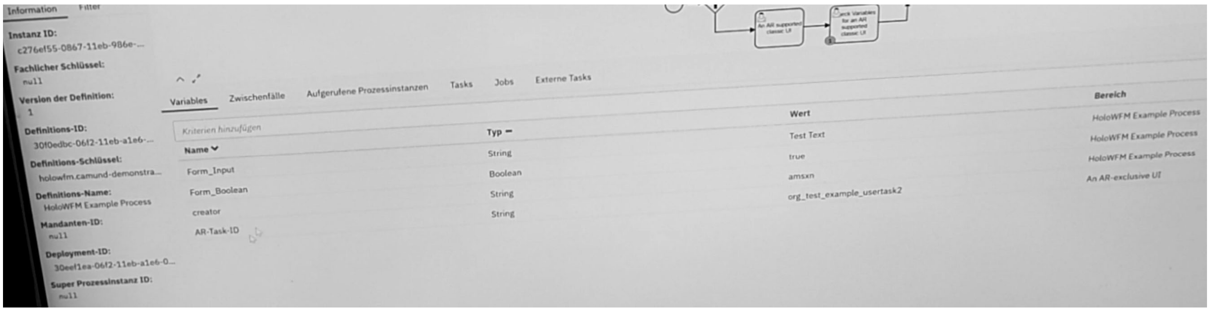


Figure 63. Screenshot from the HoloLens user's point-of-view of the web-based Camunda front end showing variables of a workflow instance.

Description: Screenshot from the HoloLens user's point-of-view of the web-based Camunda front end showing variables of a workflow instance, localized to the user task *An AR-exclusive UI*. The variable *AR-Task-ID* was created via the java class *SetExtensionElementsAsProcessInstanceVariable()* (see above). The value *org_test_example_usertask2* points at the corresponding AR content for the task. Also visible are the variables *Form_Input* and *Form_Boolean*, which hold the input values from the UI elements of the user task in Figure 58, demonstrating that the values from the AR UI were transferred to the Camunda WFMS.

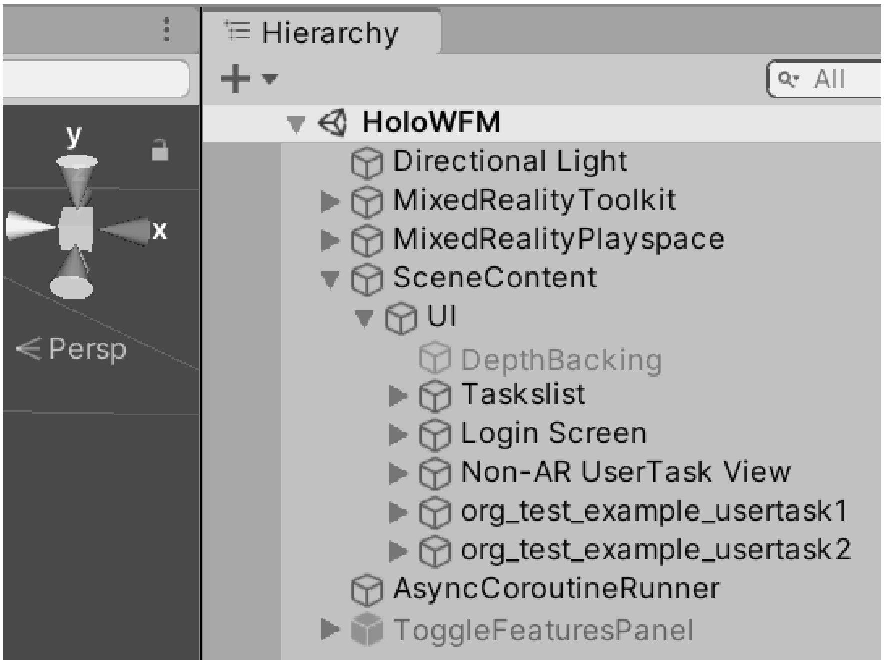


Figure 64. Screenshot of Unity depicting the AR content for an AR-supported user task.

Description: Screenshot of Unity depicting the AR content for an AR-supported user task. The object *org_test_example_usertask2* contains the user interface for an AR-supported user task, e.g., Figure 58. The object's name is used as an identifier in the BPMN extension elements.

Figure 65. Screenshot taken by HoloLens camera while pressing the corresponding button of the task *An AR-exlusive UI* in the prototype tasklist.

Figure 66. Screenshot taken by HoloLens camera of two exemplary AR objects loaded from Unity that were linked to the user task via the BPMN extension element.

5.4.3 Summative Evaluation of Performance and Effort Expectancy of Design Theory and Reference Architecture

To ascertain the usefulness of the RAD and the UML diagrams and DT contained therein in more general terms, the RAD's *performance expectancy* (PE) and *effort expectancy* (EE) was evaluated via an expert survey of potential HoloWFM developers, corresponding to the defined reference architecture view (cf. Chapter 5.3.1.4), i.e., IS and AR researchers, designers, and developers. As PE and EE as constructs are not directly measurable, the well-known scale items by Venkatesh et al. [87] were utilized. These are, for PE: usefulness (PE1), quickness (PE2), productivity (PE3), and increased chance of getting a raise (PE4); for EE: clarity (EE1), easiness to master (EE2), easiness to use (EE3), and easiness to learn (EE4).

The PE and EE were specified for the application context, i.e., for a HoloWFM. Additionally, the experts were asked about the conciseness (CON), extendibility (EXT), and explanatory power (EXP) of the artifacts, following the approach by Nickerson et al. [45] to SECs from their well-known taxonomy development method.

The questionnaire included: 1) an introductory text about the research project, 2) the extended DT, 3) a prompt to imagine an application scenario for the DT, 4) the statements on the EE, CON, EXT, and EXP, 5) the RAD's UML models and descriptions, 6) a prompt to imagine an application scenario for these, 7) the statements on the PE, EE, CON, EXT, and EXP, and 8) some socio-economic questions. For data collection, interval-scaled verbal-numeric 7-point Likert-style scales were utilized. The taxonomy was not part of the evaluation, as it had been evaluated in previous cycles.

For the sample size, the survey followed the established practice discussed in Chapter 2.9 and aimed at twelve experts. Based on an expected response rate of 50 %, the questionnaire was sent by email to a total of 24 experts, who were identified within the research institute's network as potential HoloWFM developers based on their profession and industry. A total of 13 completed questionnaires were received (actual response rate: 54.2 %). The respondents partially fulfilled multiple professional roles and included one project manager, five project leads, six research associates, three senior researchers, two multimedia developers, and one usability engineer, all active in the workflow and AR domain, possessing 1-15 years (median: 3.5, mean: 4.88) of experience in their roles. Among the experts, eleven work in large, and two in micro-sized companies/organizations.

Figure 67 depicts the boxplots of the responses. For both the DT and RAD, high levels of agreement for all items were received, with medians of m=6 and m=7. Thus, the sum scores of the PE and EE for the DT and RA with medians of m=26 and m=25 on a 7-28 scale summarize the overall evaluation well.

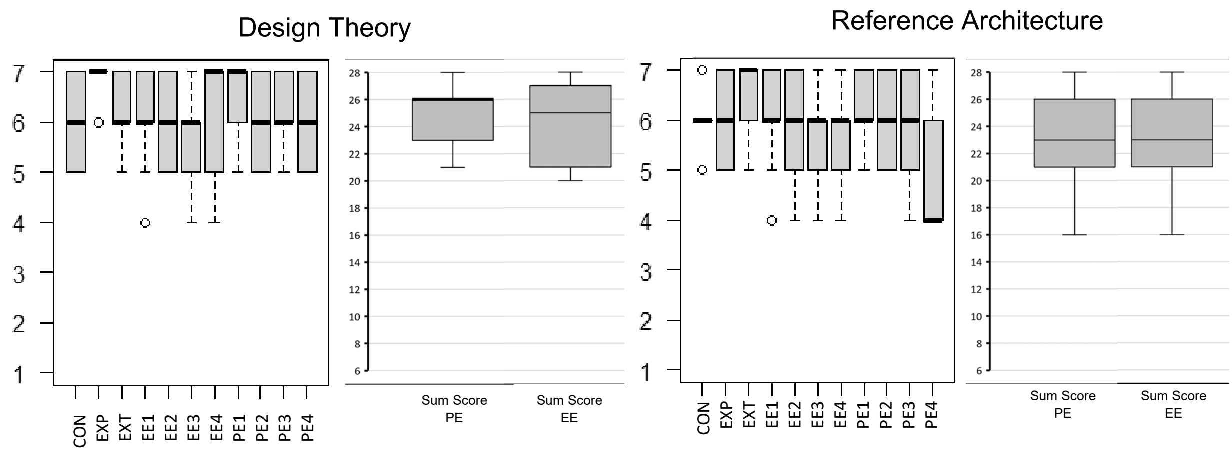


Figure 67. Boxplots for design theory and reference architecture evaluations.

To validate the quality of the constructs PE and EE, the individual *item reliability* (loadings), *composite construct reliability*, and *average variance extracted* [134] were examined. Item reliability is examined by evaluating the loadings of the measured items on their respective construct. A confirmatory factor analysis in *R* was performed for this purpose (Table 11).

Performance Expectancy		Design Theory	Reference Architecture	**Effort Expectancy**		Design Theory	Reference Architecture
Loadings	Usefulness	.554	.712	Loadings	Clarity	.582	.662
	Quickness	.998	.717		Easy to Master	.664	.585
	Productivity	.871	.998		Easy to Use	.655	.904
	Chance of Raise	.426	.435		Easy to Learn	.940	.998
	AVE	.560	.551		**AVE**	.523	.648
	CCR	.822	.820		**CCR**	.809	.876

Note. AVE = average variance extracted, CCR = composite construct reliability.

Table 11. Validation of constructs Performance Expectancy and Effort Expectancy.

It is generally known that items with low loadings (rule of thumb: < 0.4) should be carefully scrutinized as they offer little additional explanatory power but attenuate (and thus bias) parameter estimates [134, 135]. In this dissertation's models, all item loadings exceed the 0.4 limits. The average variance extracted is a measure to assess the amount of variance captured by the construct, compared to the variance due to measurement error, and should be above 0.5, which is given for all the utilized constructs and artifacts, indicating that the variance captured by the construct is greater than the measurement error [136]. Composite construct reliability measures the overall reliability of items loading on a construct and, therefore, the internal consistency of a construct. It should exceed the threshold of 0.7 [134, 135], which is given for all items and artifacts. Discriminant validity was assessed by comparing the average variance extracted with the squared correlation between the constructs [136]. To calculate the correlation, the Kendall tau coefficient was used, which is particularly appropriate for Likert-style scales [137]. The comparison shows that the average variances extracted from PE and EE (Table 11) are each higher than the squared correlations (cor) between PE and EE for both the DT ($cor^2=0.480$) and the RA ($cor^2=0.354$). Based on these validity criteria, the utilized measurement models with four items each for the constructs PE and EE are suitable for evaluation. The PE and EE constructs, as well as the underlying items, were also considered to be valid since they were adopted from Venkatesh et al.'s [87] well-known Unified Theory of Acceptance and Use of Technology (UTAUT), and these have been proven to be effective in numerous further studies.

5.5 Conclusion

Summary of the Third Design Cycle

The motivation of this three-cycled research project was to develop formalized design knowledge to support IS researchers, IS designers, and IS developers in designing, developing, and instantiating a HoloWFM. In the first two cycles, a taxonomy, a set of archetypes, and a design theory were developed and positively evaluated. While these artifacts provide guidance on a high level of abstraction, more actionable, less-abstract guidance was still necessary. Especially to provide guidance for implementation-focussed DPs like the requirement for seamless integration of AR task support and HoloWFM UI (DP 10), raised in the evaluation phase of the second cycle, system architecture-level guidance would provide value to IS researchers, IS designers, and IS developers in designing, developing, and instantiating a HoloWFM.

Therefore, in the third HoloWFM design cycle, the DT was first extended with less-abstract DFs, representing one possible set of design choices. Thus, the third research question (RQ 3) for the DRs, DPs, and DFs of a HoloWFM was finally answered.

From the developed DFs, UML diagrams for the structure and behavior of the HoloWFM information system were derived. These artifacts were finally documented according to the ISO 42010:2011 standard for documenting RADs [36]. Based on the positive three-part evaluation of this third design cycle, the RAD represents a valuable artifact to support IS researchers, IS designers, and IS developers in designing, developing, and instantiating a HoloWFM. Therefore, the fourth research question (RQ 4) for the models, model elements, and textual descriptions of a reference architecture for a HoloWFM was successfully answered.

Limitations of the Third Design Cycle

Similar to the mentioned limitations of the second design cycle, the limitations of the third HoloWFM design cycle stem from the subjectivity of design decisions. Even though the UML diagrams were systematically derived from the DT via the DFs, and the three-step evaluation confirmed the quality of the design decisions, other decisions could have been made. It is possible that some of these would have yielded a better RAD. Also, even though the expert survey followed established practices, more experts would have strengthened the validity of the results.

While the prototype instantiation yielded valuable insights and served as a well-founded evaluation event for the RAD, it is plausible that some hitherto unknown problems could arise when instantiating a complete software product from the RAD. However, RAs are only templates and are also meant to be improved by real-world knowledge (see Chapter 2.4) [61–64]. As such, this RAD evaluation is – in a sense – only formative as future changes are expected. Therefore, imperfections in the RAD do not diminish its usefulness.

Reflections on the Results of the Third Design Cycle

To properly address the DRs defined in the second design cycle, the DPs, and DFs of HoloWFM not only included functions of a web-based WFMS front end, i.e., the management and control functions defined in the WFMS RA by the Workflow Management Coalition [15]. Instead, a HoloWFM must feature additional functions like context awareness and multifunctionality. Realizing these requirements at the level of components, classes, and sequence flows demonstrated that the technical complexity of a HoloWFM is significantly greater than that of a web-based WFMS front end., e.g., relating to context awareness and functionality for multiple WFMSs.

Reflecting on the results of all three completed design cycles, tools on high, middle, and low levels of abstraction have been produced. Artifacts on an even higher level of abstraction than a taxonomy or design theory would be too generalized to provide tangible value to the HoloWFM theme, e.g., meta-models. Even less-abstract artifacts than a system-level RAD, e.g., a reference prototype implementation, would also yield little value to the wider IS community since such artifacts would be highly application scenario-specific. Also, even if some value would be provided, due to the high pace of progress in information technologies, such reference implementation would need to be continuously maintained. This would be out of the scope of this dissertation project. Further, the complete implementation of a polished HoloWFM UI would also be prohibitively expensive in the scope of this dissertation.

Consequently, there was no need for further design cycles in the multi-cyclical HoloWFM DSR project, and – based on the multitude of positive evaluation events – the research project ended successfully.

6 Summary of Artifacts, Publications, and Projects

Multiple artifacts, publications, and projects originate from this dissertation, demonstrating the impact of this dissertation on the wider IS community. An overview is depicted in Figure 68, roughly mapped to the three design cycles.

Novel Artifacts

A number of novel artifacts (grey) were developed in this dissertation, which can be characterized in terms of their artifact type, i.e., constructs, models, methods, instantiations, and design theories [42]. The first artifact developed was the taxonomy of ARSs in support of workflow execution. This artifact is a construct that originated from the first design cycle and was extended in the second design cycle. The second artifact, the three archetypes of ARSs supporting workflow executions, is also a construct and originated in the first design cycle. The third developed artifact was the design theory, which is an artifact type of its own. Originating from the second design cycle, the DT was extended in the third design cycle. In the third design cycle, the UML diagrams of the HoloWFM RA were developed. These are model-type artifacts. As the RAD also contains definitions of vocabularies, e.g., architecture viewpoints, construct-type artifacts are also present in the RAD. Even though the taxonomy and DT are part of the final ISO-compliant RAD, for clarity's sake, these are not specified in Figure 68. The instantiation of the HoloWFM RAD as a software architecture and prototype are considered instantiation-type artifacts. Finally, the linkage of a DT and RA via the connection of DFs with UML diagram elements had – to the extent known – not been demonstrated elsewhere before. Therefore, this can be considered a novel methodical artifact [42].

Publications

Multiple publications (blue) originated from this dissertation. Four of these are core contributions of this dissertation (see Chapter 2.12). A first draft of the taxonomy was published as a student paper at the poster session of the *16th International Conference on Wirtschaftsinformatik* (WI 2021) as:

- König, Edgar / **Damarowsky, Johannes** / Kühnel, Stephan (2021): *Supporting Workflow Execution with Augmented Reality: A Taxonomic Approach to the Classification of Augmented Reality Systems*. In: *16th International Conference on Wirtschaftsinformatik* (WI 2021). VHB-Jourqual 3: C [138].

Based on the gathered feedback from the community, it was reworked very extensively and published in the journal "*HMD Praxis der Wirtschaftsinformatik*":

- **Damarowsky, Johannes** / Kühnel, Stephan / Seyffarth, Tobias / Sackmann, Stefan (2022): *Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung - Entwicklung und praktische Anwendung einer Taxonomie*. In: HMD - Praxis der Wirtschaftsinformatik, Special Issue, Vol. 59(1), 2022. VHB-Jourqual 3: D [9].

A third publication, including the archetype development and taxonomy extension from the second design cycle, was submitted to the journal *Electronic Markets* and currently awaits a decision:

- **Damarowsky, Johannes** / Kühnel, Stephan / Seyffarth, Tobias / Böhmer, Martin (2023): *Understanding Augmented Reality Systems for Workflow Support – A Taxonomy and Archetypical Patterns. S*ubmitted to: Electronic Markets - The International Journal on Networked Business (awaiting decision). VHB-Jourqual 3: B [88].

The DT of the second design cycle was published at the *30th European Conference on Information Systems* (ECIS 2022) as:

- **Damarowsky, Johannes** / Kühnel, Stephan (2022): *Conceptualization and Design of a Workflow Management System Front End for Augmented Reality Headsets*. In: 30th European Conference on Information Systems (ECIS 2022). VHB-Jourqual 3: B [16].

This paper was awarded the best paper award as runner-up (2nd place) in the category research-in-progress papers. The final DT, RAD and prototype instantiation of the third design cycle were published at the *31st European Conference on Information Systems* (ECIS 2023) as:

- **Damarowsky, Johannes** / Kühnel, Stephan / Böhmer, Martin / Sackmann, Stefan (2023): *A Reference Architecture for a Workflow Management System Front End Designed for Augmented Reality Headsets*. In: 31st European Conference on Information Systems (ECIS 2023). VHB-Jourqual 3: B [89].

A final publication is currently in the final stages of preparation for the Journal *Business Information System Engineering* (BISE), which will present a holistic view of the research results, similar to this dissertation. Articles with similar scopes have recently been published in the BISE, e.g., [23, 139].

Secondary Projects

Originating from this dissertation are three third-party-funded projects (green). These illustrate the impact of this dissertation's results. The BMBF-funded project *Augmented Living Spaces* (ALIS) ran from 2021-2023 and was based on insights from the taxonomy [140, 141]. The project ALIS represents an anti-pattern in the analyzed ARSs, i.e., the analysis revealed an absence of an ARS of the archetype "installation" that utilizes spatial AR and offers workflow execution support, especially in the context of supporting the elderly.

The project *Digital Transformation in Care Facilities* (DiTiP) has recently been approved for a BMBF grant. This project, too, originates from insights gained from the taxonomy. An essential part of the project DiTiP is the utilization of an ARS of the archetype "installation", that supports care professionals without prior process modeling experience during process modeling. A core idea is the utilization of play figures, AI-based tracking, and AI-based translation to a BPMN model.

A third project originating from this dissertation is the project *Augmented Reality, Workflow and Knowledge Integration for an Innovative Object-oriented Process Guidance at Industrial Plants* (ARWINA). This project seeks a BMBF grant and currently awaits a decision. This project addresses shortcomings for holistic workflow execution support in the archetype "Advanced HMD." It also builds directly on the developed HoloWFM RAD, and the prototype will be used for this project. A core idea is the development of a novel process modeling language to enable qualitatively better knowledge management, centering on physical objects and their relations.

Secondary Publications

Stemming from the project ALIS, a number of secondary publications have been produced (turquoise). These, too, illustrate the indirect impact of this dissertation's results. A DT for ALIS was published as Böhmer / Damarowsky / Parschat / Mahn (2022) [142] in the journal "*HMD Praxis der Wirtschaftsinformatik.*" An extended DT and prototype were published as Böhmer / Damarowsky / Kühnel / Parschat / Mahn (2022) [60] at the *26th Pacific Asia Conference on Information Systems* (PACIS 2022). Finally, an RA for an ALIS was published as Böhmer/Damarowsky/Kühnel (2023) [143] at the *56th Hawaii International Conference on System Sciences* (HICSS 2023). A journal article including the DT and RA, but with an emphasis on the implications for IS management, is being prepared for submission to the *Journal of Management Information Systems* (JMIS). Another article focussing on the utilized techniques of machine learning within the ALIS project is currently being submitted to the journal BISE.

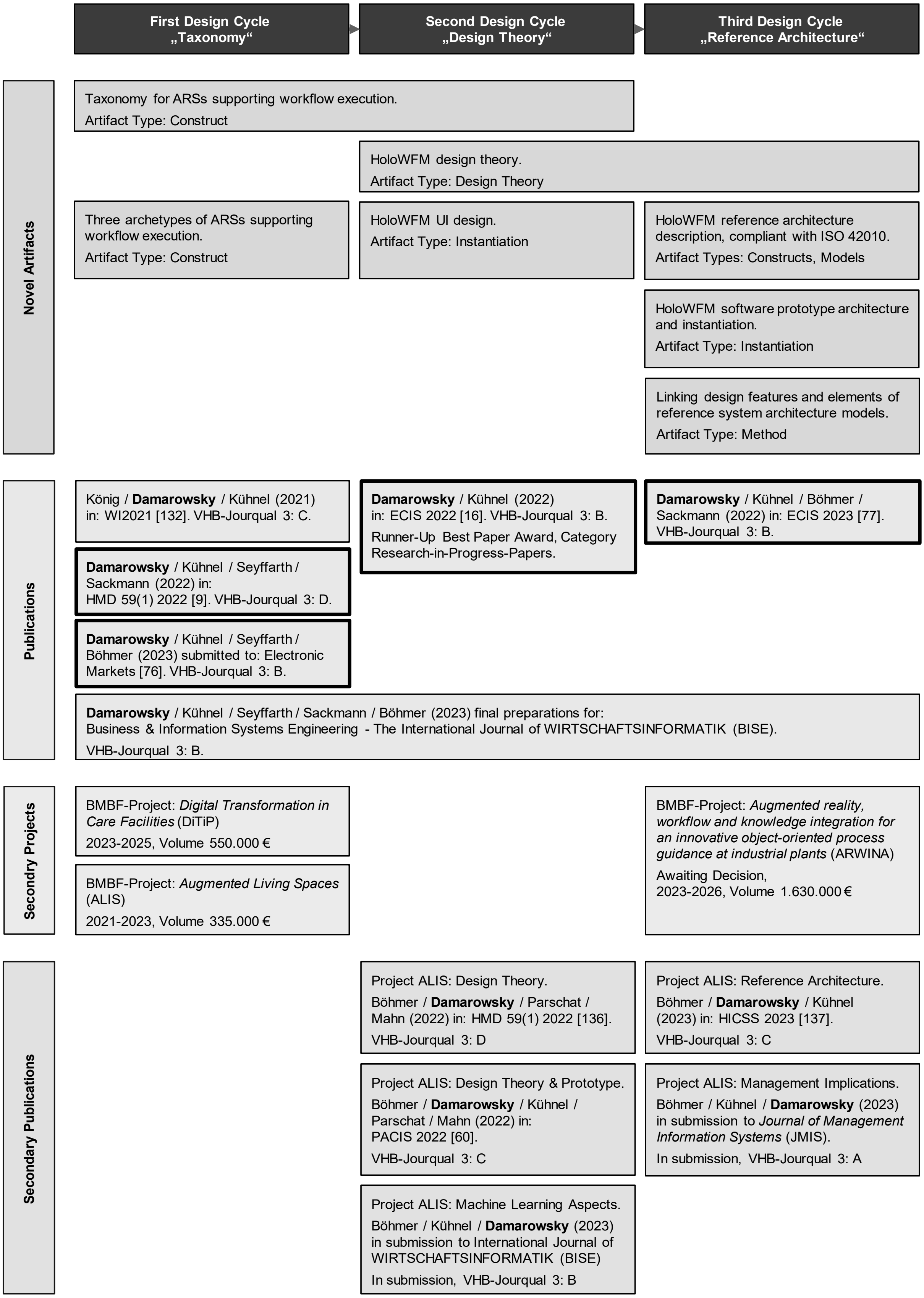


Figure 68. Artifacts, publications, and projects originating from this dissertation. Primary publications with thicker borders are core contributions of this dissertation.

7 Impact and Implications for Theory and Practice

Leaning on the comments by Benbasat and Zmud [144], it is important to consider the possible use and impact of IT artifacts after the end of the DSR project in order to adequately reflect the interdisciplinary nature of the IS discipline.

7.1 Implications for Information Systems Theory

Taxonomy

The developed taxonomy contributes a novel analytical lens for existing ARSs, focusing on support for workflow execution, in contrast to related taxonomies and frameworks [30–35]. The taxonomy, thus, not only utilizes different dimensions and characteristics but is also more detailed in several respects, especially regarding the integration with workflow management systems, the modeling of workflows, and the type of workflow support. As such, the taxonomy contributes to the IS knowledge base by providing a vocabulary of a domain and a set of defined constructs and, thus, establishing a theoretical foundation for future research efforts [44, 46].

Taxonomies cannot only be utilized to describe and classify phenomena but can also function as a foundation for sensemaking [42] and theory building [48] as *taxonomic theories* (see Chapter 2.2), according to the categories of IS theories by Gregor (2006) (theory type I, [49], p. 620). Taxonomic theories can serve as a foundation to develop other theories, e.g., explanatory theories or design theories, as the dimensions and characteristics of the taxonomies provide fundamental constructs and relationships [49, 50, 52]. In this context, the taxonomic theory implicitly contained in this dissertation's novel taxonomy serves as an underlying theory for the analysis of the 142 ARSs. Also, two projects originating from this dissertation (cf. Chapter 6) developed DTs, which are thus grounded in the taxonomic theory contained in the developed taxonomy.

Design Theory

The developed DPs of the HoloWFM DT were formulated in a prescriptive manner following the dichotomy of descriptive/prescriptive DPs developed by Fu et al. [58]. As such, they contribute to the prescriptive knowledge base of the IS community [42]. The DRs were gathered empirically with the MFGs, and the DFs represent the state of practice in software development. Thus, these DT components describe current phenomena and thus contribute to the IS community's descriptive knowledge base [42]. In terms of the five theory types defined by Gregor (2006), DTs can be categorized as theories for *design and action* (Type V, [49], p. 620). The prescriptive formulation of the DT developed within this dissertation fits this categorization as it encodes design knowledge and prescribes actions to achieve a goal and, as such, extends the theoretical foundations of the IS community.

7.2 Implications for Information Systems Research

Taxonomy

The developed taxonomy was already used to design novel artifacts and identify promising avenues of research, as demonstrated by the two research projects that originated from this dissertation's taxonomy (see Chapter 6). By utilizing the taxonomy and archetypes for the analysis and definition of ARSs, the developed taxonomy and archetypes can contribute to novel IS research endeavors.

Reference Architecture Description (Including Design Theory)

The RAD demonstrated how DFs can be linked to UML diagram elements and, thus, how a DT and a system RA can be integrated. Also, the utilization of the ISO/IEC/IEEE 42010:2011 to document the developed design knowledge. This had – to the extent known – not been previously demonstrated in the DSR literature. Therefore, the RAD contributes a novel methodology to the IS community, which is associated with its prescriptive knowledge base [42].

Further, the UML diagrams of the RA add to the prescriptive knowledge base by providing tangible design knowledge since existing studies lack such less-abstract contributions. In line with the known benefits of RADs (cf. Chapter 2.4), researchers and practitioners can more easily implement a HoloWFM or similar IS. As many studies use prototype implementations to test certain functions or scenarios, the RAD presented in this dissertation could provide tangible benefits to other researchers. Also, the RAD can be expanded to incorporate new stakeholder requirements and new technologies, thus serving as a basis for future research endeavors. Indeed, research opportunities naturally arise to define different DPs, DFs, and RADs than those developed in this dissertation since a well-known inherent weakness in the development of DFs and RADs is the subjectivity of underlying design and architectural decisions, e.g., the number and partition of DFs, systems and (sub)components. However, not all design decisions must or can be grounded in theory, and a degree of creativity is unavoidable and essential in the DSR process [132, 133]. Additionally, the DFs were from well-built DPs, and the RAD, in turn, from these DFs. Yet, each of these steps presents its own challenges, design decisions, and thus future research opportunities.

7.3 Impact on Practice

Taxonomy

For practice, both the taxonomy and archetypes offer value: the taxonomy describes what can be done, and the archetypes describe what has been done. Therefore, organizations designing and developing ARSs can save time and effort by better understanding the problem space and development alternatives. Organizations comparing ARSs during a make-or-buy decision can improve the quality of their decision-making by utilizing the taxonomy to better compare ARSs. In both cases, possible characteristics might be overlooked without the taxonomy. As the analysis of ARSs showed, few ARSs offer complex workflow execution support, but still, these research streams exist and are actively pursued. The taxonomy, therefore, shows a possible – or probable – feature set of future ARSs and thus provides value to long-term IT strategies. While the taxonomy's value for practitioners stems from its details, the archetypes are valuable for their brevity. These three types of ARSs serve as a summary of the state-of-the-art tools to enhance communication within organizations when discussing ARSs and their application, especially in regard to supporting workflow execution. More generally, both the archetypes and taxonomy serve as tools to improve understanding and communication about ARSs by providing a clearly defined vocabulary and concepts.

Reference Architecture Description (Including Design Theory)

As the positive evaluations indicate, the RAD is generally useful for practitioners. The UI design provides a tangible template to build on but also can be used as a mockup in further design studies with end-users. The requirements and principles of design from the DT guide the overall development process. Since tangible, operationalizable component- and class-level design knowledge is provided in the standard notation UML, these models can directly be utilized in system and software development. The documentation of key architectural decisions also saves time and resources, e.g., utilizing an abstraction layer between UI and WFMS, linking AR task support objects via BPMN extensions, and placing the context reasoning system outside the HoloWFM application, are not entirely obvious decisions. Thus, the well-known benefits of RADs (cf. Chapter 2.4) can be realized in practice. Finally, the RAD's complexity is not overbearing, as Figure 33 and Figure 36 summarize. Thus, the instantiation of a HoloWFM is not prohibitively difficult for companies, the main challenge being the construction of a stakeholder-specific AR UI. With the instantiations of HoloWFMs (or related artifacts) for known application scenarios of ARSs for workflow execution support (cf. Chapter 1), organizations can benefit from the superior workflow management and control functionalities and thus better integrate ARSs into an existing WFMS infrastructure. End-users, meanwhile, can effectively operate workflows and WFMSs more efficiently while benefiting from AR task support, therefore potentially increasing overall productivity.

8 Concluding Remarks and Desiderata

The goal of this dissertation was to design and ensure the usefulness of artifacts that support IS researchers, IS designers, and IS developers during the design, development, and instantiation of HoloWFMs, i.e., headset-based ARSs that enable AR-based workflow execution support for workflow participants, provide comprehensive workflow management and control capabilities and ensure usability. To achieve this goal, five research questions were formulated.

First, RQ 1 asked which dimensions and characteristics define a taxonomy of ARSs supporting workflow investigation. This question was tentatively answered in the first design cycle (Chapter 3.3) by applying the well-known taxonomy development method by Nickerson et al. [45] in combination with an extensive structured literature review to identify and characterize ARSs. This resulted in a novel taxonomy of ARSs supporting workflow execution, which was positively evaluated with an expert survey. This taxonomy was then extended in the second design cycle (Chapter 4.3.5) to include the newly conceptualized HoloWFM. The final taxonomy consists of 14 dimensions and 94 characteristics.

Second, RQ 2 sought for a meaningful set of archetypes of ARSs supporting workflow execution and their characteristics. This question was answered based on the characterizations of the ARSs that were necessary to develop the taxonomy. A cluster analysis of this data (Chapter 3.3.4) utilizing qualitative and quantitative indices to find a good number of clusters resulted in a final set of three archetypes of ARSs around which contemporary ARSs cluster (Chapter 3.3.5): *Simple HMD*, *Advanced HMD*, and *Installation*.

Third, RQ 3 requested the definition of DRs, DPs, and DFs of a HoloWFM DT. Combining extensive structured literature reviews and focus groups for the development and evaluation, in the second design cycle (Chapter 4), a tentative DT consisting of DRs and DPs was defined. RQ 3 was finally answered in the third design cycle with the definition of DFs (Chapter 5.3.1.4.2). The final DT consists of four DRs, ten DPs, and nine DFs. It is noteworthy that the principles of design of a HoloWFM are significantly greater than the functionality of web-based WFMS front ends, demonstrating that the integration of AR and WFMS into a HoloWFM needs more features and has greater complexity than web-based WFMS front ends. The DFs reflect this complexity.

Fourth, RQ 4 asked for the models, model elements, and textual descriptions of a HoloWFM RA. This question was answered in the third and final design cycle (Chapter 5) by developing a HoloWFM RAD compliant with ISO 42010:2011, centering around HoloWFM DT that was extended with DFs (see above) as well as five UML diagrams. By demonstrating that an RA can be *projected* from the DT, evaluated the HoloWFM DT. The RAD was evaluated in general via an expert survey but also via instantiation.

This was the call of RQ 5, which called for an investigation if a HoloWFM software prototype could be instantiated with currently available technology to demonstrate the feasibility of the RAD for at least one set of real technology and circumstances (cf. Figure 2). To this end, a software prototype was successfully instantiated, utilizing a *Unity* application running on the AR headset *HoloLens* and the WFMS *Camunda*.

The RAD and software prototype instantiation again demonstrated that a HoloWFM is significantly more than a web-based WFMS front end ported to an AR headset. Instead, a HoloWFM is a somewhat “universal WFMS front end, “empowered by context-aware features and fully utilizing the technical possibilities of the AR headset end-user device. This supports the knowledge contribution assessment performed in Chapter 2.11 that HoloWFM is not a routine design [42].

The positive evaluations throughout this research project indicate that the novel artifacts developed to answer the five RQs laid out above are useful to support IS researchers, IS designers, and IS developers on a high level of abstraction (taxonomy, archetypes), middle level of abstraction (DRs and DPs), as well as low level of abstraction (DFs, RAD, prototype instantiation) during the design, development, and instantiation of HoloWFMS. As such, the goal of this dissertation has been achieved.

The limitations within each design cycle have been discussed in the conclusion phase of the respective cycles, i.e., Chapters 3.5, 4.5, and 5.5. These limitations reflect the fundamentally subjective nature of design decisions during DSR projects. Even though some effort was spent on "objectifying" the design decisions, e.g., by gathering opinions from experts during focus groups and surveys, these opinions themselves are subjective as well. Thus, in a strict sense, a DSR project is unlikely to produce an optimal solution, as not all alternatives have been evaluated due to the prohibitive costs of trying out all alternatives. Replacing or adding one design requirement, design principle, design feature, or system component could improve the presented solution to the fourfold HoloWFM challenge. Other researchers may try these alternatives, but given the specific application scenario for a HoloWFM and the contemporary size of this scenario in practice, it seems more likely that the solutions presented in this dissertation will remain the only contribution to this intersection of technologies for some time. In a sense, this increases the significance of this dissertation's results.

The technologies of AR and WFMS are advancing fast and can improve much in the future. It was in this hopeful spirit that this dissertation set out to contribute to this emergent intersection. With such progress, the niche scenario of HoloWFM will grow. And while the importance of this dissertation's results will grow equally, other alternative and maybe better approaches will certainly be developed, too, e.g., to reflect new technological characteristics (taxonomy), end-user requirements (design theory), or available software (reference architecture). Also, many unanswered questions of the HoloWFM project offer complementary research opportunities. For one, further characterizing cost-effective and promising application scenarios for HoloWFM could be interesting, especially if a dynamic formula could be derived, e.g., involving hardware and software costs, process costs, etc. Another interesting venue for further research could be the question of an *optimal* UI design for AR headsets. While this dissertation presented one UI (with positive evaluations), there is certainly some more optimal UI to be designed. Another approach could investigate how the WFMS front end capabilities could be realized in a usability-ensuring manner for other ARS types, e.g., fixed installations with video see-through technology or spatial AR.

As the progress in AR and WFMS over the last years demonstrated, the hopes at this dissertation's beginning were not unfounded. When this dissertation began, the only truly viable commercial AR headset was the Microsoft HoloLens 1. In 2023, many more headsets are available, and devices like the Varjo *XR-3* [11] deliver astounding visual resolution and millimeter-precise alignment of synthetic and real objects. Recently, Apple premiered the headset *Vision Pro* [145], which could finally elevate AR and VR technology to the mass consumer market. Combined with the near-photorealism of Unreal Engine 5 (e.g., the game *Unrecord* by DRAMA [146]) and coupled with current photo and video AI technologies like Midjourney [147] or Runway [148], at least the AR-side of HoloWFM seems to progress well.

There is also chance and progress on the WFMS side of things. Novel light-weight WFMSs like Camunda [26] or Signavio [27] focus on building workflows in BPMN notation on top of existing heterogenic IT landscapes, gathering and sending information from diverse systems and softwares via APIs and microservices [26, 27]. This approach – in theory – should enable easier replacement of single systems and software and should be easier to introduce to organizations and existing IT landscapes. This challenges older, monolithic concepts of process-aware ISs (e.g., ERPs) that utilize their own workflow notations and aim to integrate the entire IT landscape of an organization within them, e.g., the cliché of "SAP." Irregardless of how the business process management software industry develops, the influence of lightweight WFMSs has already been lasting, e.g., SAP SE bought Signavio [149].

However, while these developments seem generally positive, it became continuously clearer during this dissertation that great and rather fundamental challenges still exist within the workflow domain. With HoloWFM, the basic question of how to integrate AR and WFMS for AR task support in a high-usability manner has been addressed, at least in principle. A HoloWFM end-user could use a HoloWFM to instantiate a new workflow or choose the next workflow task in an AR-supported business scenario. But *which* workflow to initiate, *which* task to choose next? And if that were clear, which AR content would deliver optimal task support, and could this content be generated automatically?

Some aspects of these questions are addressed in the field of business process prescriptive analysis [150]. However, on the one hand, the existing solutions in the state of the art are not adequate to natively integrate AR aspects and process prescription. On the other, complex industrial workflows, e.g., repair of industrial plants, cannot be addressed properly due to fundamental negligence of the attributes and relationships between physical parts. These findings inspired the project ARWINA, which seeks a BMBF grant and currently awaits a decision (cf. Chapter 6). The artifacts of the HoloWFM dissertation project will directly serve as a fundament for the project ARWINA. The taxonomy will allow to precisely characterize the ARWINA ARS. The RADs' DT and RA models will be a basis for designing and developing a new ARWINA ARS. The software prototype instantiation will also be reused and further developed. Thus, the HoloWFM dissertation project presented herein will carry on in spirit with ARWINA.

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Appendix

Appendix A: Author's statement on the work shares in the article "Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung - Entwicklung und praktische Anwendung einer Taxonomie"

The article "Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung - Entwicklung und praktische Anwendung einer Taxonomie" was co-authored. The following table gives an overview of the authors' contributions to the article.

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Johannes Damarowsky	JD
Stephan Kühnel	SK
Tobias Seyffarth	TS
Stefan Sackmann	StS

Aspect	Authors
Research concept	JD
Research methodology	JD, SK
Problem and objective	JD with participation of StS
Literature review	JD
Conceptualisation of the topic	JD
Evaluation of the literature and creation of the concept matrix of analysed augmented reality systems	JD
Development of dimensions and characteristics of the taxonomy	JD
Quantitative evaluation	JD, SK
Discussion and final evaluation	JD
Preparation of the manuscript	JD, SK, TS, StS
Review and revision before submission	JD, SK, TS
Revision after review	JD

Appendix B: Full text of the article "Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung – Entwicklung und praktische Anwendung einer Taxonomie"

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Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung - Entwicklung und praktische Anwendung einer Taxonomie

Zusammenfassung. Die Ausführung von Workflows ist in vielen Anwendungsfeldern zunehmend mit einer Verarbeitung von Kontextinformationen verbunden. Dies ermöglicht es, den Nutzern die richtige Information zur richtigen Zeit zur Verfügung zu stellen, um die Workflow-Ausführung optimal zu unterstützen. Ein aktueller Ansatz, um eine kontextsensitive Unterstützung zu realisieren sind Augmented Reality-Systeme. Diese verarbeiten Kontextinformationen und liefern notwendige und hilfreiche Workflow-Informationen immersiv und intuitiv, um den Nutzer zu unterstützen und zu entlasten. Da sich die technischen Implementierungen in diesem Feld sehr unterschiedlich ausgestalten, wird in diesem Beitrag eine Taxonomie entwickelt, die es ermöglicht, Augmented Reality-Systeme einheitlich zu systematisieren. Mit dem resultierenden einheitlichen Vokabular bietet die Taxonomie eine praktisch nutzbare Grundlage, um state-of-the-art Augmented Reality-Systeme zu klassifizieren, Trends und Forschungslücken in der Literatur zu identifizieren sowie die Entwicklung neuer Augmented Reality-Systeme methodisch zu unterstützen. Für die Entwicklung der Taxonomie wurden insgesamt 142 Augmented Reality-Systeme analysiert, mit speziellem Hinblick auf die bereitgestellte Workflow-Unterstützung. Die wahrgenommene Nützlichkeit der Taxonomie wurde durch eine Befragung von Augmented Reality-System und Workflow-Management-Experten evaluiert. Zudem werden zwei neuartige Augmented Reality-Systeme, die innovative Ansätze für die Unterstützung der Workflow-Ausführung darstellen, als praktische Beispiele der Anwendung der Taxonomie vorgestellt.

Schlüsselwörter: Workflow-Ausführung, Workflow-Management-System, Context-Sensitive Information, Context-Aware Information Systems, Augmented Reality, Taxonomie.

Abstract. The execution of workflows in many application fields is increasingly linked to the processing of context information. This makes it possible to provide users with the right information at the right time in order to optimally support workflow execution. A current approach to realize context-sensitive support are augmented reality systems. These process contextual information and deliver necessary and helpful workflow information immersively and intuitively to support and relieve the user. Since technical implementations in this field vary widely, this paper develops a taxonomy that makes it possible to systematize augmented reality systems in a uniform way. With the resulting unified vocabulary, the taxonomy provides a practically usable basis for classifying state-of-the-art augmented reality systems, identifying trends and research gaps in the literature, and methodically supporting the development of new augmented reality systems. For the development of the taxonomy, a total of 142 augmented reality systems were analyzed, with special regard to the provided workflow support. The perceived usefulness of the taxonomy was evaluated through a survey of experts in the domain of augmented reality systems and workflow management. In addition, two novel augmented reality systems that represent innovative approaches to workflow execution support are presented as practical examples of applications of the taxonomy.

Keywords: Augmented Reality, Workflow Execution, Workflow Management System, Context-Sensitive Information, Context-Aware Information Systems, Taxonomy.

1 Einleitung

In vielen Organisationen ist es eine praktische Herausforderung, während der Ausführung von Workflows die richtige Information zur richtigen Zeit am richtigen Ort - also kontextsensitiv - bereitzustellen (Krcmar 2006). Ein derzeit diskutierter und genutzter Ansatz, den damit verbundenen Herausforderung zu begegnen, ist Augmented Reality (AR) (bspw. Blanco-Novoa et al. 2018; Chicaiza et al. 2018; Hofmann et al. 2019; Liebmann et al. 2019; Limbu et al. 2019; Metzger et al. 2018; Wang et al. 2016).

AR erweitert die reale Umgebung um zusätzliche Informationen. Diese synthetischen Objekte werden meist visuell dargestellt, auch wenn grundsätzlich alle Sinne angesprochen werden können. Die synthetischen Objekte reagieren auf die reale Umgebung und passen sich dieser an. AR ist also interaktiv und läuft in Echtzeit ab (Azuma et al. 2001). Sogenannte AR-Systeme (ARS) implementieren AR in Informationssystemen (IS) durch den Einsatz von bspw. Wearables, Headsets, Handgeräten oder stationären Systemen (Makris et al. 2013; Metzger et al. 2018; Neges et al. 2015; Wang et al. 2016).

Eine AR-Unterstützung ist natürlich nicht für alle Workflows sinnvoll oder möglich. Während eine Systematisierung sinnvoller Einsatzgebiete für AR derzeit noch intensiv erforscht wird, kann für einzelne Szenarien durch die intuitive und freihändige Bereitstellung kontextsensitiver Informationen mittels AR bereits ein deutlicher Mehrwert aufgezeigt werden. So wurde beispielsweise bei der kollaborativen Planung, Fertigung, Service, Wartung, Lagerkommissionierung, Prozesstraining und -modellierung eine erhöhte Effizienz bei der Workflow-Ausführung festgestellt, die u.a. aus reduzierten Fehlerraten und Ausführungszeiten, einer geringeren kognitiven Belastungen oder weniger benötigtem Training resultiert (Erkoyuncu et al. 2017; Hanson et al. 2017; Hofmann et al. 2019; Jetter et al. 2018; Lampen et al. 2019; Seiger et al. 2021; Wang et al. 2016).

Workflows sind Geschäftsprozesse, welche ganz oder teilweise computergestützt bereitgestellt und von Workflow-Management-Systemen (WfMS) verarbeitet werden. Diese Softwaresysteme ermöglichen die Definition von Workflow-Modellen, interpretieren, instanziieren und verwalten diese, integrieren ggf. externe Anwendungen und ermöglichen Interaktionen mit menschlichen Workflow-Beteiligten (Workflow Management Coalition 1995). Um das Zusammenspiel von AR, Workflows und WfMS systematisch zu charakterisieren und einheitlich beschreiben zu können, bieten sich Taxonomien als Methode an. Eine Taxonomie kann als eine Menge von Dimensionen definiert werden, die jeweils wieder eine Menge von Charakteristiken enthalten, welche zusammen die möglichen Ausprägungen der jeweiligen Dimension erschöpfend darstellen (Nickerson et al. 2013). Durch die Abstraktion der realen Komplexität von Objekten auf diese Dimensionen und Charakteristiken ermöglichen Taxonomien einen einfacheren Vergleich von Ähnlichkeiten und Unterschieden zwischen Objekten. Bei der Analyse von Objektgruppen können aggregierte Ausprägungen der Taxonomie, wie ein häufiges gemeinsames Auftreten oder Fehlen von Charakteristiken, genutzt werden, um zusätzliche Erkenntnisse zu generieren (Bailey 1994). Darüber hinaus tragen Taxonomien zur deskriptiven Wissensbasis bei, indem sie ein Vokabular für eine Domäne und eine Menge von Konstrukten bereitstellen und damit eine Grundlage für zukünftige Forschungsbemühungen schaffen (Hevner et al. 2004; March und Smith 1995).

Aktuell sind nur wenige allgemeine Taxonomien für ARS verfügbar (Kalawsky et al. 2000; Klinker et al. 2018; Milgram und Kishino 1994; Wang et al. 2013). Speziell die Schnittmenge von AR, WfMS und Workflow-Ausführung wird bislang von keiner dieser Arbeiten betrachtet. Das Fehlen eines klar definierten Vokabulars der Begriffe und Konzepte erschwert den Vergleich zwischen verschiedenen ARS und die Identifizierung von Mustern innerhalb der Literatur. Dadurch wird es schwieriger, ARS formal zu charakterisieren, Trends, relevante Literatur und Forschungslücken zu identifizieren sowie neue Forschungsprojekte und Entwicklungen von ARS zu steuern. Um diese Mehrwerte zukünftig zu ermöglichen, wird in diesem Beitrag eine Erweiterung und Aktualisierung der derzeit existierenden Taxonomien vorgenommen, welche die ARS im Hinblick auf ihre Integration mit WfMS charakterisieren und ihre Unterstützung der Workflow-Ausführung detailliert beschreiben. Folglich definieren wir unsere Forschungsfrage:

Welche Dimensionen und Charakteristiken einer Taxonomie beschreiben aktuelle Augmented-Reality-Systeme zur Unterstützung der Workflow-Ausführung?

Die Entwicklung der Taxonomie erfolgt auf Basis des bekannten Ansatzes zur Entwicklung von Taxonomien nach Nickerson et al. (2013) sowie einer strukturierten Literaturrecherche nach vom Brocke et al. (2009). Bevor in Kapitel 3 der Forschungsansatz detailliert beschrieben wird, werden in Kapitel 2 für eine bessere Anschaulichkeit einige ARS exemplarisch vorgestellt. In Kapitel 4 wird die entwickelte Taxonomie zur Klassifikation von ARS, welche die Workflow-Ausführung unterstützen, mit ihren Kategorien, Dimensionen und Charakteristiken vorgestellt. In Kapitel 5 wird die Taxonomie mittels einer Expertenbefragung evaluiert und in Kapitel 6 die praktische Nützlichkeit und Anwendbarkeit demonstriert, indem Erkenntnisse aus den analysierten 142 ARS und die Entwicklung zweier neuartiger ARS vorgestellt werden. Das Kapitel 7 bietet eine Zusammenfassung dieses Beitrags und einen Ausblick.

2 Augmented Reality-Systeme in der Praxis

In der aktuellen Forschungsliteratur wird ein weites Spektrum verschiedener ARS diskutiert, die sich beispielsweise in der verwendeten Hardware, den dargestellten AR-Formaten oder den bereitgestellten Workflow-Unterstützungen unterscheiden. Um diese Bandbreite aufzuzeigen, werden nachfolgend drei exemplarische Implementierungen von ARS vorgestellt.

Abb. 1 Augmented Reality-System aus Blanco-Novoa et al. (2018)

Das erste Beispiel wird in Blanco-Novoa et al. (2018) vorgestellt. In dieser Arbeit werden Werften durch den Einsatz eines mobilen ARS unterstützt, indem Smartphones zur Erweiterung der Realität um synthetische Inhalte genutzt werden. Mittels eingebauter Kamera können so bspw. visuelle Marker wie QR-Codes erkannt werden, um dann das Kamerabild mit kontextsensitiven synthetischen Inhalten, bspw. Materialbeschreibungen zu überlagern (siehe Abb. 1). Im Kontrast zu mobilen ARS demonstrieren Hou et al. (2013) ein fest installiertes ARS. Hier werden Kameras und Projektoren verwendet, um Nutzer bei der Durchführung einer analogen Bauanleitung durch zusätzliche Inhalte zu unterstützen (Abb. 2). Das vorgestellte ARS erlaubt es dem Nutzer, freihändig zu arbeiten und vermeidet es, zusätzlichen Geräte hinzu zu ziehen oder am Körper zu tragen.

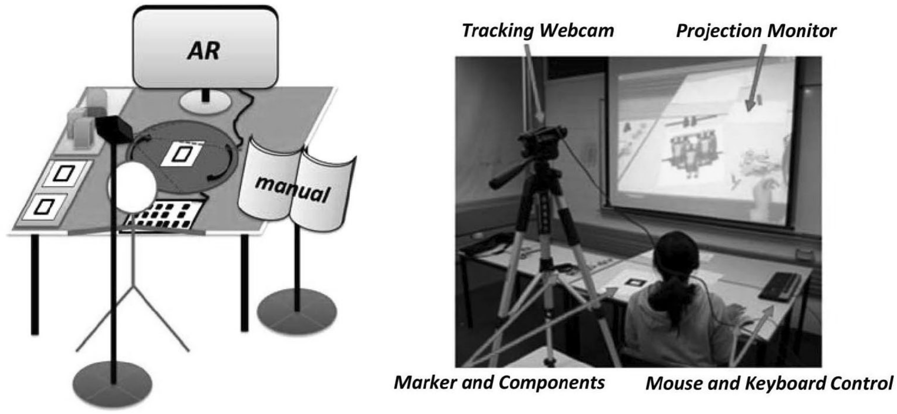


Abb. 2 Augmented Reality-System aus Hou et al. (2013)

Eine dritte Implementierungsmöglichkeit von ARS zeigen Liu et al. (2018). Für den medizinischen Kontext werden in diesem Beispiel besonders immersiv synthetische Inhalte über ein AR-Headset bereitgestellt. Die Abb. 3 zeigt wie über die Berechnung der relativen Positionen zwischen AR-Headset, des blau markierten Marker-Würfels und des erkannten Knochen-Modells ein präzises Feedback visualisiert wird, ob ein medizinisches Instrument im richtigen Winkel gehalten wird (grün) oder nicht (rot).

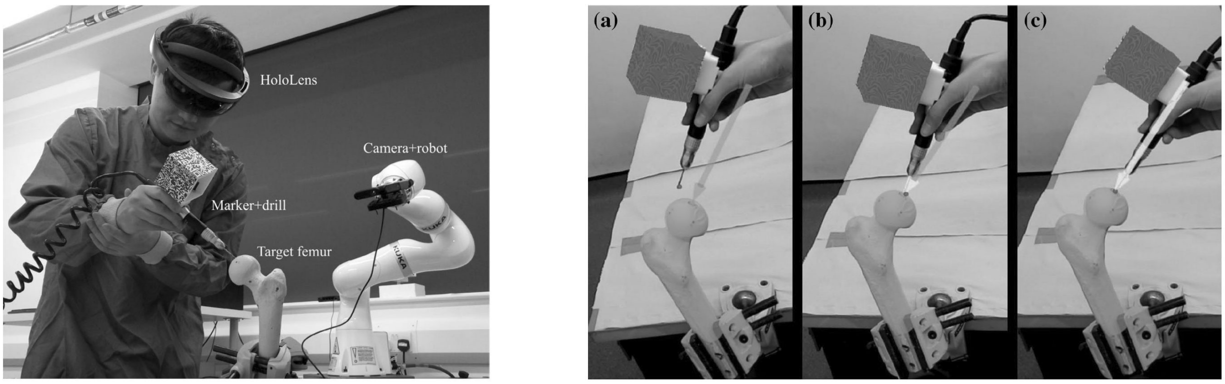


Abb. 3 Augmented Reality-System aus Liu et al. (2018)

Um die drei exemplarischen ARS in einer gemeinsamen Nomenklatur beschreiben und vergleichen zu können, erscheinen bereits einige Dimensionen und Charakteristiken naheliegend. So erscheint der Typ des zur Implementierung genutzten Endgeräts - Smartphone, stationäre Anlage oder AR-Headset - augenscheinlich geeignet. Alle drei ARS nutzen QR-Codes bzw. visuelle Marker, um die synthetischen Inhalte immersiv mit den realen Objekten darzustellen. Auch die Repräsentation der synthetischen Inhalte - Text, Bilder, 2D und 3D Formen - scheint geeignet zum Vergleich. Besonders die bereitgestellte Unterstützung bei der Workflow-Ausführung ist eine interessanteste Dimension für die Praxis. Während das Beispiel in Abb. 1 allgemein hilfreiche Informationen für die Workflow-Ausführung bereitstellt, gibt das ARS in Abb. 2 dem Benutzer, basierend auf den Sensorinformationen, konkrete Anweisungen für die nächste Handlung. In Abb. 3 werden die Sensorinformationen genutzt, um eine Abweichung der aktuellen Ausführung einer Workflow-Aufgabe zu erkennen und dem Benutzer eine präzise, immersive Korrekturanweisung zu vermitteln.

Dieser beispielhafte Vergleich dieser ARS zeigt zum einen deutliche Unterschiede, aber auch erste Ansätze für Dimensionen und Charakteristika einer möglichen Taxonomie auf, um ARS zur Unterstützung der Workflow-Ausführung zu beschreiben. Die Beispiele werfen konsequenterweise aber auch die Fragen auf, welche weiteren relevanten Dimensionen und Charakteristika existieren, um ARS umfänglich zu klassifizieren. Diese Frage wird in den folgenden Kapiteln methodisch untersucht und beantwortet.

3 Methodischer Ansatz und aktueller Forschungsstand

Die angewendete Methode zur Entwicklung der Taxonomie nach Nickerson et al. (2013) umfasst fünf zentrale Schritte, welche in Abb. 4 zusammengefasst und im Folgenden erläutert werden.

Der erste Schritt beinhaltet die **Definition einer Meta Characteristic**, das heißt, eines umfassenden Merkmals auf höchster Abstraktionsebene. Die Meta- Characteristic – in unserem Fall "Eigenschaften von ARS, welche die Workflow-Ausführung unterstützen" – bildet die Grundlage für die Auswahl und Ableitung von Dimensionen sowie spezifischen (Sub-)Charakteristika der späteren Taxonomie.

Der zweite Schritt der Methode umfasst die **Definition von Ending Conditions**, anhand derer bestimmt wird, wann die resultierende Taxonomie einen zufriedenstellenden Zustand erreicht hat. Dabei werden die von Nickerson et al. vorgeschlagenen 8 objektiven und 5 subjektiven Ending Conditions (OEC, SEC) (vgl. Nickerson et al. 2013, S. 344) angewandt. Die OEC1 fordert, dass alle relevanten Objekte oder eine repräsentative Stichprobe untersucht wurden. Die OEC2 bezieht sich auf die Beschreibung der Objekte durch die Dimensionen und Charakteristika. Werden mehrere Objekte zusammengefasst oder differenziert, muss geprüft werden, ob die Taxonomie angepasst werden sollte. Die OEC 3 fordert, dass für jedes definierte Charakteristikum der Taxonomie mindestens ein untersuchtes Objekt vorliegt. Es sollen nicht alle vorstellbaren Charakteristika aufgeführt werden. Die OEC 4 definiert, dass die Taxonomie-Entwicklung nicht abgeschlossen sein kann, wenn bei der Untersuchung von Objekten noch neue Dimensionen oder Charakteristika gefunden werden. Die OEC5 fordert das gleiche, jedoch das Zusammenlegen und Aufteilen von Dimensionen und Charakteristika. Die OEC6 und OEC7 fordern, dass die Dimensionen resp. Charakteristika in diesen einzigartig sind und keine Redundanz zwischen diesen vorliegt. Die OEC8 legt dies auch für Kombinationen von Charakteristika fest. Die 5 SEC sind Prägnanz (SEC1), Robustheit (SEC2), Vollständigkeit (SEC3), Erweiterbarkeit (SEC4) und Erklärungskraft (SEC5). SEC 1 bezieht sich auf die Anzahl der Dimensionen, die für eine aussagekräftige Taxonomie hinreichend groß sein muss, jedoch nicht zu umfangreich oder überfordernd sein darf. SEC2 zielt darauf ab, dass durch die Dimensionen und Charakteristika der Taxonomie eine ausreichende Differenzierung zwischen Realobjekten möglich sein muss. SEC3 befasst sich mit der Vollständigkeit der Taxonomie, d.h. damit, ob alle relevanten Dimensionen und Charakteristika der Realobjekte auch tatsächlich identifiziert wurden. SEC4 adressiert die zukünftige Erweiterbarkeit bzw. Anpassbarkeit der Taxonomie um weitere Dimensionen und Charakteristika, bspw. wenn neue technologische Entwicklungen es erfordern. SEC5 adressiert schließlich die Erklär- bzw. Aussagekraft der Taxonomie. Dieses Kriterium fordert nicht nur aussagekräftige Erklärungen der Dimensionen und Charakteristika der Taxonomie selbst, sondern auch die Möglichkeit zur Ableitung von erklärendem Wissen über bereits klassifizierte Realobjekte.

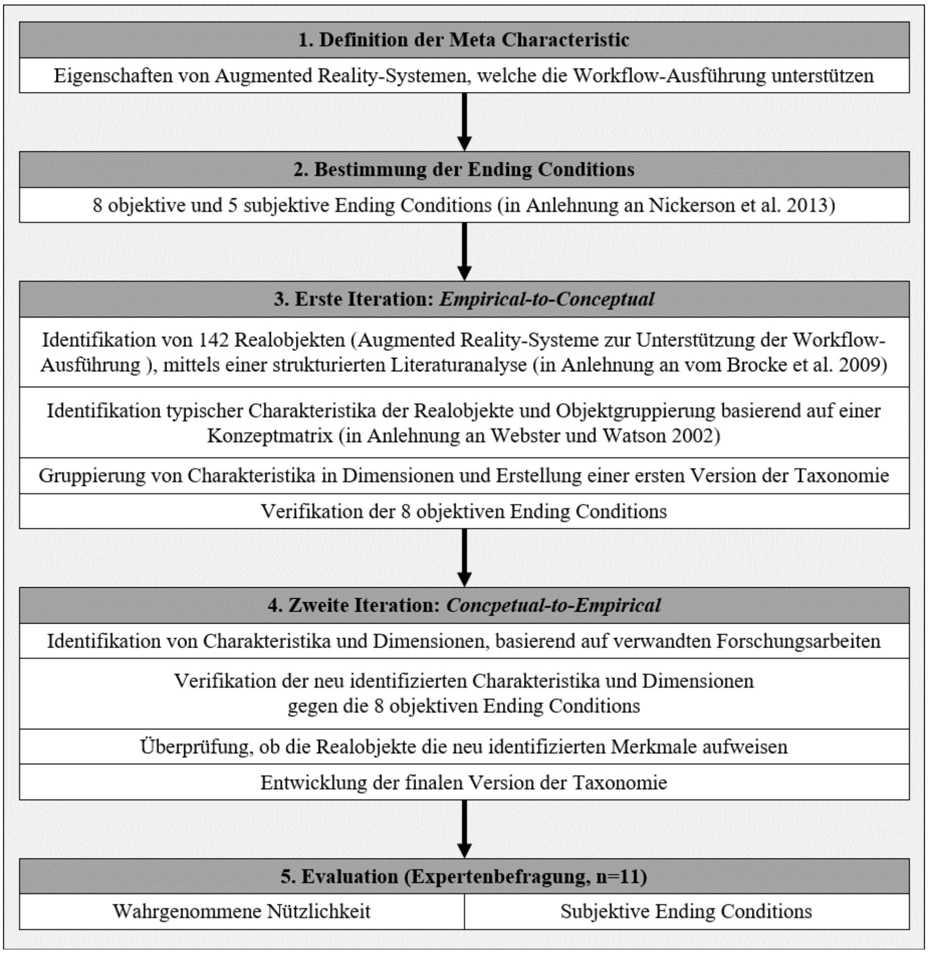


Abb. 4 Forschungsansatz (in Anlehnung an Nickerson et al. 2013)

Im dritten und vierten Schritt der Methode erfolgt anschließend die iterative **Entwicklung der Taxonomie** selbst, wofür grundsätzlich zwei Ansätze zur Verfügung stehen: 1) der Empirical-to-Conceptual-Ansatz, bei dem zunächst reale Objekte – im Kontext unserer Studie ARS – identifiziert werden, gefolgt von der Analyse und Gruppierung ihrer Dimensionen und Charakteristika, und 2) der Conceptual-to-Empirical-Ansatz, bei dem Dimensionen und Charakteristika zunächst unabhängig von Realobjekten konzeptualisiert werden.

Die Entwicklung der angestrebten Taxonomie wurde im dritten Schritt der Methode in einer ersten Iteration durch den Empirical-to-Conceptual-Ansatz eingeleitet. Nickerson et al. empfehlen hierfür die Durchführung einer Literaturrecherche zur Identifikation von Realobjekten (vgl. Nickerson et al. 2013, S. 345). Dementsprechend wurde hierzu eine strukturierte Literaturrecherche zu relevanten ARS gemäß des Ansatzes von vom Brocke et al. (2009) durchgeführt. Die Abb. 5 bietet einen Überblick über den Ablauf der strukturierten Literaturrecherche.

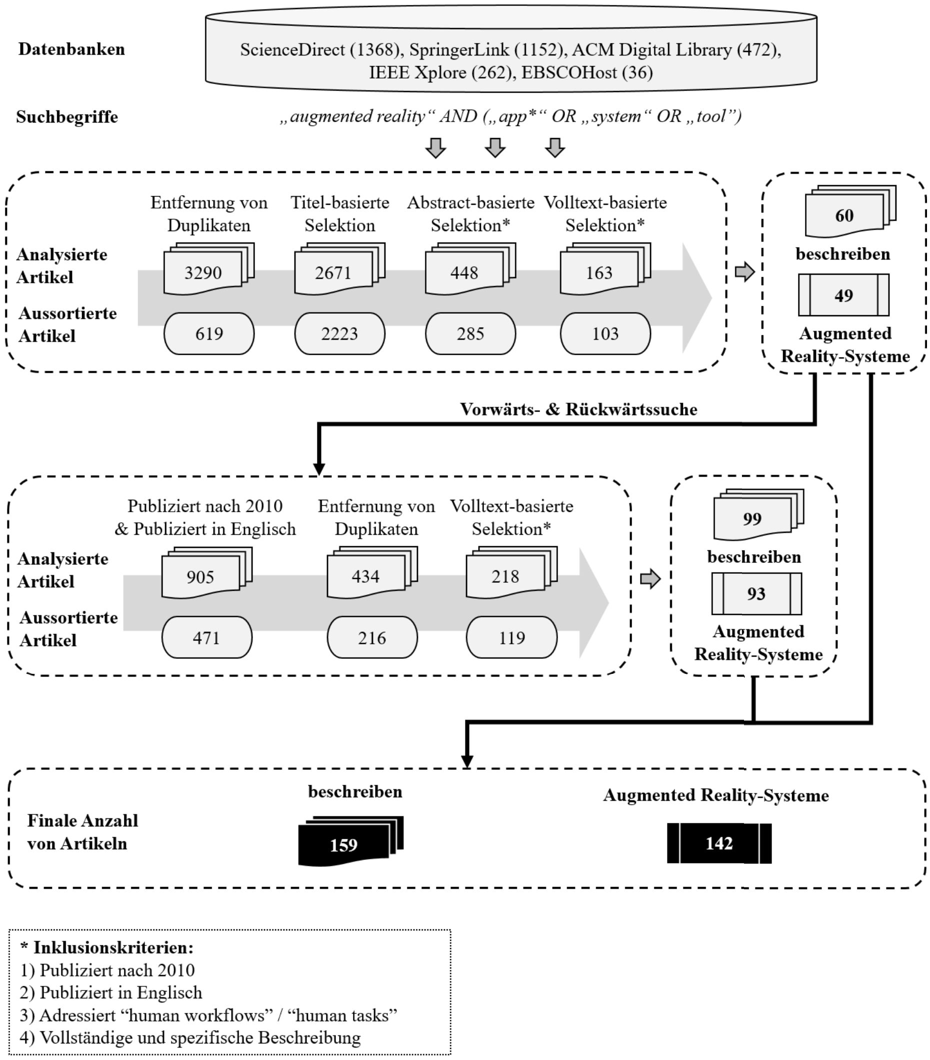


Abb. 5 Prozess und Ergebnisse der strukturierten Literaturrecherche

Um eine möglichst breite Masse an Suchergebnissen zu erhalten, wurden insgesamt fünf Datenbanken durchsucht: ACM Digital Library, EBSCOHost, IEEE Xplore, ScienceDirect und SpringerLink. Der Forschungsfrage folgend, wurden dabei folgende vier Suchbegriffe verwendet: 1. "augmented reality", 2. "system", 3. "app" und 4. "tool". Da wir in unserem Beitrag explizit AR untersuchen, haben wir den Begriff "Mixed Reality" nicht berücksichtigt, da dieser das gesamte Realitäts-Virtualitäts-Kontinuums beschreibt und somit eine Obermenge von AR bezeichnet (Milgram 1994). Die vier Suchbegriffe wurden mit verschiedenen Suchoperatoren kombiniert und in den Datenbanken getestet. Dabei zeigte sich, dass die einfache Verknüpfung aller Suchbegriffe mit OR-Operatoren zu mehr als 100.000 Ergebnissen führt. Durch die Kombination der Begriffe 2, 3 und 4 mit einem OR-Operator und die Ergänzung des Begriffs "augmented reality" mit einem AND-Operator wurde eine handhabbare Menge von 3.290 Suchergebnissen erreicht. In Anlehnung an vom Brocke et al. 2009 wurden diese Ergebnisse anschließend in fünf Schritten selektiert: 1) Entfernung von Duplikaten, 2) Titel-basierte Selektion, 3) Abstract-basierte Selektion, 4) Volltext-basierte Selektion und 5) Rückwärtssuche.

Für die Auswahl wurden vier Inklusionskriterien (IK) definiert, anhand derer über die Relevanz der jeweiligen Artikel entschieden wurde: Um Aktualität zu gewährleisten, wurden nur Artikel berücksichtigt, die nach 2010 veröffentlicht wurden und demnach in zeitlicher Nähe zur Veröffentlichung relevanter Verbraucherprodukte standen, wie beispielsweise der Google Glass im Jahr 2012 oder der Microsoft HoloLens im Jahr 2015 (IK1). Es wurden nur englischsprachige Artikel berücksichtigt (IK2). Artikel, die ARS adressieren, wurden dann als relevant klassifiziert, wenn sie einen vollständigen ARS-Prototypen oder ein vollständiges ARS-Design beinhalten (IK3). Demgemäß wurden keine Artikel berücksichtigt, die lediglich Visionen oder nur einzelne Funktionen von ARS beschreiben. Das beschriebene ARS sollte zudem einen menschenbezogenen Workflow oder einen menschenbezogene Workflow-Aufgabe in irgendeiner Weise adressieren (IK4). Es wurden demnach keine ARS berücksichtigt, denen es an einem spezifischen Bezug zur Workflows fehlt, wie bspw. ARS, die für reine Bildungszwecke entwickelt wurden oder ARS, die lediglich ein verbessertes Situationsbewusstsein ermöglichen.

Die resultierende Menge an Literatur umfasste zunächst 60 Artikel, die ARS zur Unterstützung der Workflow-Ausführung beschreiben. Um die angestrebten Dimensionen und Charakteristika relevanter ARS zu identifizieren, wurde eine Autoren-zentrierte Analyse durchgeführt, wie sie von Webster und Watson (2002) beschrieben wird. Dabei zeigte sich, dass einige Artikel die gleichen ARS beschreiben, wodurch sich die Menge der zu analysierenden Realobjekte von 60 auf 49 reduzierte. Die anschließende Vorwärts- und Rückwärtssuche brachte insgesamt 905 weitere Ergebnisse hervor, von denen 434 die definierten IK erfüllten. Nach der Entfernung von Duplikaten verblieben 218 Artikel für eine Volltext-basierte Selektion, wobei wiederum 93 relevante ARS identifiziert werden konnten.

Die insgesamt 142 resultierenden ARS wurden schließlich, wie von Webster und Watson (2002) empfohlen, in einer Konzeptmatrix erfasst, anhand derer ihre Charakteristika analysiert und in Dimensionen gruppiert wurden. Die Konzeptmatrix ist im Appendix als Anhang A beigefügt.

In Anlehnung an die Ausführungen zu Ex-ante-Evaluationen von Pries-Heje et al. (2008) wurden die 8 objektiven Endbedingungen bereits im Rahmen der ersten Iteration der Taxonomie-Entwicklung berücksichtigt. Darüber hinaus wurde im vierten Schritt der Methode (siehe Abb. 4, Schritt 4) zur Entwicklung einer Taxonomie eine weitere Iteration nach Nickerson et al. (2013) durchgeführt und dabei den Conceptual-to-Empirical-Ansatz implementiert (Nickerson et al. 2013). Ziel war es dabei, die entstehende Taxonomie mit anderen Taxonomien von ARS und Referenzarchitekturen für AR und WfMS zu vergleichen und zu evaluieren, ob bestehende Artefakte möglicherweise noch zusätzliche Charakteristika oder auch widersprüchliche Ergebnisse beinhalten (Kalawsky et al. 2000; Klinker et al. 2018; Limbu et al. 2019; MacWilliams et al. 2004; Milgram und Kishino 1994; van Krevelen und Poelman 2010; Wang et al. 2013; WFMC 1995).

In diesem Zusammenhang wurde insbesondere die von Wang et al. (2013) vorgeschlagene Taxonomie betrachtet, da diese allgemein Implementierungs-relevante Charakteristika von ARS beschreibt und damit eine Teilmenge der angestrebten Taxonomie für ARS zur Unterstützung bei der Workflow-Ausführung ist. Während die Taxonomien im Allgemeinen übereinstimmen, unterscheiden sie sich teilweise im Abstraktionsgrad und in der Formulierung. So bezieht sich die entwickelte Taxonomie bspw. auf "Zweihandgeräte", während Wang et al. (2013) zwischen "Tablet" und "Laptop" unterscheiden. Eine derart feine Aufschlüsselung der Charakteristiken würde die von uns angestrebte Taxonomie jedoch unnötig verkomplizieren und wäre daher nicht mit der OEC2 vereinbar (vgl. Nickerson et al. 2013, S. 344). Außerdem wurden für die entstehende Taxonomie Implementierungs-relevante Charakteristika so definiert, dass sie mit der Arbeit von van Krevelen und Poelman (2010) im Einklang sind, die technische Implementierungsmöglichkeiten von ARS ausführlich beschreibt. Darüber hinaus wurde die entstehende Taxonomie mit dem ID4AR-Framework von Limbu et al. (2019) abgeglichen, welches 11 Arten von synthetischen Handlungsanweisungen beschreibt, allerdings ohne Berücksichtigung von Workflows. Das Framework steht nicht im Widerspruch zu der entwickelten Taxonomie, obwohl ein strukturierter und feingranularer Ansatz gewählt wurde.

Schlussendlich fanden sich in der Literatur auch Charakteristika, die bei der Analyse der 142 ARS bisher nicht identifiziert wurden, wie beispielsweise akustisches und mechanisches Tracking, Geruch und Geschmack als Output oder verschiedene Workflow-Management-Funktionen (Craig 2013; MacWilliams et al. 2004; Milgram und Kishino 1994; WFMC 1995). Entsprechend der OEC3 (vgl. Nickerson et al. 2013, S. 344) wurden diese Merkmale bei der Taxonomie-Entwicklung jedoch nicht berücksichtigt, da sie bisher nicht zur Unterstützung der Workflow-Ausführung eingesetzt werden. Die zweite Iteration des Taxonomie-Entwicklungsprozesses bestätigte somit die identifizierten Dimensionen und Charakteristika, sodass die 8 objektiven Endbedingungen als erfüllt angesehen werden können. Die 5 subjektiven Endbedingungen werden hingegen separat im Rahmen der **Evaluation der Taxonomie**, welche den fünften Schritt der Methode zur Taxonomie-Entwicklung darstellt (siehe Abb. 4, Schritt 5). Dieser wird in Abschnitt 5 beschrieben. Die endgültige Taxonomie als Ergebnis des vierten Schritts der Methode ist in Abb. 6 dargestellt und wird im folgenden Abschnitt 4 erläutert.

4 Eine Taxonomie für Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung

Da bei der Taxonomie-Entwicklung 14 Dimensionen identifiziert wurden, werden diese der Übersichtlichkeit halber anhand der folgenden vier Kategorien zusammengefasst: 1) Gerät, 2) Tracking-System, 3) Synthetischer Inhalt und 4) Workflow. Die einzelnen Dimensionen werden im Folgenden detailliert beschrieben, die identifizierten Charakteristika benannt und anhand der in Kapitel 2 vorgestellten exemplarischen ARS erläutert.

4.1 Kategorie: Gerät

In der Kategorie "Gerät" werden alle Dimensionen zusammengefasst, die die technische Interaktion des Nutzers mit einem ARS charakterisieren. Einige ARS sind mit mehreren Komponenten oder Geräten auf der Seite der Nutzer realisiert, so dass diese ARS mehrere Merkmale in mehreren Dimensionen aufweisen.

Die **Dimension "Typ"** beschreibt die konkreten Geräte, die die Interaktion des Nutzers mit dem ARS ermöglichen. Ein Beispiel für ein *Einhandgerät* ist das ARS von Blanco-Novoa et al. (2018) (siehe Abschnitt 2), welches auf einem Smartphone umgesetzt wurde. Das ARS von Hou et al. (2013) ist ein Beispiel für *Stationäre Geräte.* Im medizinischen ARS von Liu et al. (2018) kommt dagegen mit einem AR-Headset ein *Kopfgetragenes Gerät* zum Einsatz. Auch finden sich in den identifizierten ARS weitere Charakteristika für die Dimension "Typ", wie *Körpergetragene Geräte*, die am Körper getragen werden und hauptsächlich als Smartwatches (Wang et al. 2013) realisiert sind und *Zweihandgeräte*, bspw. Tablets (Neges et al. 2015).

Die **Dimension "Architektur"** beschreibt die physikalische Beschaffenheit eines ARS. Alle Komponenten eines ARS können physikalisch in ein *Einzelgerät* integriert sein, wie beispielsweise im medizinischen ARS von Liu et al. (2018) in einem AR-Headset oder im ARS von Blanco-Novoa et al. (2018) als Smartphone. Alternativ können die angeschlossenen Geräte physikalisch getrennt aber *Verbundene Geräte* sein, z. B. Kopfhörer und Smartphone (Aldaz et al. 2015) oder wie dies im stationären ARS von Hou et al. (2013) der Fall ist. Sind die einzelnen Komponenten in einer weiteren Stufe (semi-)permanent verbunden, wird die Architektur als *Integriertes Gerät* charakterisiert (bspw. Lahanas et al. 2015).

Die exklusive **Dimension "Nutzersystem"** beschreibt, wie viele Personen gleichzeitig denselben synthetischen Inhalt wahrnehmen können. Dies kann wie im medizinischen ARS von Liu et al. (2018) ein *Einzelbenutzer* sein. Alternativ kann das ARS als *Mehrbenutzer*-System umgesetzt sein, wie bspw. das stationären ARS von Hou et al. (2013) oder das Smartphone-basierte ARS von Blanco-Nova et al. (2018).

	Dimensionen	Charakteristiken				
Gerät	Typ	Körpergetragene Geräte (10)	Kopfgetragene Geräte (70)			
		Einhandgeräte (22)	Zweihandgeräte (29)	Stationäre Geräte (53)		
	Architektur	Einzelgerät (70)	Verbundene Geräte (40)	Integrierte Geräte (37)		
	Nutzersystem*	Einzelbenutzer (100)	Mehrbenutzer (42)			
	Ausgabe	Projektor (15)	Transparenter Bildschirm (15)	Videomonitor (77)		
		Stationäre Lautsprecher (3)	Mobile Lautsprecher (20)	Haptisch (6)		
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele (68)	Visuelle Merkmalbasierte Objektverfolgung (43)	Räumliche Karte (13)		
		Vernetzte Externe Optische Sensoren (4)	Trägheit und Orientierung (26)			
		GPS (3)	RFID (2)	Keine (27)		
	Objekt-positions-verfolgung	Visuell Markerbasiert (65)	Visuell Merkmalsbasiert (61)			
		Vernetzte Externe Optische Sensoren (1)	GPS (1)	RFID (3)	Magnetisch (5)	Keine (23)
	Benutzer-interaktions-verfolgung	Handgesten (23)	Augenverfolgung (6)	Körperhaltung (4)		
		Mechanisch & Berührung (60)	Sprache (21)	Zeiger (3)	Keine (52)	
Synthetisch Inhalte	Repräsentation	Text (78)	Bild (64)	Video (19)		
		2D Form (97)	3D Form (92)	Animation (23)	Akustik (14)	Haptisch (6)
	Visuelle Ausrichtung	Fixiert (42)	Nähe (98)	Nicht-transparente Überlagerung (50)	Transparente Überlagerung (52)	
	Benutzer-interaktion	Keine (83)	Selektion (49)	Manipulation (29)		
	Inhalts-steuerung	Manuell (6)	Automatisch (51)	Hybrid (82)		
Workflow	Workflow-Verarbeitung*	Impliziter Workflow (96)	Implizite Workflow-Aufgabe (36)			
		Modellierter Workflow & Implizite Workflow-Engine (10)				
	Workflow-Management	Keine (105)	Workflow-Instanziierung (18)	Navigation zur nächsten oder vorherigen Workflow-Aufgabe (20)		
		Workflow-Abbruch (2)	Workflow-Pfad ändern (8)			
		Workflow-Aufgaben-Übersicht (7)	Workflow-Aufgabe wechseln (4)			
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription (4)	Nicht-sichtbare reale Objekte visualisieren (32)	Echtzeitdaten (17)		
		Automatische Abweichungserkennung (10)	Anweisung (61)	Demonstration (5)		
		Routing (6)	Telefonie (2)	Fernunterstützung (18)	Teleoperation (15)	
		Dokumentation (17)	Dateneingabe (13)	Datenscan (3)		
		Prozessmodellierung (1)	Synthetische Objektmodellierung (1)			
		Hilfsinformation (127)	Workflow-Training (9)			

*Anmerkung: * = Dimensionen mit exklusiven Charakteristiken. (#): Absolute Auftrittshäufigkeit der Charakteristik in den 142 analysierten ARS.*

Abb. 6 Taxonomie für Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung.

Die **Dimension "Ausgabe"** kann zur Informationsvermittlung im Prinzip alle menschlichen Sinne ansprechen. In den in Kapitel 2 vorgestellten Beispielen werden überwiegend visuelle Medien genutzt. Das ARS von Blanco-Novoa et al. (2018) wird auf einem Smartphone implementiert, also einem *Videomonitor*, der die via Kamera aufgenommene Realität auf einem undurchsichtigen Bildschirm um synthetische Inhalte erweitert. Alternativ kann, wie bspw. beim AR-Headset von Liu et al. (2018), ein *Transparenter Bildschirm* verwendet werden, welcher vor den Augen des Nutzers angebracht ist und auf welchem die synthetischen Inhalte projiziert werden. Im stationären ARS von Hou et al. (2013) wird wiederum ein Beamer als *Projektor* verwendet, der Bilder lokal auf Oberflächen und Objekte projiziert. In der Literatur konnten neben visuellen noch akustische und haptische Medien als Ausgaben identifiziert werden. Die akustische Ausgabe kann, wie bspw. bei Fiorentino et al. (2014), entweder über (semi-)fest installierte *Stationäre Lautsprecher* oder wie bspw. bei Chicaiza et al. (2018) mittels Kopfhörer über *Mobile Lautsprecher*, erfolgen. Die *haptische Ausgabe* erfolgt bei getragenen Geräten in der Regel über Vibration (Wang et al. 2013).

4.2 Kategorie: Verfolgungssysteme

Ein ARS muss weder Objekte noch die eigene Position oder Benutzerinteraktionen verfolgen, um die richtigen synthetischen Inhalte auszuwählen (bspw. Berkemeier et al. 2013; Ferrari et al. 2016; Fiorentino et al. 2014; Liu et al. 2018). Daher werden alle Dimensionen in dieser Kategorie durch "*Keine*" ergänzt.

Die **Dimension "ARS-Positionsverfolgung"** beschreibt, wie das ARS seine Position in Bezug auf die Umgebung oder bestimmte Objekte verfolgt, um synthetische Informationen auszuwählen, anzuzeigen oder mit realen Objekten abzugleichen. Viele ARS verfolgen ihre Position nur in Bezug auf Objekte, um synthetische Inhalte in der richtigen Perspektive anzuzeigen, da die relative Position des ARS aus der Verzerrung der verfolgten *Bildziele*, z. B. QR-Codes oder Fotos, berechnet werden kann, wie bspw. Blanco-Novoa et al. (2018) und Liu et al. (2018) zeigen. Alternativ dazu berechnet die *Visuelle Merkmalbasierte Objektverfolgung* die relative Position des ARS anhand der bekannten Form eines Objekts (Makris et al. 2013). Auf ähnliche Weise kann ein ARS die lokale Umgebung scannen und eine *Räumliche Karte* erstellen, um seine eigene Position sowie "räumliche Anker" darin zu verfolgen, so dass der Benutzer synthetische Objekte auf jeder realen Oberfläche fixieren kann (Liebmann et al. 2019). *Vernetzte externe optische Sensoren*, z. B. eine Reihe von Infrarotkameras, können visuelle Marker auf Objekten verfolgen und aus den kombinierten Daten deren räumliche Orientierung ableiten (Henderson und Feiner 2011). Speziell entwickelte *Trägheits- und Orientierungssensoren* bestehen aus Beschleunigungsmessern, Gyroskopen oder Magnetometern (Liebmann et al. 2019). Positionsinformationen können auch durch den Einsatz netzwerkorientierter Sensoren wie *GPS* (Dünser et al. 2012) oder *RFID*-Tags und -Sensoren (Blanco-Novoa et al. 2018) gewonnen werden.

Die **Dimension "Objektpositionsverfolgung"** umfasst ähnliche Merkmale, zeigt sich jedoch bei der Analyse der 142 ARS trotz der Ähnlichkeit unabhängig von der ARS Positionsverfolgung. Es können analog *Visuell Markerbasierte* und *Visuell Merkmalsbasierte* Ansätze sowie *Vernetzte Externe Optische Sensoren*, *GPS* und *RFID* genutzt werden. Zusätzlich können Objekte auch *magnetisch* verfolgt werden, was insbesondere für medizinische Geräte genutzt wird (Ferrari et al. 2016).

Die **Dimension "Benutzerinteraktionsverfolgung"** umfasst vordefinierte *Handgesten*, die meist über optische Sensoren erkannt werden (Arroyave-Tobón et al. 2015). Die *Augenverfolgung* misst die Blickrichtung über Pupillenbewegungen oder deren Sichtbarkeit (Aldaz et al. 2015). Auch die allgemeine *Körperhaltung* des Benutzers kann zur Interaktion genutzt werden, z. B. das Neigen des Kopfes (Aldaz et al. 2015). Mit Hilfe von mechanischen und taktilen Sensoren (z. B. Tasten oder Touchscreen) kann *Mechanisch* und mittels *Berührungen* interagiert werden, wie bspw. bei Hou et al. (2013). Mikrofone ermöglichen eine *Sprachsteuerung*, wie bspw. Blanco-Novoa et al. (2018). Auch *Zeiger* können zur Interaktion genutzt werden, z. B. ein Laserpointer, der von den Kameras des ARS verfolgt wird (Andersen et al. 2016).

4.3 Kategorie: Synthetische Inhalte

Alle ARS nutzen per Definition eine Form von synthetischen Inhalten.

Die **Dimension "Repräsentation"** korreliert zwar mit der obigen Dimension "Ausgabe", ist jedoch nicht Deckungsgleich. Wir unterscheiden zwischen *Text*, *Bildern*, *Videos*, *2D-Formen*, *3D-Formen*, *Animationen*, *akustischen* und *haptischen* Repräsentationen (Arroyave-Tobón et al. 2015; Lahanas et al. 2015; Limbu et al. 2019; Metzger et al. 2018; Wang et al. 2016).

Die **Dimension "Visuelle Ausrichtung"** beschreibt die Ausrichtung des visuellen synthetischen Inhalts an die Umgebung aus Sicht des Benutzers. Dieser kann *fixiert* sein, bspw. wie bei einem Menü in einem AR-Headset oder auf einem Smartphone. Der Inhalt kann in der *Nähe* eines Objekts oder Markers ausgerichtet sein oder diesen kongruent überlagern, entweder als *nicht-transparente Überlagerung* oder als t*ransparente Überlagerung* (Berkemeier et al. 2019; Makris et al. 2013). Bei Liu et al. (2018) ist bspw. sowohl eine nicht-transparente Überlagerung für das Knochen-Modell und den QR-Marker dargestellt, als auch der Abweichungsindikator in der Nähe (siehe Abb. 3). In den untersuchten ARS wurden alle akustischen Inhalte nutzerzentriert ausgerichtet, obwohl dies theoretisch auch anders sein könnte.

Die **Dimension "Benutzerinteraktion"** beschreibt grob-granular, wie der Benutzer mit dem synthetischen Inhalt während der Ausführung der Workflow-Aufgabe interagiert, entweder gar nicht (*keine*), wie bspw. bei Liu et al. (2018), durch *Selektion* von Inhalten (z. B. Menüpunkte bei Arroyave-Tobón et al. 2015) oder durch *Manipulation* des synthetischen Inhalts, z. B. durch Änderung der Farbe, Form, Skalierung, Position, Orientierung oder Einfügen und Löschen von Objekten (Arroyave-Tobón et al. 2015).

Die **Dimension "Inhaltssteuerung"** gibt an, wie der synthetische Inhalt während der Ausführung der Workflow-Aufgabe instanziiert wird. Bei einer *automatischen* Steuerung werden die synthetischen Inhalte ohne Zutun des Nutzers dargestellt. Ein *hybrider* Ansatz benötigt gelegentlich eine Nutzereingabe, bspw. in Menüs. Die *manuelle* Steuerung benötigt für jede Änderung im dargestellten synthetischen Inhalt eine Nutzersteuerung (Arroyave-Tobón et al. 2015).

4.4 Kategorie: Workflow

In dieser Kategorie betrachten wir die ARS aus der Perspektive von Workflows und WfMS. Wir orientieren uns an der Definiton der Workflow Management Coalition (1995) und verstehen Workflows als Geschäftsprozess, welche ganz oder teilweise computergestützt bereitgestellt und von WfMS verarbeitet werden. Ein WfMS ist daher ein Software-System und ermöglicht als solches die Definition, Interpretation, Instanziierung, Verwaltung und das Management von Workflow-Modellen, ermöglicht die Integration von externen Anwendungen und bietet eine Benutzeroberfläche für menschliche Workflow-Beteiligte. (Workflow Management Coalition 1995). In Anbetracht des Funktionsumfangs aktueller WfMS (bspw. Camunda oder Signavio) sowie dem genutzten de facto Standard für Workflowmodellierung BPMN, adressieren WfMS und insb. deren Management-Funktionen – in unserer Perspektive – sowohl stellenbezogene Workflows, welche von einer Personalstelle an einem Arbeitsplatz ausgeführt werden, als auch stellenübergreifende Workflows. Für die Erstellung der Taxonomie wurden die ARS speziell aus der Perspektive der Unterstützung der Workflow-Ausführung betrachtet. Dabei verfolgen wir einen breiten Ansatz und schließen einige Randfälle der üblichen Definitionen von Workflows und Workflow-Management-Systemen (WfMS) ein.

Die exklusive **Dimension "Workflow-Verarbeitung"** beschreibt die formale Darstellung und Verarbeitung von Workflows. Ein *Impliziter Workflow* liegt vor, wenn die Abfolge der von einem ARS präsentierten synthetischen Inhalte durch logische Stufen, Phasen, Auslöser oder Bedingungen strukturiert ist, d.h. nicht immer alle synthetischen Inhalte gleichzeitig präsentiert werden. Beispielsweise sind bei Hou et al. (2013) die synthetischen Anweisungen in einem Workflow geordnet und werden je nach Fortschritt im Abarbeiten der Bauanleitung sichtbar (siehe Abb. 2). Bei (Metzger et al. 2018) werden Sprachbefehle eingesetzt, um durch den impliziten Workflow zu navigieren. Im Kontrast dazu werden in einer *Impliziten Workflow-Aufgabe* immer alle Inhalte gleichzeitig präsentiert. Bspw. werden bei Ferrari et al. (2016) während einer chirurgischen Workflow-Aufgabe immer alle medizinische Instrumente visualisiert. Ein modellierter Workflow beschreibt die Struktur der synthetischen Inhalte in einer formalisierten Notation, z. B. Petri-Netze oder XML-Schemata (Neges et al. 2015). In diesem Fall verwendet das ARS einen *Modellierten Workflow & Implizite Workflow-Engine*, die das Modell interpretiert und die Darstellung der entsprechenden synthetischen Inhalte steuert (Neges et al. 2015). Allerdings wurde in keinem der untersuchten 142 ARS eine Workflow-Engine oder ein WfMS explizit erwähnt.

Die **Dimension "Workflow-Management"** beschreibt die Möglichkeiten des Benutzers, Workflow-Instanzen zu steuern und zu verwalten. Diese Dimension orientiert sich am Interface 5 „Administration & Monitoring Tools“ sowie Interface 2 „Workflow Client Applications“ des WfMS Referenzmodels der Workflow Management Coalition (1995). Das Interface 1 „Process Definition Tools“ ordnen wir in die nachfolgende Dimension ein. Die meisten analysierten ARS bieten *keine* Möglichkeit für das Workflow-Management an. Einige ARS erlauben dem Benutzer eine gezielte *Workflow-Instanziierung* (Chicaiza et al. 2018), die *Navigation Zur Nächsten Oder Vorherigen Workflow-Aufgabe* (Berkemeier et al. 2019) oder einen *Workflow-Abbruch* der laufenden Instanz (Chicaiza et al. 2018), z. B. über ein visuelles Menü. Wenn der Workflow verzweigt ist, können einige ARS basierend auf den Eingaben des Benutzers den *Workflow-Pfad Ändern* (Neges et al. 2015). Einige ARS können mehrere aktive Aufgaben verwalten und dem Benutzer eine *Workflow-Aufgaben-Übersicht* bereitstellen, d.h. laufende und/oder zugewiesene Aufgaben anzeigen (Evans et al. 2017). Mit manchen ARS kann ein Nutzer die *Workflow-Aufgaben wechseln*, d.h. eine Aufgabe aus einer anderen Workflow-Instanz auszuführen (Evans et al. 2017).

Die **Dimension "Workflow-Aufgaben-Unterstützung"** gibt an, wie synthetische Inhalte den Benutzer bei der Workflow-Ausführung unterstützen. Mittels *Prozess-Präskription* kann die nächste, beste Aufgabe ausgewählt werden, welche die Ziele des Workflows realisiert. Dies erfordert eine komplexe Verarbeitung des relevanten Kontextes, um auf die nächstbeste Aufgabe zu schließen, was normalerweise eine Form der Prozessvorhersage und/oder Prozesssimulation beinhaltet (Gröger et al. 2014). In Makris et al. (2013) beispielsweise unterstützt ein ARS einen Maschinen-Demontage-Workflow, indem es die möglichen Bewegungen von Teilen simuliert und dann das nächstbeste zu entfernende Teil anhand der Anzahl der möglichen Bewegungen auswählt und anschließend visualisiert.

Eine passive Workflow-Führung wird durch die *Visualisierung von nicht sichtbaren realen Objekten* bereitgestellt, z. B. bei visuell verdeckten, aber magnetisch verfolgten medizinische Instrumente während einer Operation (Ferrari et al. 2016). Auch *Echtzeitdaten* können Orientierung bieten, z. B. Daten von Handmessgeräten oder Datenbankabfragen (Liebmann et al. 2019). Solche Daten können auch die Ergebnisse einer *automatischen Abweichungserkennung* darstellen, die erkennt, ob eine Aufgabe im Arbeitsablauf falsch ausgeführt wird, noch nicht abgeschlossen ist oder fehlerhaft abgeschlossen wurde. Dies ist beispielsweise bei Liu et al. (2018) umgesetzt.

Eine aktivere Führung erfolgt durch *Anweisungen*, die dem Benutzer signalisieren, was zu tun ist und eine visuelle Anleitung zur Durchführung einer Aufgabe oder eines Handgriffs beinhalten kann (Berkemeier et al. 2019). In einer *Demonstration* ist diese Anleitung kontextspezifisch und animiert, z. B. zeigt sie, wo ein Schraubenschlüssel angesetzt und wie er gedreht werden muss, um eine bestimmte Schraube einzuschrauben (Fiorentino 2014).

Ähnlich kontextspezifisch in Bezug auf den realen Standort eines ARS ist das dynamische *Routing* eines Benutzers zu einem bestimmten Ort (Dünser et al. 2012).

Für kollaborative Formen der Führung von Arbeitsabläufen können Experten per *Telefon* (Berkemeier et al. 2019) oder *Fernunterstützung* hinzugezogen werden, welche die Videotelefonie erweitert, indem sie gleichzeitig Zugriff auf das Sichtfeld des Benutzers gewährt und es den entfernten Experten ermöglicht, anleitende synthetische Inhalte zu erstellen, z. B. Annotationen im Sichtfeld des Benutzers zu zeichnen (Limbu et al. 2019).

Ein ARS kann neue AR-basierte Wege zur Ausführung von Workflow-Aufgaben ermöglichen. *Teleoperation* ermöglicht die AR-gestützte Programmierung, Steuerung und allgemeine Interaktion mit Maschinen oder Robotern (Andersen et al. 2016).

Die Sensordaten des ARS während einer Workflow-Aufgabe können als *Dokumentation* aufgezeichnet werden, z. B. in Form von Videos des Sichtfeldes des Benutzers (Chicaiza et al. 2018). Über die Verwendung von Navigations- und Verwaltungsmenüs hinaus kann der Benutzer eine manuelle *Dateneingabe* über Texteingabe, Spracherkennung oder Multiple-Choice-Auswahl vornehmen (Neges et al. 2015). Eine Variante davon ist ein *Datenscan*, bei dem der Benutzer die Sensoren des ARS auf eine bestimmte Art und Weise ansteuert, um bestimmte Daten zu erfassen, z. B. durch das Scannen eines Barcodes (Feng et al. 2014).

Die *Prozessmodellierung* umfasst eine Menge spezieller synthetischer Inhalte und Funktionen, um einen Arbeitsablauf oder Prozess in einem formalen Modell zu dokumentieren, z. B. in der Notation der Ereignisgesteuerten Prozesskette (EPK) (Metzger et al. 2018).

In ähnlicher Weise beschreibt die *synthetische Objektmodellierung* das Modellieren, Konstruieren, Stapeln, Montieren, etc. von synthetischen Objekten, beispielsweise während eines Computer-Aided-Design (CAD)-Workflows (Arroyave-Tobón et al. 2015).

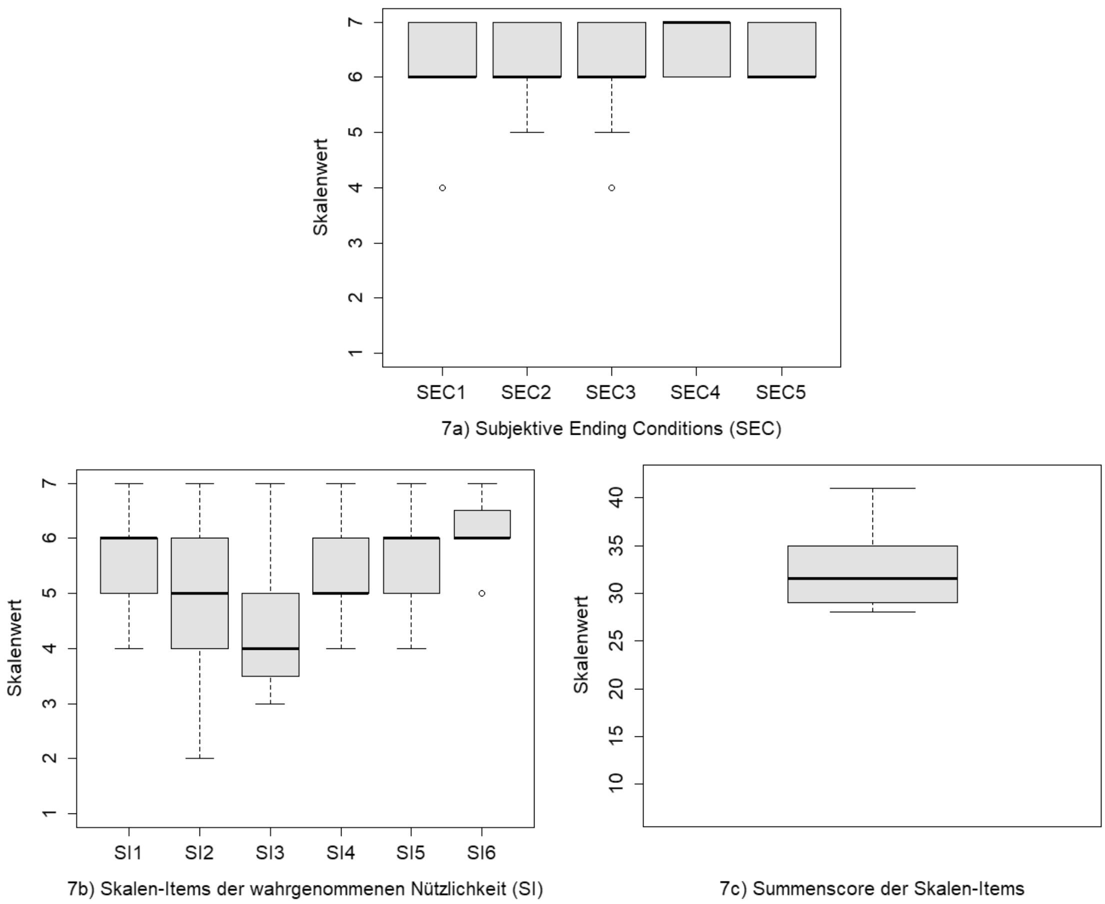
Alle unterstützenden synthetischen Inhalte, die sich nicht genauer in die oben genannten Merkmale einordnen lassen, werden als *Hilfsinformationen* bezeichnet, z. B. das Hervorheben interessanter realer Objekte (Evans et al. 2017). Während schließlich jede Workflow-Ausführung als Trainingsinstrument dienen kann und viele ARS in Demonstrationsszenarien entwickelt und getestet werden, bezieht sich das *Workflow-Training* auf spezielle Arten von synthetischen Inhalten und Funktionen, die das Training explizit erleichtern sollen oder explizit für Trainingsszenarien entwickelt werden, z. B. wenn der Benutzer eine Trainingsaufgabe wiederholen muss, bis eine bestimmte Ausführungsgeschwindigkeit erreicht ist, oder wenn ein Workflow auf einem virtuellen Trainingsobjekt ausgeführt wird (Lahanas et al. 2015).

5 Evaluation der Taxonomie

Unsere Evaluationsstrategie umfasst insgesamt drei Schritte: 1) eine Ex-ante-Evaluation der OEC, 2) eine Ex-post-Evaluation der SEC und 3) eine summative Evaluation der wahrgenommenen Nützlichkeit unserer Taxonomie.
In Anlehnung an Pries-Heje et al. (2008) wurde die Ex-ante-Evaluation der OEC bereits im Rahmen der zwei Iterationen unseres Taxonomie-Entwicklungsprozesses durchgeführt. Zusätzlich heben Nickerson et al. (2013) auch die Bedeutung der SEC besonders hervor (vgl. Abschnitt 2). Um eine sinnvolle Beurteilung dieser Aspekte zu ermöglichen und um darüber hinaus eine summative Bewertung der wahrgenommenen Nützlichkeit unserer Taxonomie zu realisieren, haben wir eine Expertenbefragung durchgeführt. Die Bewertung der wahrgenommenen Nützlichkeit wird von Nickerson et al. (2013) auch direkt für summative Evaluationen von Taxonomien empfohlen

und ist in diesem Kontext eines der am häufigsten verwendeten Evaluationskriterien (Nickerson et al. 2013; Szopinski et al. 2019). Da die wahrgenommene Nützlichkeit ein nicht direkt messbares Konstrukt ist, haben wir für die summative Evaluation auf die sechs bekannten Skalen-Items (si) von Davis (1989) zurückgegriffen: Schnelligkeit (SI1), Performanz (SI2), Produktivität (SI3), Effektivität (SI4), Einfachheit (SI5), und Gesamtnutzen (SI6). Wir haben sowohl die SEC als auch die SI für unseren Anwendungskontext spezifiziert, d.h. für eine Taxonomie von ARS zur Unterstützung der Workflow-Ausführung (SEC) und für die Anwendung der Taxonomie zur Aufgabenbewältigung (SI), z.B. zur Auswahl von ARS.

Der initial erstellte Fragebogen enthielt einen einleitenden Text über das Forschungsprojekt, die Taxonomie selbst, eine kurze Erläuterung jeder Dimension und Charakteristik sowie zugehörige Fragen/Aussagen zu den SEC und SI. Für die Datenerhebung verwendeten wir intervallskalierte verbal-numerische 7-Punkt-Likert-Skalen (1=Stimme gar nicht zu, ..., 7=Stimme stark zu). In einem Pretest stellten wir den initialen Fragebogen fünf erfahrenen Testpersonen zur Verfügung und erhielten die Rückmeldung, dass zusätzliche Informationen zur Taxonomie und zum Nutzungskontext für die Beantwortung hilfreich sein könnten. Daher ergänzten wir den Fragebogen mit kurzen Beispielen und einem umfangreichen Handout zur Erklärung der Taxonomie. Zur Nachvollziehbarkeit ist der endgültige Fragebogen in Anhang B enthalten.



Legende. SEC1 = Prägnanz, SEC2 = Robustheit, SEC3 = Vollständigkeit, SEC4 = Erweiterbarkeit, SEC5 = Erklärkraft, SI1 = Schnelligkeit, SI2 = Performanz, SI3 =Produktivität, SI4 = Effektivität, SI5 = Einfachheit, SI6 = Gesamtnutzen.

Abb. 7 Boxplots der Evaluationsergebnisse.

Bei der Wahl der Stichprobengröße haben wir uns an der sogenannten "10±2-Regel" (Hwang und Salvendy 2010) orientiert, die besagt, dass 8 bis 12 Befragte für Evaluationen der Nützlichkeit ausreichend sind. Ausgehend von einer erwarteten Rücklaufquote von 50% haben wir den Fragebogen an insgesamt 24 Experten verschickt und 11 ausgefüllte Fragebögen zurückerhalten (tatsächliche Rücklaufquote: 46%). Zu den Befragten gehörten ein

Senior Manager, ein IT-Projektmanager, ein AR-Ingenieur, ein Software & Solution Engineer, ein Multimedia-Designer, ein Softwareentwickler, zwei Forschungsleiter und drei wissenschaftliche Mitarbeiter, die sich in Praxis bzw. Forschung alle mit ARS und Workflows befassen. Von den Experten arbeiten 6 in großen, 3 in mittleren und 2 in Kleinstunternehmen/Organisationen.

Die Abb. 7 zeigt die Ergebnisse der Expertenbefragung in Form von Boxplots, wobei die Bewertungsergebnisse der SEC in Abb. 7a) dargestellt sind (Abb. 7, oben). Der zugrundeliegende Datensatz ist in Anhang C zu finden. Der Median (m) der Ergebnisse für SEC1, SEC2, SEC3 und SEC5 ist jeweils m=6, der Median der Ergebnisse für SEC4 ist sogar m=7. Bei der Auswertung von SEC1 und SEC3 zeigen sich Ausreißer mit dem Wert 4 (teilweise Übereinstimmung). Die Gesamtergebnisse zeigen jedoch ein sehr hohes Maß an Zustimmung, was darauf hindeutet, dass die subjektiven Endbedingungen als erfüllt angesehen werden können. Folglich kann unsere Taxonomie als prägnant, robust, vollständig, erweiterbar und erklärend angesehen werden.

Bezüglich der Skalen-Items (Abb. 7b) erhielten wir hohe Zustimmungen für SI1, SI5 und SI6, jeweils mit einem Median von m=6. Der Median von SI4 liegt bei m=5, wobei die Abstimmungsergebnisse zwischen 4 (teilweise Zustimmung) und 7 (starke Zustimmung) schwanken. Der Median von SI2 liegt ebenfalls bei m=5 und damit über dem Skalenwert der teilweisen Zustimmung, zeigt aber eine größere Schwankung auf als SI4 (Skalenwerte 2 bis 7). Dies kommt dadurch zustande, dass zwei Befragte unterhalb des Skalenwertes der teilweisen Zustimmung abgestimmt haben. Der Median von SI3 liegt bei m=4 (teilweise Zustimmung). Auch hier schwanken die Abstimmungsergebnisse recht stark zwischen den Skalenwerten 3 und 7. Betrachtet man nur die Mediane, so zeigen SI1, SI2, SI4, SI5 und SI6 eine Bewertung oberhalb der teilweisen Zustimmung. Insbesondere die hohe Bewertung von SI6 (Gesamtnutzen) mit m=6 kann als Bestätigung für die allgemeine Nützlichkeit der Taxonomie angesehen werden. Diese Interpretation wird auch durch den Boxplot der Summenscores der wahrgenommenen Nützlichkeit gestützt, ermittelt aus der Summe der Skalen-Items der Fragebogen-Rückmeldungen (Abb. 7c). Hier liegt auf einer Skala von 7-42 der Mittelwert bei 32,5 und der Median bei 31,5.

Aufgrund der großen Schwankungen in den Abstimmungsergebnissen für SI2 und SI3 haben wir die Experten erneut kontaktiert und ihnen die Möglichkeit geboten, Ergebnisse unterhalb des Skalenwertes von 4 zu begründen, mit dem Ziel, mögliche Anpassungspotenziale für unsere Taxonomie abzuleiten. Drei Teilnehmer antworteten auf diese Folgefrage. Anhand der Antworten zeigte sich, dass der Einsatz von Taxonomien in der Praxis bisher kaum verbreitet ist, weshalb es für Praktiker insbesondere schwierig ist, deren Auswirkungen auf die Arbeitsleistung (si2) und Produktivität (si3) zu beurteilen. Unserer Meinung nach schränkt dieses Feedback die Nützlichkeit unserer Taxonomie insgesamt jedoch nicht ein. Dennoch wollen wir das wertvolle Feedback in zukünftiger Forschung nutzen, um einen engeren Transfer zwischen Wissenschaft und Praxis herzustellen, z. B. im Rahmen von sinnvollen Anwendungsfällen unserer Taxonomie.

6 Anwendung der Taxonomie

Um das Feedback der Evaluationsteilnehmer im vorherigen Kapitel aufgreifen möchten wir nun die Anwendbarkeit unserer Taxonomie demonstrieren. Einerseits kann die Taxonomie genutzt werden, um bestehende ARS zu kategorisieren. Dies haben wir exemplarisch für die in Kapitel 2 eingeführten Beispiele während der Erläuterung der Taxonomie in Kapitel 4 durchgeführt. Die Einordnung von ARS in die Taxonomie erlaubt es einerseits, ein ARS wirkungsvoll mit einem bekannten Vokabular zu beschreiben und macht es somit einfacher, dieses zu verstehen und darüber zu kommunizieren, bspw. im Zuge wissenschaftlicher Debatten. Ebenfalls haben wir die, in der strukturierten Literaturrecherche identifizierten, 142 ARS in die Taxonomie eingeordnet. Die Betrachtung der aggregierten Klassifizierungen ermöglicht einen wirkungsvollen Überblick über den aktuellen Forschungsstand und erleichtert die Analyse. Die Häufigkeit und Korrelation des Auftretens von Charakteristika ermöglicht die einfachere Identifikation von Trends, Best Practices und Forschungslücken innerhalb der Schnittmenge von AR, Workflows und WfMS.

Um dies zu demonstrieren, diskutieren wir im Folgenden zwei exemplarische Erkenntnisse aus der Analyse der 142 in die Taxonomie eingeordneten ARS. Erstens zeigt sich, dass sich die meisten der analysierten ARS auf spezifische Anwendungsszenarien konzentrieren und nur einen begrenzten, spezialisierten Funktionsumfang bieten. Wir halten es jedoch für wahrscheinlich, dass bedeutende Herausforderungen, Forschungsansätze und -fragen, bspw. in Bezug auf Designwissen, Software-Architektur und User Experience, identifiziert werden könnten, wenn viele verschiedene Unterstützungsfunktionen integriert und mehrere Anwendungsszenarien mit einem einzigen ARS adressiert werden würden. Die zweite Erkenntnis ist, dass es eine Gelegenheit zu geben scheint, Konzepte aus dem Workflow-Management systematisch mit der AR-Forschung zu integrieren. Einerseits ist festzustellen, dass 10 der analysierten ARS eine formale Modellierung für die logische Struktur der AR-Inhalte nutzen und somit implizit auch eine Workflow-Engine, um diese zu interpretieren. Zusätzlich unterstützten viele ARS bereits einige Workflow-Management-Funktionen, wie die Auswertung dieser Dimension zeigt (vgl. Abb. 6). In Bezug auf die Workflow-Aufgaben-Unterstützung ist festzustellen, dass eine Vielzahl von Ansätzen existieren und insbesondere auch Ansätze, welche aus dem Workflow-Management bekannt sind, bspw. die Änderung des Workflow-Pfads aufgrund von Kontextinformationen oder die Empfehlung des nächstbesten Prozessschrittes (Prozess-Präskription). Andererseits jedoch verwendet kein ARS eine Standardmodellierungssprache wie bspw. den de facto Standard Business Process Model and Notation (BPMN) und in keiner ARS-Beschreibung wurde explizit eine Workflow-Engine oder ein WfMS zur Verarbeitung dieser Workflow-Modelle erwähnt. Die aus dem WfMS Referenzmodell der Workflow Management Coalition (1995) bekannten Workflow-Management Funktionen werden von keinem ARS vollständig adressiert und Workflow-Aufgaben-Unterstützungen, welche auf formalen Workflow-Modellen basieren, werden von nur wenigen ARS angeobten. Insgesamt sind im State-of-the-Art also bereits viele Ansätze und Konzepte aus der Workflow-Management-Domäne vorhanden, eine systematische Integration mit der AR-Domäne ist bislang jedoch nicht erfolgt. Es scheint somit eine Gelegenheit für eine solche Integration zu geben, bspw. konzeptionell zur Verbindung von Referenzarchitekturen oder gestalterisch zur Schaffung von Designwissens über ARS.

Um Forschungslücken zu adressieren kann die Taxonomie auch genutzt werden, um in einer strukturierten Weise neue ARS zu entwerfen. Dies haben wir im Rahmen unserer eigenen Forschung für zwei ARS bereits umgesetzt.

Erstens haben wir so das ARS für das laufende BMBF-Verbundprojekt Augmented Living Spaces (ALiS) entworfen, welches mittels AR-Inhalten zum Erhalt der Selbstständigkeit kognitiv eingeschränkter Menschen in ihren eigenen Wohnräumen beitragen soll. Dieses ARS basiert auf spatialer AR, sodass die Nutzer keine Geräte tragen müssen, um die AR-Inhalte zu nutzen (Bimber und Raskar 2005). Stattdessen werden visuelle und akustische Inhalte mit Projektoren und Lautsprechern wiedergegeben. Es adressiert somit die relative Unterrepräsentation der spatialen AR in den 142 analysierten ARS, von welchen lediglich 15 Projektoren und 3 stationäre Lautsprecher nutzen. In Kombination mit Eye-Tracking (6), Erkennung von Körperhaltungen (4) und allgemeiner Positionsverfolgung, z. B. über RFID (3), wollen wir eine nahtlose und dennoch individuelle Unterstützung für Benutzer an vordefinierten Orten erzeugen. Es soll Echtzeitdaten (17) von Umgebungssensoren nutzen, um dann bspw. animierte (23) und akustische (14) Warnhinweise zu geben, z.B. bei heißen Herdplatten. Routing-Funktionen (6) könnten zu verlorenen Gegenständen oder bestimmten Räumen führen. Diese verschiedenen AR-Unterstützungsfunktionen werden als Workflows modelliert und mittels des WfMS Camunda ausgeführt, welches die übrigen Sensoren, Datenspeicher, Datenverarbeitung und Ausgabegeräte integriert. Die Unterstützungsworkflows werden in einem, in Entwicklung befindlichen Erweiterungsdialekt der BPMN modelliert, welche speziell die Anforderungen von ARS adressieren. Die Nutzung eines WFMS ermöglicht die schnelle Modellierung und Implementierung in einer Standardnotation, die einfache Integration verschiedener Systeme (bspw. Unity für AR; NodeRED für Sensoren) sowie auch das effektive Management der Workflows. Zudem können die Workflow-Logs mit Standardwerkzeugen analysiert werden.

Zweitens läuft an der Professur für Wirtschaftsinformatik, insb. Betriebliches Informationsmanagement der Martin-Luther-Universität Halle-Wittenberg das Forschungsprojekt HoloWFM, welches die Lücke bezüglich WfMS-Management-Funktionalitäten in den 142 analysierten ARS adressiert. Das so entstehende ARS wird gemäß dem bekannten WfMS Referenzmodell der Workflow Management Coalition (1995) alle WfMS Front End-Funktionen, im Sinne einer Workflow Client Application implementieren und damit die Dimension „Workflow-Management" der Taxonomie erweitern. Dieses ARS solle den Nutzern ermöglichen effektiv, effizient und benutzerfreundlich mit einem WfMS zu interagieren und gleichzeitig von anderen AR-basierten Funktionen zur Unterstützung der Workflow-Ausführung zu profitieren, wodurch zusätzliche Geräte überflüssig würden und Medienbrüche vermieden werden können. Während das Forschungsprojekt auf die Schaffung von Designwissen angelegt ist, wird ein HoloWFM-Prototyp die API des WfMS Camunda nutzen, um die Funktionalität des AR-Front Ends zu demonstrieren und das Gesamtprojekt zu evaluieren.

7 Zusammenfassung und Ausblick

In diesem Beitrag wurde eine Taxonomie zur Charakterisierung von ARS vorgestellt, welche die Workflow-Ausführung unterstützen. Durch eine strukturierte Literaturrecherche wurden 142 relevante ARS identifiziert und aus deren Eigenschaften eine Taxonomie bestehend aus 14 Dimensionen und 83 Charakteristiken abgeleitet. Die Taxonomie wurde abschließend mit einer Bewertung der wahrgenommenen Nützlichkeit (Davis 1989) positiv evaluiert. Zwei mit der Taxonomie entwickelte ARS wurden als Beispiele für die Anwendbarkeit vorgestellt.

Für eine adäquate Interpretation der Ergebnisse sollten die folgenden Limitationen berücksichtigt werden. Erstens basierte die Taxonomie auf einer strukturierten Literaturrecherche und umfasste nur Charakteristiken, die in den analysierten ARS identifiziert wurden. Zweitens ist eine inhärente Schwäche jeder Taxonomie-Entwicklung die Subjektivität der zugrundeliegenden Designentscheidungen. Wie der Vergleich mit verwandten Beiträgen gezeigt hat, sind andere Einteilungen der Charakteristiken möglich (Kalawsky et al. 2000; Klinker et al. 2018; Milgram und Kishino 1994; Wang et al. 2013). Die getroffenen Designentscheidungen werden jedoch durch die evaluierten objektiven und subjektiven Endbedingungen von Nickerson et al. (2013) und die Evaluation unserer Taxonomie mit Experten untermauert. Drittens waren die Beschreibungen der analysierten ARS im Kontext der Taxonomie oft schwer zu interpretieren, wodurch einige ARS falsch klassifiziert sein können.

Eine Taxonomie basiert auf den aktuell existierenden Objekten. Die hier vorgestellte Taxonomie thematisiert mit Augmented Reality und Workflow-Management-Systemen zwei sich schnell entwickelnde Technologien. Somit wird diese Taxonomie höchstwahrscheinlich in Zukunft angepasst werden müssen, um die technologischen Fortschritte zu reflektieren. Für Augmented Reality könnten dies neue sensorische Kanäle für die Ein- und Ausgabe sein, welche teilweise bereits in der Literatur identifiziert, jedoch in den untersuchten ARS nicht festgestellt wurden. Für das Management von Workflows ist es wahrscheinlich, dass neue ARS sich dem, in der bekannten Referenzarchitektur der Workflow Management Coalition postulierten, Interaktionsspektrum annähern. Die Workflow-Aufgaben-Unterstützung könnte besonders durch neue Entwicklung im Maschinellen Lernen profitieren. Zuletzt wird auch der weitere Praxiseinsatz Erkenntnisse generieren, die in einer Weiterentwicklung der Taxonomie einfließen könnten.

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Appendix C: Appendix of the article "Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung – Entwicklung und praktische Anwendung einer Taxonomie"

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Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung - Entwicklung und praktische Anwendung einer Taxonomie

Appendix

Anhang A: Konzeptmatrix

* = Dimensionen mit gegenseitig ausschließenden Charakteristiken

	Dimension	Charakteristik	Augmented Reality-Systeme												
			[1]	[2, 3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11–13]	[14]	[15]	[16]
Gerät	Typ	Körpergetragene Geräte													
		Kopfgetragene Geräte	X		X	X	X	X	X			X	X	X	X
		Einhandgeräte	X	X					X	X	X				
		Zweihandgeräte							X						
		Stationäre Geräte			X							X			X
	Architektur	Einzelgerät				X	X		X	X	X	X		X	X
		Verbundene Geräte	X	X	X			X							X
		Integrierte Geräte										X	X		
	Nutzersystem	Einzelbenutzer	X		X		X	X		X	X	X	X		X
		Mehrbenutzer				X			X			X		X	
	Ausgabe	Projektor										X			
		Transparenter Bildschirm	X		X	X	X		X			X	X	X	X
		Videomonitor		X				X	X	X	X				
		Stationäre Lautsprecher													
		Mobile Lautsprecher	X			X	X	X	X	X				X	
		Haptisch													
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele	X	X	X	X			X		X	X			X
		Visuelle Merkmalbasierte Objektverfolgung			X					X				X	
		Räumliche Karte													
		Vernetzte Externe Optische Sensoren													X
		Trägheit und Orientierung			X				X					X	
		GPS					X	X							
		RFID							X						
		Keine											X		
	Objekt-positions-verfolgung	Visuell Markerbasiert	X			X			X		X	X			
		Visuell Merkmalsbasiert		X	X					X		X	X	X	X
		Vernetzte Externe Optische Sensoren													
		GPS													
		RFID							X						
		Magnetisch													
		Keine					X	X							
	Benutzer-interaktions-verfolgung	Handgesten										X	X		
		Augenverfolgung	X												
		Körperhaltung													
		Mechanisch & Berührung							X	X	X	X			
		Sprache	X				X	X	X				X		
		Zeiger													
		Keine		X	X	X								X	X
Synthetic Content	Repräsentation	Text	X			X	X	X	X	X		X		X	X
		Bild	X			X	X	X	X	X		X		X	X
		Video								X			X	X	
		2D Form	X			X		X	X	X		X		X	X
		3D Form		X	X	X			X		X		X		X
		Animation		X		X					X	X	X		
		Akustik	X			X	X	X							
		Haptisch													
	Visuelle Ausrichtung	Fixiert					X	X					X		
		Nähe	X						X	X	X	X		X	X
		Nicht-transparente Überlagerung	X	X					X	X					
		Transparente Überlagerung			X	X			X						
	Benutzer-interaktion	Keine	X	X	X	X	X	X	X	X				X	X
		Selektion										X	X		
		Manipulation									X		X		
	Inhalts-steuerung	Manuell													
		Automatisch		X	X								X	X	
		Hybrid	X			X	X	X	X	X	X	X			X
Workflow	Workflow-Verarbeitung*	Implizite Workflow-Aufgabe			X						X				
		Impliziter Workflow	X	X		X	X		X	X		X	X	X	X
		Modellierter Workflow & Implizite Workflow-Engine						X							
	Workflow-Management	Keine	X	X	X	X	X		X		X		X	X	
		Workflow-Instanziierung						X		X		X			
		Navigation zur nächsten oder vorherigen Workflow-Aufgabe						X				X			X
		Workflow-Abbruch								X					
		Workflow-Pfad ändern						X							
		Workflow-Aufgaben-Übersicht													
		Workflow-Aufgabe wechseln													
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription													
		Nicht-sichtbare reale Objekte visualisieren							X						
		Echtzeitdaten				X	X		X			X			
		Autoamtische Abweichungserkennung							X						X
		Anweisung					X	X	X			X			X
		Demonstration													
		Routing					X								
		Telefonie					X								
		Fernunterstützung				X			X					X	
		Teleoperation											X		
		Dokumentation						X	X	X					
		Dateneingabe						X							
		Datenscan					X	X							
		Prozessmodellierung													
		Synthetische Objektmodellierung													
		Hilfsinformation	X	X	X	X	X	X	X	X	X	X		X	X
		Workflow-Training													

Dimension		Charakteristik	Augmented Reality-Systeme												
			[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	[25]	[26]	[27]	[28, 29]	[30]
Gerät	Typ	Körpergetragene Geräte													
		Kopfgetragene Geräte			X		X		X			X	X		X
		Einhandgeräte		X		X									
		Zweihandgeräte						X	X						
		Stationäre Geräte	X							X	X				
	Architektur	Einzelgerät		X	X	X	X		X			X		X	
		Verbundene Geräte	X					X		X			X		X
		Integrierte Geräte									X				
	Nutzersystem	Einzelbenutzer			X	X	X		X	X		X	X		X
		Mehrbenutzer	X	X							X			X	
	Ausgabe	Projektor	X												
		Transparenter Bildschirm			X		X		X			X	X	X	X
		Videomonitor		X		X		X	X	X	X				
		Stationäre Lautsprecher	X												
		Mobile Lautsprecher		X										X	
		Haptisch												X	
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele					X			X	X		X	X	X
		Visuelle Merkmalbasierte Objektverfolgung		X				X							
		Räumliche Karte			X	X			X			X	X	X	
		Vernetzte Externe Optische Sensoren													
		Trägheit und Orientierung										X	X	X	
		GPS													
		RFID													
		Keine	X												
	Objekt-positions-verfolgung	Visuell Markerbasiert	X							X	X		X	X	X
		Visuell Merkmalsbasiert		X		X	X	X				X	X	X	
		Vernetzte Externe Optische Sensoren													
		GPS													
		RFID													
		Magnetisch									X				
		Keine			X				X						
	Benutzer-interaktions-verfolgung	Handgesten					X					X		X	
		Augenverfolgung					X							X	
		Körperhaltung													
		Mechanisch & Berührung	X			X			X	X	X		X		
		Sprache					X		X						
		Zeiger													
		Keine		X	X			X							X
Synthetic Content	Repräsentation	Text	X			X	X		X			X	X	X	
		Bild	X		X			X		X		X		X	
		Video			X			X						X	
		2D Form	X	X			X	X				X	X	X	X
		3D Form	X			X		X	X		X	X	X	X	X
		Animation									X			X	
		Akustik	X				X							X	
		Haptisch												X	
	Visuelle Ausrichtung	Fixiert						X	X			X		X	
		Nähe	X	X	X	X			X		X	X	X	X	X
		Nicht-transparente Überlagerung						X		X			X	X	X
		Transparente Überlagerung						X						X	
	Benutzer-interaktion	Keine	X	X	X	X		X		X					X
		Selektion					X		X			X		X	
		Manipulation									X		X	X	
	Inhalts-steuerung	Manuell							X						
		Automatisch		X	X			X		X					
		Hybrid	X			X	X				X	X	X	X	X
Workflow	Workflow-Verarbeitung*	Implizite Workflow-Aufgabe			X			X					X		
		Impliziter Workflow	X	X		X	X		X	X	X	X		X	X
		Modellierter Workflow & Implizite Workflow-Engine													
	Workflow-Management	Keine		X	X	X	X	X	X	X	X		X		X
		Workflow-Instanziierung							X			X		X	
		Navigation zur nächsten oder vorherigen Workflow-Aufgabe	X									X		X	
		Workflow-Abbruch													
		Workflow-Pfad ändern													
		Workflow-Aufgaben-Übersicht												X	
		Workflow-Aufgabe wechseln													
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription													
		Nicht-sichtbare reale Objekte visualisieren						X							
		Echtzeitdaten			X	X		X				X	X		
		Autoamtische Abweichungserkennung									X		X		X
		Anweisung	X	X			X	X	X	X				X	
		Demonstration	X											X	
		Routing										X			
		Telefonie													
		Fernunterstützung		X										X	
		Teleoperation								X					
		Dokumentation							X					X	
		Dateneingabe							X			X			
		Datenscan													
		Prozessmodellierung													
		Synthetische Objektmodellierung													
		Hilfsinformation	X		X	X	X	X	X	X	X	X	X	X	X
		Workflow-Training									X				

Dimension		Charakteristik	Augmented Reality-Systeme												
			[31]	[32]	[33]	[34]	[35]	[36]	[37]	[38, 39]	[40, 41]	[42, 43]	[44]	[45]	[46]
Gerät	Typ	Körpergetragene Geräte	X		X										
		Kopfgetragene Geräte	X	X	X		X	X	X	X	X	X	X	X	
		Einhandgeräte			X			X							X
		Zweihandgeräte				X				X					
		Stationäre Geräte								X					
	Architektur	Einzelgerät		X	X	X	X	X	X	X	X		X		X
		Verbundene Geräte	X							X		X			
		Integrierte Geräte								X				X	
	Nutzersystem	Einzelbenutzer	X	X	X	X	X	X	X	X	X	X	X	X	X
		Mehrbenutzer													
	Ausgabe	Projektor													
		Transparenter Bildschirm	X	X	X			X	X	X	X	X	X		
		Videomonitor			X	X	X	X						X	X
		Stationäre Lautsprecher													
		Mobile Lautsprecher											X		
		Haptisch													
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele	X		X			X	X		X		X	X	
		Visuelle Merkmalbasierte Objektverfolgung							X	X					
		Räumliche Karte							X			X			X
		Vernetzte Externe Optische Sensoren											X		
		Trägheit und Orientierung							X	X		X	X		
		GPS													
		RFID													
		Keine		X		X	X								
	Objekt-positions-verfolgung	Visuell Markerbasiert	X		X	X		X			X	X		X	
		Visuell Merkmalsbasiert				X			X	X					X
		Vernetzte Externe Optische Sensoren													
		GPS													
		RFID													
		Magnetisch													
		Keine		X			X						X		
	Benutzer-interaktions-verfolgung	Handgesten							X	X		X			
		Augenverfolgung													
		Körperhaltung													
		Mechanisch & Berührung	X		X	X	X								X
		Sprache		X			X				X		X		
		Zeiger													
		Keine						X						X	
Synthetic Content	Repräsentation	Text	X	X	X	X			X	X	X				
		Bild	X	X		X			X	X	X		X		
		Video								X	X				
		2D Form	X		X				X	X		X	X		
		3D Form	X		X	X		X	X	X		X		X	X
		Animation	X					X							
		Akustik											X		
		Haptisch													
	Visuelle Ausrichtung	Fixiert	X	X		X					X				
		Nähe	X		X			X	X			X			X
		Nicht-transparente Überlagerung	X		X	X		X				X	X		X
		Transparente Überlagerung	X			X		X		X		X	X	X	
	Benutzer-interaktion	Keine	X		X			X		X	X		X	X	
		Selektion				X	X		X			X			X
		Manipulation		X					X						X
	Inhalts-steuerung	Manuell		X											X
		Automatisch						X					X	X	
		Hybrid	X		X	X	X		X	X	X	X			
Workflow	Workflow-Verarbeitung*	Implizite Workflow-Aufgabe													
		Impliziter Workflow	X	X			X	X	X	X	X	X	X	X	X
		Modellierter Workflow & Implizite Workflow-Engine			X	X									
	Workflow-Management	Keine						X		X	X	X	X	X	X
		Workflow-Instanziierung	X	X	X		X								
		Navigation zur nächsten oder vorherigen Workflow-Aufgabe					X		X						
		Workflow-Abbruch													
		Workflow-Pfad ändern				X									
		Workflow-Aufgaben-Übersicht	X												
		Workflow-Aufgabe wechseln			X										
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription													
		Nicht-sichtbare reale Objekte visualisieren						X				X			X
		Echtzeitdaten										X			
		Autoamtische Abweichungserkennung								X					
		Anweisung	X		X	X	X		X	X					
		Demonstration							X	X					
		Routing							X			X			
		Telefonie													
		Fernunterstützung													
		Teleoperation	X									X			
		Dokumentation			X		X		X	X	X				
		Dateneingabe			X	X	X		X						X
		Datenscan													
		Prozessmodellierung		X											
		Synthetische Objektmodellierung													
		Hilfsinformation	X		X	X	X	X	X	X	X	X	X	X	X
		Workflow-Training								X					

Dimension		Charakteristik	Augmented Reality-Systeme												
			[47]	[48, 49]	[50, 51]	[52]	[53]	[54, 55]	[56]	[57, 58]	[59]	[60]	[61]	[62]	[63]
Gerät	Typ	Körpergetragene Geräte				X	X								X
		Kopfgetragene Geräte	X		X	X		X	X	X	X		X	X	X
		Einhandgeräte												X	
		Zweihandgeräte					X					X			
		Stationäre Geräte		X	X					X	X				X
	Architektur	Einzelgerät	X		X			X	X	X		X	X		
		Verbundene Geräte		X		X	X				X			X	
		Integrierte Geräte													X
	Nutzersystem	Einzelbenutzer	X	X	X	X		X	X		X	X	x	x	
		Mehrbenutzer					X			X					x
	Ausgabe	Projektor		X							X				
		Transparenter Bildschirm	X		X			X	X	X	X		x	x	x
		Videomonitor				X	X			X	X	X			
		Stationäre Lautsprecher								X					
		Mobile Lautsprecher	X							X					x
		Haptisch				X	X								
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele		X		X	X	X	X	X			x	x	
		Visuelle Merkmalbasierte Objektverfolgung	X		X	X		X				X			
		Räumliche Karte													
		Vernetzte Externe Optische Sensoren													
		Trägheit und Orientierung	X		X									x	
		GPS													
		RFID													
		Keine									X				x
	Objekt-positions-verfolgung	Visuell Markerbasiert	X	X		X	X	X	X	X	X		x	x	
		Visuell Merkmalsbasiert			X	X						X			
		Vernetzte Externe Optische Sensoren													
		GPS													
		RFID													
		Magnetisch													
		Keine													x
	Benutzer-interaktions-verfolgung	Handgesten	X			X		X							x
		Augenverfolgung	X											x	
		Körperhaltung												x	
		Mechanisch & Berührung		X			X			X	X				
		Sprache	X					X						x	x
		Zeiger													
		Keine			X				X			X	x		x
Synthetic Content	Repräsentation	Text		X		X	X		X	X	X			x	
		Bild		X		X	X	X	X	X	X		x	x	
		Video						X							
		2D Form		X	X	X	X	X	X	X	X		x		
		3D Form			X		X	X	X	X		X	x		x
		Animation					X		X		X	X			
		Akustik													x
		Haptisch				X	X								
	Visuelle Ausrichtung	Fixiert					X	X	X		X			x	x
		Nähe	X	X	X	X	X	X	X	X	X		x		
		Nicht-transparente Überlagerung	X	X	X		X	X				X			
		Transparente Überlagerung	X		X		X	X	X		X	X			
	Benutzer-interaktion	Keine		X	X				X	X	X		x	x	x
		Selektion	X			X	X	X							
		Manipulation				X	X			X	X				
	Inhalts-steuerung	Manuell													
		Automatisch										X	x		x
		Hybrid	X	X	X	X	X	X	X	X	X			x	
Workflow	Workflow-Verarbeitung*	Implizite Workflow-Aufgabe			X								x		
		Impliziter Workflow	X	X			X	X	X	X		X		x	x
		Modellierter Workflow & Implizite Workflow-Engine				X					X				
	Workflow-Management	Keine	X	X	X				X	X	X	X	x		x
		Workflow-Instanziierung				X					X			x	
		Navigation zur nächsten oder vorherigen Workflow-Aufgabe				X		X							
		Workflow-Abbruch													
		Workflow-Pfad ändern									X				
		Workflow-Aufgaben-Übersicht													
		Workflow-Aufgabe wechseln													
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription													
		Nicht-sichtbare reale Objekte visualisieren	X		X										
		Echtzeitdaten				X									
		Autoamtische Abweichungserkennung			X	X			X						
		Anweisung		X		X	X	X	X	X	X				
		Demonstration										X			
		Routing													
		Telefonie													
		Fernunterstützung					X			X					x
		Teleoperation													
		Dokumentation					X							x	
		Dateneingabe	X					X						x	
		Datenscan													
		Prozessmodellierung													
		Synthetische Objektmodellierung													
		Hilfsinformation	X	X	X	X	X	X	X	X	X	X	x	x	x
		Workflow-Training	X				X								

Dimension		Charakteristik	[64]	[65]	[66]	[67]	[68]	[69]	[70]	[71]	[72]	[73]	[74]	[75]	[76]
			Augmented Reality-Systeme												
Gerät	Typ	Körpergetragene Geräte													
		Kopfgetragene Geräte			X				X	X	X	X			X
		Einhandgeräte		X					X					X	
		Zweihandgeräte					X		X						
		Stationäre Geräte	X	X		X		X		X			X		
	Architektur	Einzelgerät			X		X			X	X	X		X	X
		Verbundene Geräte		X		X			X						
		Integrierte Geräte	X	X				X					X		
	Nutzersystem	Einzelbenutzer	X		X	X		X			X	X		X	X
		Mehrbenutzer		X			X		X	X			X		
	Ausgabe	Projektor		X		X		X					X		
		Transparenter Bildschirm			X				X	X	X	X			X
		Videomonitor	X						X					X	
		Stationäre Lautsprecher													
		Mobile Lautsprecher									X				
		Haptisch													
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele				X	X		X		X				X
		Visuelle Merkmalbasierte Objektverfolgung	X	X	X				X	X		X			
		Räumliche Karte													
		Vernetzte Externe Optische Sensoren													
		Trägheit und Orientierung		X						X				X	X
		GPS												X	
		RFID													
		Keine						X					X		
	Objekt-positions-verfolgung	Visuell Markerbasiert				X			X		X				X
		Visuell Merkmalsbasiert	X	X	X			X	X	X		X	X		
		Vernetzte Externe Optische Sensoren													
		GPS												X	
		RFID													
		Magnetisch													
		Keine					X							X	
	Benutzer-interaktions-verfolgung	Handgesten						X		X					X
		Augenverfolgung													
		Körperhaltung													
		Mechanisch & Berührung		X					X					X	
		Sprache								X	X				
		Zeiger		X	X										
		Keine	X			X						X	X		
Synthetic Content	Repräsentation	Text					X			X	X			X	X
		Bild					X	X	X	X	X				
		Video						X							
		2D Form	X	X		X	X	X	X	X	X	X	X	X	X
		3D Form	X		X	X			X		X			X	X
		Animation											X		
		Akustik													
		Haptisch													
	Visuelle Ausrichtung	Fixiert					X	X		X				X	
		Nähe	X	X			X	X	X	X	X		X	X	X
		Nicht-transparente Überlagerung					X		X						
		Transparente Überlagerung			X	X	X	X	X		X	X	X		X
	Benutzer-interaktion	Keine	X			X						X	X		
		Selektion			X			X	X	X	X			X	X
		Manipulation		X					X						
	Inhalts-steuerung	Manuell													
		Automatisch				X						X	X		
		Hybrid	X	X	X		X	X	X	X	X			X	X
Workflow	Workflow-Verarbeitung*	Implizite Workflow-Aufgabe													
		Impliziter Workflow	X	X	X	X	X	X	X	X	X	X	X	X	X
		Modellierter Workflow & Implizite Workflow-Engine													
	Workflow-Management	Keine	X	X	X	X	X	X	X			X	X	X	
		Workflow-Instanziierung								X	X				
		Navigation zur nächsten oder vorherigen Workflow-Aufgabe									X				X
		Workflow-Abbruch													
		Workflow-Pfad ändern													
		Workflow-Aufgaben-Übersicht								X					X
		Workflow-Aufgabe wechseln													X
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription													
		Nicht-sichtbare reale Objekte visualisieren		X		X			X			X			
		Echtzeitdaten													
		Autoamtische Abweichungserkennung													
		Anweisung	X					X	X		X			X	X
		Demonstration													
		Routing												X	
		Telefonie													
		Fernunterstützung					X		X						
		Teleoperation		X											
		Dokumentation					X			X					
		Dateneingabe								X					
		Datenscan													
		Prozessmodellierung													
		Synthetische Objektmodellierung													
		Hilfsinformation	X	X	X	X		X	X	X	X	X	X	X	X
		Workflow-Training													

Dimension		Charakteristik	Augmented Reality-Systeme												
			[77–80]	[81]	[82, 83]	[84]	[85]	[86]	[87]	[88]	[89]	[90]	[91]	[92]	[93]
Gerät	Typ	Körpergetragene Geräte							X						X
		Kopfgetragene Geräte						X	X		X	X			X
		Einhandgeräte					X								X
		Zweihandgeräte			X		X						X	X	
		Stationäre Geräte	X	X		X				X					
	Architektur	Einzelgerät			X		X				X	X	X	X	
		Verbundene Geräte				X				X					X
		Integrierte Geräte	X					X	X						
	Nutzersystem	Einzelbenutzer			X		X		X		x	X	X	X	X
		Mehrbenutzer	X	X		X		X		X	X				
	Ausgabe	Projektor				X				X					
		Transparenter Bildschirm							X		X	X			
		Videomonitor	X	X	X		X	X					X	X	X
		Stationäre Lautsprecher													
		Mobile Lautsprecher									X			X	
		Haptisch													
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele	X		X		X	X		X					
		Visuelle Merkmalbasierte Objektverfolgung							X				X		
		Räumliche Karte					X		X		X				
		Vernetzte Externe Optische Sensoren						X							X
		Trägheit und Orientierung					X		X		X				
		GPS													
		RFID													
		Keine		X		X								X	
	Objekt-positions-verfolgung	Visuell Markerbasiert	X		X		X	X							
		Visuell Merkmalsbasiert				X			X				X		
		Vernetzte Externe Optische Sensoren						X							
		GPS													
		RFID													
		Magnetisch		X											
		Keine								X	X	X		X	X
	Benutzer-interaktions-verfolgung	Handgesten				X					X				
		Augenverfolgung							X						
		Körperhaltung							X						
		Mechanisch & Berührung	X		X		X							X	X
		Sprache													
		Zeiger													
		Keine		X			X	X		X		X	X		
Synthetic Content	Repräsentation	Text	X				X		X	X	X	X	X	X	X
		Bild					X		X		X	X	X	X	X
		Video												X	
		2D Form	X	X	X	X	X		X	X	X	X	X	X	X
		3D Form	X		X			X			X		X	X	X
		Animation											X	X	X
		Akustik									X				
		Haptisch													
	Visuelle Ausrichtung	Fixiert	X				X							X	X
		Nähe	X		X	X	X	X	X	X	X	X	X		X
		Nicht-transparente Überlagerung		X				X							X
		Transparente Überlagerung	X		X						X	X	X		
	Benutzer-interaktion	Keine	X	X		X	X	X	X			X	X		
		Selektion			X						X			X	X
		Manipulation			X						X				
	Inhalts-steuerung	Manuell													
		Automatisch	X	X				X				X	X	X	
		Hybrid			X	X	X		X	X	X				X
Workflow	Workflow-Verarbeitung*	Implizite Workflow-Aufgabe		X										X	
		Impliziter Workflow	X		X	X	X	X		X	X	X	X		X
		Modellierter Workflow & Implizite Workflow-Engine							X						
	Workflow-Management	Keine	X	X	X	X	X	X	X	X	X	X	X	X	X
		Workflow-Instanziierung													
		Navigation zur nächsten oder vorherigen Workflow-Aufgabe													
		Workflow-Abbruch													
		Workflow-Pfad ändern													
		Workflow-Aufgaben-Übersicht													
		Workflow-Aufgabe wechseln													
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription													
		Nicht-sichtbare reale Objekte visualisieren		X											X
		Echtzeitdaten													
		Autoamtische Abweichungserkennung													
		Anweisung				X			X	X	X	X	X		X
		Demonstration													
		Routing					X								
		Telefonie													
		Fernunterstützung								X	X				
		Teleoperation			X									X	
		Dokumentation													
		Dateneingabe													
		Datenscan													
		Prozessmodellierung													
		Synthetische Objektmodellierung													
		Hilfsinformation	X			X	X	X	X	X	X	X	X	X	X
		Workflow-Training													

Dimension		Charakteristik	Augmented Reality-Systeme												
			[94]	[95]	[96]	[97]	[98]	[99]	[100]	[101]	[102]	[103]	[104]	[105]	[106]
Gerät	Typ	Körpergetragene Geräte			x										
		Kopfgetragene Geräte						x	x		x				
		Einhandgeräte						x							
		Zweihandgeräte						x				x			
		Stationäre Geräte	x	x		x	x		x	x			x	x	x
	Architektur	Einzelgerät			x			x			x	x			
		Verbundene Geräte	x	x			x		x				x	x	
		Integrierte Geräte				x							x		x
	Nutzersystem	Einzelbenutzer		x	x	x		x	x		x	x			x
		Mehrbenutzer	x				x			x			x	x	
	Ausgabe	Projektor											x		
		Transparenter Bildschirm			x			x		x	x				x
		Videomonitor	x	x		x	x	x	x			x	x	x	
		Stationäre Lautsprecher													
		Mobile Lautsprecher										x			
		Haptisch													
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele	x	x					x		x		x	x	x
		Visuelle Merkmalbasierte Objektverfolgung					x	x				x			
		Räumliche Karte													
		Vernetzte Externe Optische Sensoren													
		Trägheit und Orientierung													
		GPS													
		RFID													
		Keine			x	x				x			x		
	Objekt-positions-verfolgung	Visuell Markerbasiert	x	x					x	x	x		x	x	x
		Visuell Merkmalsbasiert				x	x	x		x		x			
		Vernetzte Externe Optische Sensoren													
		GPS													
		RFID													
		Magnetisch													
		Keine			x										
	Benutzer-interaktions-verfolgung	Handgesten									x				
		Augenverfolgung													
		Körperhaltung													
		Mechanisch & Berührung	x	x		x									
		Sprache													
		Zeiger													
		Keine			x		x	x	x	x			x	x	x
Synthetic Content	Repräsentation	Text	x	x	x			x				x	x		
		Bild	x					x				x	x		
		Video					x						x		
		2D Form	x	x						x		x	x	x	x
		3D Form	x	x		x			x		x	x		x	x
		Animation										x			
		Akustik										x			
		Haptisch													
	Visuelle Ausrichtung	Fixiert			x					x					
		Nähe	x	x			x	x	x		x	x		x	
		Nicht-transparente Überlagerung				x									x
		Transparente Überlagerung				x									
	Benutzer-interaktion	Keine	x	x	x		x	x	x	x		x	x	x	x
		Selektion				x					x				
		Manipulation				x					x				
	Inhalts-steuerung	Manuell		x											
		Automatisch			x		x	x	x	x			x	x	x
		Hybrid	x			x					x				
Workflow	Workflow-Verarbeitung*	Implizite Workflow-Aufgabe			x		x			x					x
		Impliziter Workflow	x			x		x	x		x		x	x	
		Modellierter Workflow & Implizite Workflow-Engine		x								x			
	Workflow-Management	Keine	x		x	x	x	x		x	x		x	x	x
		Workflow-Instanziierung													
		Navigation zur nächsten oder vorherigen Workflow-Aufgabe		x											
		Workflow-Abbruch													
		Workflow-Pfad ändern							x			x			
		Workflow-Aufgaben-Übersicht													
		Workflow-Aufgabe wechseln													
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription							x						
		Nicht-sichtbare reale Objekte visualisieren					x								x
		Echtzeitdaten			x								x		
		Autoamtische Abweichungserkennung							x						
		Anweisung	x	x				x	x			x			
		Demonstration													
		Routing													
		Telefonie													
		Fernunterstützung										x			
		Teleoperation									x				
		Dokumentation													
		Dateneingabe													
		Datenscan													
		Prozessmodellierung													
		Synthetische Objektmodellierung													
		Hilfsinformation	x	x	x	x	x	x	x	x	x	x	x	x	x
		Workflow-Training		x											

Dimension		Charakteristik	Augmented Reality-Systeme												
			[107, 108]	[109]	[110]	[111]	[112, 113]	[114]	[115]	[116]	[117]	[118]	[119]	[120]	[121]
Gerät	Typ	Körpergetragene Geräte													
		Kopfgetragene Geräte		X		X						X	X	X	X
		Einhandgeräte		X			X								
		Zweihandgeräte				X				X					
		Stationäre Geräte	X	X	X	X		X	X		X				
	Architektur	Einzelgerät				X	X			X			X	X	X
		Verbundene Geräte				X			X						
		Integrierte Geräte	X	X	X			X			X	X			
	Nutzersystem	Einzelbenutzer	X	X	X	X	X		X	X	X	X	X	X	X
		Mehrbenutzer						X							
	Ausgabe	Projektor			X										
		Transparenter Bildschirm		X									X	X	X
		Videomonitor	X	X		X	X	X	X	X	X	X			
		Stationäre Lautsprecher			X										
		Mobile Lautsprecher					X								
		Haptisch							X						
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele		X	X	X	X		X			X	X	X	
		Visuelle Merkmalbasierte Objektverfolgung	X					X		X	X				
		Räumliche Karte													X
		Vernetzte Externe Optische Sensoren													
		Trägheit und Orientierung										X			X
		GPS													
		RFID													
		Keine													
	Objekt-positions-verfolgung	Visuell Markerbasiert		X	X	X	X		X			X	X	X	
		Visuell Merkmalsbasiert	X					X		X	X				X
		Vernetzte Externe Optische Sensoren													
		GPS													
		RFID													
		Magnetisch													
		Keine													
	Benutzer-interaktions-verfolgung	Handgesten										X			X
		Augenverfolgung													
		Körperhaltung													X
		Mechanisch & Berührung		X	X	X	X		X	X					
		Sprache													X
		Zeiger										X			
		Keine	X					X			X	X	X	X	
Synthetic Content	Repräsenta-tion	Text		X	X	X	X				X		X		X
		Bild		X			X						X		
		Video													
		2D Form			X	X	X	X			X			X	X
		3D Form	X	X		X	X	X	X	X	X	X		X	X
		Animation					X								X
		Akustik			X		X								
		Haptisch							X						
	Visuelle Ausrichtung	Fixiert		X		X									
		Nähe	X	X	X	X	X	X	X		X	X	X	X	X
		Nicht-transparente Überlagerung	X	X		X		X		X		X			
		Transparente Überlagerung	X	X				X		X					X
	Benutzer-interaktion	Keine	X	X	X			X			X	X	X	X	
		Selektion		X		X	X		X	X					X
		Manipulation								X					X
	Inhalts-steuerung	Manuell													
		Automatisch	X					X			X			X	
		Hybrid		X	X	X	X		X	X					X
Workflow	Workflow-Verarbeitung*	Implizite Workflow-Aufgabe						X						X	
		Impliziter Workflow		X		X	X		X	X	X	X	X		X
		Modellierter Workflow & Implizite Workflow-Engine	X		X										
	Workflow-Management	Keine		X	X	X		X	X	X	X	X	X	X	X
		Workflow-Instanziierung													
		Navigation zur nächsten oder vorherigen Workflow-Aufgabe													
		Workflow-Abbruch													
		Workflow-Pfad ändern	X				X								
		Workflow-Aufgaben-Übersicht													
		Workflow-Aufgabe wechseln					X								
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription	X				X								
		Nicht-sichtbare reale Objekte visualisieren	X					X		X				X	
		Echtzeitdaten									X				
		Autoamtische Abweichungserkennung													
		Anweisung	X			X	X						X		
		Demonstration													
		Routing													
		Telefonie										X			
		Fernunterstützung													
		Teleoperation		X	X				X		X				X
		Dokumentation													
		Dateneingabe					X								
		Datenscan													
		Prozessmodellierung													
		Synthetische Objektmodellierung													
		Hilfsinformation	X	X	X	X	X	X	X	X	X	X	X	X	X
		Workflow-Training													

Dimension		Charakteristik	Augmented Reality-Systeme												
			[122]	[123]	[124]	[125]	[126]	[127]	[128]	[129]	[130]	[131]	[132]	[133]	[134]
Gerät	Typ	Körpergetragene Geräte												X	X
		Kopfgetragene Geräte												X	X
		Einhandgeräte										X			
		Zweihandgeräte				X		X			X	X			
		Stationäre Geräte	X	X	X		X		X	X			X		
	Architektur	Einzelgerät				X					X	X			
		Verbundene Geräte			X			X							
		Integrierte Geräte	X	X			X		X	X			X	X	X
	Nutzersystem	Einzelbenutzer	X	X		X		X				X		X	X
		Mehrbenutzer			X		X		X	X	X		X		
	Ausgabe	Projektor			X										
		Transparenter Bildschirm							X					X	X
		Videomonitor	X	X		X	X	X		X	X	X	X		
		Stationäre Lautsprecher													
		Mobile Lautsprecher													X
		Haptisch													
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele	X	X		X		X	X		X	X			
		Visuelle Merkmalbasierte Objektverfolgung				X							X	X	X
		Räumliche Karte													
		Vernetzte Externe Optische Sensoren													
		Trägheit und Orientierung												X	X
		GPS													
		RFID												X	
		Keine			X		X			X					
	Objekt-positions-verfolgung	Visuell Markerbasiert	X	X		X			X		X	X			
		Visuell Merkmalsbasiert		X		X		X					X	X	X
		Vernetzte Externe Optische Sensoren													
		GPS													
		RFID												X	
		Magnetisch								X					
		Keine			X		X								
	Benutzer-interaktions-verfolgung	Handgesten		X											
		Augenverfolgung													
		Körperhaltung													
		Mechanisch & Berührung	X	X	X	X		X			X	X		X	X
		Sprache													
		Zeiger													
		Keine					X		X	X			X		
Synthetic Content	Repräsentation	Text	X	X		X		X			X	X		X	X
		Bild	X					X				X		X	X
		Video					X								X
		2D Form	X	X	X	X		X		X	X	X	X	X	X
		3D Form	X	X		X		X	X		X	X	X	X	X
		Animation			X										
		Akustik													X
		Haptisch													
	Visuelle Ausrichtung	Fixiert	X								X	X		X	X
		Nähe	X	X		X	X	X			X	X		X	X
		Nicht-transparente Überlagerung							X	X			X		X
		Transparente Überlagerung			X				X				X		
	Benutzer-interaktion	Keine	X		X		X		X	X	X	X	X		X
		Selektion		X		X		X						X	
		Manipulation		X				X							
	Inhalts-steuerung	Manuell													
		Automatisch	X				X		X	X			X		
		Hybrid		X	X	X		X			X	X		X	X
Workflow	Workflow-Verarbeitung*	Implizite Workflow-Aufgabe					X	X	X	X			X		
		Impliziter Workflow	X	X	X	X					X	X		X	X
		Modellierter Workflow & Implizite Workflow-Engine													
	Workflow-Management	Keine	X	X			X	X	X	X	X		X		X
		Workflow-Instanziierung													
		Navigation zur nächsten oder vorherigen Workflow-Aufgabe	X		X	X						X			
		Workflow-Abbruch													
		Workflow-Pfad ändern												X	
		Workflow-Aufgaben-Übersicht													
		Workflow-Aufgabe wechseln													
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription													X
		Nicht-sichtbare reale Objekte visualisieren					X		X	X					
		Echtzeitdaten											X		
		Autoamtische Abweichungserkennung													
		Anweisung	X	X	X	X					X	X		X	X
		Demonstration													
		Routing													
		Telefonie													
		Fernunterstützung					X				X				
		Teleoperation						X							
		Dokumentation										X			
		Dateneingabe													
		Datenscan													
		Prozessmodellierung													
		Synthetische Objektmodellierung													
		Hilfsinformation	X	X	X	X	X	X	X		X	X	X	X	X
		Workflow-Training								X					X

Dimension		Charakteristik	Augmented Reality-Systeme												
			[135]	[136]	[137]	[138]	[139]	[140]	[141]	[142]	[143]	[144]	[145]	[146]	[147]
Gerät	Typ	Körpergetragene Geräte													
		Kopfgetragene Geräte		X	X	X		X			X		X		X
		Einhandgeräte													
		Zweihandgeräte	X				X								
		Stationäre Geräte							X	X		X		X	
	Architektur	Einzelgerät	X	X	X	X	X	X							X
		Verbundene Geräte									X				
		Integrierte Geräte							X	X		X	X	X	
	Nutzersystem	Einzelbenutzer	X	X	X	X	X		X	X	X		X		X
		Mehrbenutzer						X				X		X	
	Ausgabe	Projektor													
		Transparenter Bildschirm		X				X	X	X	X				X
		Videomonitor	X		X	X	X		X			X	X	X	
		Stationäre Lautsprecher													
		Mobile Lautsprecher													
		Haptisch	X												
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele	X		X			X							
		Visuelle Merkmalbasierte Objektverfolgung				X	X		X	X		X	X		X
		Räumliche Karte													
		Vernetzte Externe Optische Sensoren													
		Trägheit und Orientierung					X								
		GPS													
		RFID													
		Keine		X			X				X			X	
	Objekt-positions-verfolgung	Visuell Markerbasiert	X		X			X							
		Visuell Merkmalsbasiert			X	X	X		X	X		X	X		X
		Vernetzte Externe Optische Sensoren													
		GPS													
		RFID													
		Magnetisch												X	
		Keine		X							X				
	Benutzer-interaktions-verfolgung	Handgesten			X										
		Augenverfolgung													
		Körperhaltung													
		Mechanisch & Berührung	X		X		X		X	X			X		X
		Sprache		X											
		Zeiger													
		Keine				X		X			X	X		X	
Synthetic Content	Repräsentation	Text	X	X	X		X						X		X
		Bild	X	X			X								
		Video									X				
		2D Form		X	X	X	X	X	X			X	X	X	
		3D Form			X	X		X	X	X		X	X		X
		Animation											X		
		Akustik													
		Haptisch	X												
	Visuelle Ausrichtung	Fixiert		X							X				X
		Nähe	X			X	X	X					X		
		Nicht-transparente Überlagerung			X	X			X	X		X		X	X
		Transparente Überlagerung				X	X		X	X		X			X
	Benutzer-interaktion	Keine		X		X		X			X	X	X	X	
		Selektion	X		X		X								
		Manipulation			X				X	X					
	Inhalts-steuerung	Manuell							X	X					
		Automatisch		X		X		X			X	X		X	
		Hybrid	X		X		X						X		X
Workflow	Workflow-Verarbeitung*	Implizite Workflow-Aufgabe		X		X		X	X	X	X	X		X	
		Impliziter Workflow	X		X		X						X		X
		Modellierter Workflow & Implizite Workflow-Engine													
	Workflow-Management	Keine		X	X	X		X	X	X	X	X		X	
		Workflow-Instanziierung					X								
		Navigation zur nächsten oder vorherigen Workflow-Aufgabe	X												
		Workflow-Abbruch													
		Workflow-Pfad ändern													
		Workflow-Aufgaben-Übersicht	X										X		
		Workflow-Aufgabe wechseln													X
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription													
		Nicht-sichtbare reale Objekte visualisieren				X			X	X		X		X	X
		Echtzeitdaten									X				
		Autoamtische Abweichungserkennung													
		Anweisung	X			X							X		
		Demonstration													
		Routing													
		Telefonie													
		Fernunterstützung													
		Teleoperation					X								
		Dokumentation		X											
		Dateneingabe													
		Datenscan													
		Prozessmodellierung													
		Synthetische Objektmodellierung			X										
		Hilfsinformation	X			X	X	X	X	X	X	X	X		X
		Workflow-Training	X					X							

Dimension		Charakteristik	Augmented Reality-Systeme											
			[148]	[149]	[150]	[151]	[152]	[153]	[154]	[155]	[156]	[157]	[158]	[159]
Gerät	Typ	Körpergetragene Geräte												
		Kopfgetragene Geräte		X			X	X		X				
		Einhandgeräte										X		X
		Zweihandgeräte	X			X	X		X			X		X
		Stationäre Geräte			X				X		X		X	
	Architektur	Einzelgerät	X	X		X		X						X
		Verbundene Geräte					X		X	X		X	X	
		Integrierte Geräte			X						X			
	Nutzersystem	Einzelbenutzer		X		X	X	X		X	X			X
		Mehrbenutzer	X		X				X			X	X	
	Ausgabe	Projektor							X				X	
		Transparenter Bildschirm		X			X	X						
		Videomonitor	X		X	X	X		X	X	X	X		X
		Stationäre Lautsprecher												
		Mobile Lautsprecher										X		
		Haptisch							X					
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele					X		X	X				X
		Visuelle Merkmalbasierte Objektverfolgung	X	X	X	X	X							
		Räumliche Karte												
		Vernetzte Externe Optische Sensoren												
		Trägheit und Orientierung				X								
		GPS												
		RFID												
		Keine						X			X	X	X	
	Objekt-positions-verfolgung	Visuell Markerbasiert					X	X		X				X
		Visuell Merkmalsbasiert	X	X	X	X	X							
		Vernetzte Externe Optische Sensoren												
		GPS												
		RFID					X							
		Magnetisch									X			
		Keine							X			X	X	
	Benutzer-interaktions-verfolgung	Handgesten								X				
		Augenverfolgung												
		Körperhaltung							X					
		Mechanisch & Berührung	X	X	X	X	X	X	X			X		
		Sprache		X								X		
		Zeiger												
		Keine									X		X	X
Synthetic Content	Repräsentation	Text		X	X	X	X	X				X		X
		Bild		X		X	X	X					X	X
		Video		X		X							X	
		2D Form				X	X		X	X	X	X	X	X
		3D Form	X		X	X	X		X	X	X			X
		Animation												X
		Akustik												
		Haptisch							X					
	Visuelle Ausrichtung	Fixiert		X		X	X	X				X		
		Nähe	X	X		X	X		X	X	X	X	X	X
		Nicht-transparente Überlagerung	X		X	X					X			
		Transparente Überlagerung	X		X	X							X	
	Benutzer-interaktion	Keine			X						X		X	X
		Selektion	X	X		X	X	X	X	X		X		
		Manipulation	X			X			X	X				
	Inhalts-steuerung	Manuell												
		Automatisch	X		X						X		X	X
		Hybrid		X		X	X	X	X	X		X		
Workflow	Workflow-Verarbeitung*	Implizite Workflow-Aufgabe	X		X		X		X	X	X	X		X
		Impliziter Workflow		X		X		X					X	
		Modellierter Workflow & Implizite Workflow-Engine												
	Workflow-Management	Keine	X		X				X	X	X	X	X	X
		Workflow-Instanziierung		X				X						
		Navigation zur nächsten oder vorherigen Workflow-Aufgabe				X	X							
		Workflow-Abbruch		X										
		Workflow-Pfad ändern												
		Workflow-Aufgaben-Übersicht				X								
		Workflow-Aufgabe wechseln												
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription												
		Nicht-sichtbare reale Objekte visualisieren	X		X	X					X			
		Echtzeitdaten					X							
		Autoamtische Abweichungserkennung												
		Anweisung				X	X						X	
		Demonstration												
		Routing												
		Telefonie												
		Fernunterstützung		X					X			X		
		Teleoperation												
		Dokumentation		X										
		Dateneingabe												
		Datenscan						X						
		Prozessmodellierung								s				
		Synthetische Objektmodellierung												
		Hilfsinformation			X	X	X			X	X		X	X
		Workflow-Training												

Anhang B: Genutzter Fragebogen der Evaluation

Wahrgenommenen Nützlichkeit einer Taxonomie für Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung

In jüngster Zeit sind verschiedene Ansätze entstanden, welche die Workflow-Ausführung mit Augmented-Reality-Systemen (ARS) unterstützen und sich der Herausforderung stellen, Nutzern kontextabhängige Informationen zu liefern. Obwohl es bereits einige Bemühungen gab, bestehende ARS zu systematisieren, existiert nach unserem besten Wissen und Gewissen bisher keine ganzheitliche Taxonomie, welche die Dimensionen und Eigenschaften von ARS im Kontext der Unterstützung der Workflow-Ausführung adressiert. Unsere Forschung dient der Identifikation dieser Dimensionen und Eigenschaften, anhand derer bestehende ARS klassifiziert und Potenziale für neue Systeme sowie Forschungslücken identifiziert werden können. Das Ergebnis unserer Studie ist eine Taxonomie, welche aus 4 Kategorien, 17 Dimensionen und 96 Merkmalen besteht. Die Taxonomie soll Praktikern bei der Auswahl von ARS zur Unterstützung der Workflow-Ausführung, und Systementwicklern und Forschern bei der Identifizierung neuer AR-Themen und Fragestellungen helfen.

Im Rahmen dieses Fragebogens wollen wir die wahrgenommene Nützlichkeit der angesprochenen Taxonomie evaluieren. Bitte füllen Sie hierfür den nachfolgenden Fragebogen aus.

Alle Fragen werden vollständig anonym erhoben und nur für den Zweck der Evaluation der Taxonomie herangezogen. Die Daten werden zum Zwecke der Auswertung aggregiert und insbesondere im Rahmen deskriptiver Auswertungen genutzt. Aus diesen Auswertungen ist kein Rückschluss auf Ihr persönliches Antwortverhalten möglich.

Nach Abschluss des Forschungsprojektes werden Ihre Daten umgehend gelöscht. Die Beantwortung aller Fragen erfolgt vollständig freiwillig, d.h. Sie können gerne auf die Beantwortung einzelner Fragen oder des ganzen Fragebogens verzichten.

Generelle Anmerkungen oder Fragen zum Fragebogen oder zur Studie können Sie gerne an xxx richten. Falls Sie Interesse an den Ergebnissen der Umfrage haben, können Sie dies ebenfalls durch eine E-Mail an die oben angegebene E-Mail-Adresse kundtun.

Da der vorliegende Fragebogen auf wohlbekannten Items basiert, die sich englischsprachigen Studien etabliert haben, werden die Fragen in englischer Sprache gestellt.

Die Bearbeitung des Fragebogens bedarf ca. 10 Minuten. Wir danken Ihnen für die Bereitschaft zur Teilnahme an unserer Umfrage!

Mit freundlichen Grüßen,
Die Autoren.

Erläuterungen zur Taxonomie

Was ist eine Taxonomie?

Eine Taxonomie ist ein Werkzeug zur formalen Systematisierung einer Gruppe von Objekten. Jedes dieser Objekte wird analysiert und anhand seiner Eigenschaften klassifiziert. Für die gesamte Gruppe der Objekte werden sog. Dimensionen definiert, welche sog. Charakteristika als Ausprägung haben. Bspw. ist die „Farbe“ eines Gegenstandes eine Dimension und die konkreten Farbtöne („rot“, „blau“, etc.) die Charakteristika dieser Dimension. Die Charakteristika einer Dimension können sowohl exklusiv sein als auch mehrere Werte angenommen werden, je nach Dimension.

Die vorliegende Taxonomie

Die abgebildete Taxonomie entstand aus der Analyse von Augmented-Reality-Systemen (ARS) zur Unterstützung der Workflow-Ausführung. Als Informationsgrundlage wurde die Fachliteratur der letzten 10 Jahre betrachtet. Dabei wurden nur Dimensionen und Charakteristika aufgenommen, welche tatsächlich in diesen ARSs gefunden wurden. Es existieren grundsätzlich also noch viele weitere mögliche Eigenschaften, die in die Taxonomie aufgenommen werden könnten. Diese sind jedoch hier nicht abgebildet.

Da einige ARSs mit mehreren Endgeräten implementiert wurden, sind die meisten Dimensionen nicht exklusiv. Wo dies dennoch der Fall ist, wurde dies mit einem Stern markiert (*).

Augmented Reality-Systeme

Was ist ein ARS? In unserer Definition können ARS in verschiedenen Erscheinungsformen existieren, einige Beispiele:

1. Ein „Microsoft HoloLens“ AR-Headset, auf welchem eine Software läuft, die Arbeiter bei der Ausführung eines Anschaltprozesses einer Anlage unterstützt, indem die nächsten Arbeitsschritte angezeigt werden.
2. Eine Kombination aus Vibrations-Armbändern und einem Smartphone, welche Nutzer einerseits haptisch darauf aufmerksam macht, wenn eine neue Aufgabe vorliegt und andererseits durch eine App auf dem Smartphone die Darstellung von synthetischen 3D-Modellen ermöglicht.
3. Fest in einem Lagerhaus installierte Kameras, Beamer, Mikrofone und Lautsprecher, welche genutzt werden, um Arbeiter beim Einsammeln von Waren für Bestellungen zu unterstützen.

Die von uns betrachteten AR-Systeme dienen der Unterstützung der Ausführung von Workflows in verschiedenen betrieblichen Kontexten und Anwendungsdomänen. Immer steht jedoch der Bezug zum Workflow im Vordergrund. Manche ARS unterstützen nur einzelne Workflow Tasks, andere sind auf die Unterstützung ganzer Workflows oder sogar für Workflow Management konzipiert. Die vorliegende Taxonomie soll diese Bandbreite abdecken und alle ARS beschreiben, welche für die Unterstützung von Workflows genutzt werden.

Taxonomie für Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung

Die nachfolgende Grafik stellt die Taxonomie für Augmented Reality-Systeme zur Unterstützung der Workflow-Ausführung dar. Bitte betrachten Sie die Taxonomie vor der Beantwortung der Fragen. Ausführungen zu den Dimensionen und Charakteristiken finden Sie im Beitrag, der Ihnen im Anhang bereitgestellt wird.

	Dimensionen	Charakteristiken				
Gerät	Typ	Körpergetragene Geräte	Kopfgetragene Geräte			
		Einhandgeräte	Zweihandgeräte	Stationäre Geräte		
	Architektur	Einzelgerät	Verbundene Geräte	Integrierte Geräte		
	Nutzersystem*	Einzelbenutzer	Mehrbenutzer			
	Ausgabe	Projektor	Transparenter Bildschirm	Videomonitor		
		Stationäre Lautsprecher	Mobile Lautsprecher	Haptisch		
Verfolgungssystem	ARS-Positions-verfolgung	Bildziele	Visuelle merkmalbasierte Objektverfolgung	Räumliche Karte		
		Vernetzte externe optische Sensoren	Trägheit und Orientierung			
		GPS	RFID	Keine		
	Objekt-positions-verfolgung	Visuell markerbasiert	Visuell merkmalsbasiert			
		Vernetzte externe optische Sensoren	GPS	RFID	Magnetisch	Keine
	Benutzer-interaktions-verfolgung	Handgesten	Augenverfolgung	Körperhaltung		
		Mechanisch & Berührung	Sprache	Zeiger	Keine	
Synthetisch Inhalte	Repräsentation	Text	Bild	Video		
		2D Form	3D Form	Animation	Akustik	Haptisch
	Visuelle Ausrichtung	Fixiert	Nähe	Nicht-transparente Überlagerung	Transparente Überlagerung	
	Benutzer-interaktion	Keine	Selektion	Manipulation		
	Inhalts-steuerung	Manuell	Automatisch	Hybrid		
Workflow	Workflow-Verarbeitung*	Impliziter Workflow	Implizite Workflow-Aufgabe			
		Modellierter Workflow & implizite Workflow-Engine				
	Workflow-Management	Keine	Workflow-Instanziierung	Navigation zur nächsten oder vorherigen Workflow-Aufgabe		
		Workflow-Abbruch	Workflow-Pfad ändern			
		Workflow-Aufgaben-Übersicht	Workflow-Aufgabe wechseln			
	Workflow-Aufgaben-Unterstützung	Prozess-Präskription	Nicht-sichtbare reale Objekte visualisieren	Echtzeitdaten		
		Automatische Abweichungserkennung	Anweisung	Demonstration		
		Routing	Telefonie	Fernunterstützung	Teleoperation	
		Dokumentation	Dateneingabe	Datenscan		
		Prozessmodellierung	Synthetische Objektmodellierung			
		Hilfsinformation	Workflow-Training			

** = Dimensionen mit exklusiven Charakteristika, nur eine Auswahl möglich*

Fragebogen

Szenario: *Stellen Sie sich vor Sie arbeiten in der Rolle eines IT-System-Designers und sind mit der Entwicklung eines neuen Augmented Reality-Systems betraut. Dieses System soll ein Workflow-Management-Systeme und Workflows nutzen, um die AR-Inhalte zu steuern. Das Ziel des Systems ist die Unterstützung von Menschen bei der Ausführung von Workflows durch Nutzung von AR-Inhalten.*

Basierend auf diesem Szenario, wie würden Sie die folgenden Aussagen bewerten?

Aussagen zur wahrgenommenen Nützlichkeit

	Stimme überhaupt nicht zu			Stimme teilweise zu			Stimme völlig zu	Keine Aussage
(SI1) Die Taxonomie ermöglicht es mir, meine Aufgaben schneller zu erledigen (z. B. Auswahl des richtigen ARS zur Workflow-Unterstützung oder Identifizierung neuer AR-Herausforderungen).	☐	☐	☐	☐	☐	☐	☐	☐
(SI2) Die Verwendung der der Taxonomie verbessert die Leistung in meinem Beruf (z. B. Auswahl des richtigen ARS zur Workflow-Unterstützung oder Identifizierung neuer AR-Herausforderungen).	☐	☐	☐	☐	☐	☐	☐	☐
(SI3) Die Verwendung der Taxonomie steigert meine Produktivität (z. B. Auswahl des richtigen ARS zur Workflow-Unterstützung oder Identifizierung neuer AR-Herausforderungen).	☐	☐	☐	☐	☐	☐	☐	☐
(SI4) Die Verwendung der Taxonomie verbessert meine Effektivität in meinem Beruf (z. B. Auswahl des richtigen ARS zur Workflow-Unterstützung oder Identifizierung neuer AR-Herausforderungen).	☐	☐	☐	☐	☐	☐	☐	☐
(SI5) Die Verwendung der Taxonomie macht mir meinen Beruf einfacher (z. B. Auswahl des richtigen ARS zur Workflow-Unterstützung oder Identifizierung neuer AR-Herausforderungen).	☐	☐	☐	☐	☐	☐	☐	☐
(SI6) Alles in allem beurteile ich die Taxonomie als nützlich für meinen Beruf.	☐	☐	☐	☐	☐	☐	☐	☐

Prägnanz, Eindeutigkeit, Vollständigkeit, Erweiterbarkeit und Erklärungskraft

	Stimme überhaupt nicht zu			Stimme teilweise zu			Stimme völlig zu	Keine Aussage
(SEC1) Prägnanz Erlaubt die Anzahl der Dimensionen, dass die Taxonomie aussagekräftig ist, ohne dass sie unübersichtlich oder überfordernd zu wirken?	☐	☐	☐	☐	☐	☐	☐	☐
(SEC2) Eindeutigkeit Ermöglichen die Dimensionen und Charakteristika eine ausreichende Differenzierung zwischen den Objekten, resp. ARS?	☐	☐	☐	☐	☐	☐	☐	☐
(SEC3) Vollständigkeit Können alle Objekte, resp. ARS, oder eine (zufällige) Stichprobe von Objekten innerhalb einer Domäne klassifiziert werden?	☐	☐	☐	☐	☐	☐	☐	☐
(SEC4) Erweiterbarkeit Können neue Dimensionen und Charakteristiken einfach hinzugefügt werden?	☐	☐	☐	☐	☐	☐	☐	☐
(SEC5) Erklärungskraft Sind alle Dimensionen und Charakteristiken der ARS hinreichend verständlich erklärt?	☐	☐	☐	☐	☐	☐	☐	☐

Soziodemographische Daten

Für eine weitere Auswertung der Daten freuen wir uns über die freiwillige Angabe weiterer soziodemographischer Daten.

(Sozio 1) Welchem Geschlecht fühlen Sie sich zugehörig?

☐ männlich ☐ weiblich ☐ divers

(Sozio 2) Wie alt sind Sie?

____________________ Jahre

(Sozio 3) Wie viel Berufserfahrung haben Sie?

____________________ Jahre

(Sozio 4) In welcher Branche arbeiten Sie im Moment?

- ☐ Consulting
- ☐ Finanzwesen
- ☐ Forschung und Entwicklung
- ☐ IT-Dienstleistungen
- ☐ Versicherung
- Andere: ____________________________

(Sozio 5) Welcher Kategorie kann die Organisation oder das Unternehmen, in dem Sie arbeiten, zugeordnet werden?

- ☐ Kleinstunternehmen (weniger als 9 Mitarbeitende und ein Jahresumsatz bis 2 Mio. Euro)
- ☐ Kleines Unternehmen (weniger als 49 Mitarbeitende und ein Jahresumsatz bis 10 Mio. Euro)
- ☐ Mittleres Unternehmen (weniger als 250 Mitarbeitende und ein Jahresumsatz bis 50 Mio. Euro)
- ☐ Großes Unternehmen (mehr als 250 Mitarbeitende und ein Jahresumsatz von mehr als 50 Mio. Euro)

(Sozio 6) Was ist Ihre aktuelle Rolle in Ihrem Job?

____

(Sozio 7) Wie lange arbeiten Sie bereits in dieser Rolle?

____________________ Jahre

Gerne können Sie uns weiteres Feedback zur wahrgenommenen Nützlichkeit der Taxonomie geben.

____

____

Vielen Dank für Ihre Zeit und Teilnahme an unserer Umfrage.

Anhang C: Datensatz der Rückmeldungen der Fragebögen

Fragen	**Fragebogen-Rückmeldung Nr.**					
	1	**2**	**3**	**4**	**5**	**6**
SI1	7	6	6	6	5	4
SI2	7	2	3	4	5	NA
SI3	7	3	3	3	5	4
SI4	7	6	5	5	5	NA
SI5	6	5	6	5	7	5
SI6	7	6	6	6	7	6
SEC1	7	6	6	4	6	6
SEC2	7	6	5	5	6	6
SEC3	7	6	6	6	4	5
SEC4	7	7	6	6	7	6
SEC5	7	7	6	6	6	7
Sozio1	m	m	m	w	m	m
Sozio 2	34	53	30	27	34	31
Sozio 3	7.5	25	4	4	9	5
Sozio 4	Forschung & Entwicklung	Forschung & Entwicklung	Forschung & Entwicklung	Forschung & Entwicklung	Forschung & Entwicklung	Consulting, Forschung & Entwicklung, IT-Dienstleistungen
Sozio 5	groß	groß	kleinst	kleinst	groß	medium
Sozio 6	PostDoc	Head of Research	Developer	Multimedia Design	Research Associate	Software & Solution Engineer
Sozio 7	1,5	11	4	4	9	3,5

Anmerkung: SI# = Skalen-Items von Davis (1989) [160]
SEC# = Subjektive Endbedingungen von Nickerson et al. (2013) [161]
Sozio # = Sozio-demographische Fragen

Fragen	Fragebogen-Rückmeldung Nr.				
	7	8	9	10	11
SI1	5	6	5	7	5
SI2	7	5	6	5	5
SI3	5	4	5	5	4
SI4	7	4	5	6	5
SI5	7	4	6	6	5
SI6	7	5	6	6	6
SEC1	6	NA	6	7	7
SEC2	7	7	6	7	6
SEC3	7	7	6	7	7
SEC4	7	7	6	7	7
SEC5	6	7	6	7	6
Sozio1	m	d	m	m	m
Sozio 2	25	36	31	34	31
Sozio 3	4	13	10	10	4.5
Sozio 4	Consulting, Forschung & Entwicklung	IT-Services, Forschung & Entwicklung	IT-Services, Forschung & Entwicklung	Consulting, IT-Dienstleistungen	Consulting, IT-Dienstleistungen
Sozio 5	groß	groß	groß	medium	medium
Sozio 6	AR-Engineer, Research Assistant	Research Assistant	Research Assistant	Senior Manager	IT-Project Manager
Sozio 7	1	6	6	1,25	1,5

Anmerkung: SI# = Skalen-Items von Davis (1989)
SEC# = Subjektive Endbedingungen von Nickerson et al. (2013)
Sozio # = Sozio-demographische Fragen

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Appendix D: Author's statement on the work shares in the article "Understanding Augmented Reality Systems for Workflow Support – A Taxonomy and Archetypical Patterns"

The article *"Understanding Augmented Reality Systems for Workflow Support – A Taxonomy and Archetypical Patterns"* was co-authored. The following table gives an overview of the authors' contributions to the article.

Authors:

Johannes Damarowsky	JD
Stephan Kühnel	SK
Tobias Seyffarth	TS
Martin Böhmer	MB

Aspect	Author(s)
Research concept	JD
Research methodology	JD, SK
Problem and objective	JD
Literature research	JD
(Re)conceptualisation of the topic	JD
Continued development of the characteristics and dimensions of the taxonomy	JD
Cluster analysis and development of archetypes	JD, SK
Discussion of the contributions and conclusion	JD
Preparation of the manuscript	JD
Review and revision before submission	JD, SK, TS, MB
Revision after review	JD

Appendix E: Full text of the article "Understanding Augmented Reality Systems for Workflow Support – A Taxonomy and Archetypical Patterns"

Acknowledgement of the original source of publication

The original version of this article was submitted to the journal *Electronic Markets (Springer Nature)* and currently awaits a decision.

VHB Jourqual 3: B.

Electronic Markets
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Electronic Markets – The International Journal on Networked Business

[Manuscript Template]

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JEL classification	O310 Innovation and Invention: Processes and Incentives (see http://www.aeaweb.org/journal/jel_class_system.html or https://www.aeaweb.org/jel/guide/jel.php)
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Abstract

Recently, several approaches to supporting workflow execution with augmented reality systems (ARS) have emerged to address the challenge of providing context-sensitive information to users. Although there are some efforts to systematize ARSs, no taxonomy exists addressing the workflow execution support by ARSs. Thus, there is a lack of a precise vocabulary and a set of possible descriptive constructs. This makes it challenging to compare ARSs, identify trends and research gaps within the literature, and guide new research efforts. To address this research gap, we analyzed 142 ARSs with respect to their workflow execution support and developed a novel taxonomy containing 14 dimensions and 83 characteristics. We assessed its perceived usefulness via domain expert interviews. Additionally, we utilized cluster analysis techniques to develop three archetypes of ARSs supporting workflow execution. Finally, we conceptualized three novel ARS types using the taxonomy, representing promising research approaches for workflow execution support.

Introduction

In recent years, augmented reality (AR) technology has become widely researched and applied for almost all domains, most prominently healthcare, logistics, and manufacturing (e.g., Berkemeier et al., 2019; Feng et al., 2014; Ferrari et al., 2016; X. Wang et al., 2016). AR combines real and synthetic information interactively and in real-time within a real environment. Synthetic objects react to and align with the real environment, thus creating an immersive experience while preserving the user's ability to navigate the environment (Azuma et al., 2001). So-called AR systems (ARS) implement AR in information systems (IS) to create this AR experience for users and can utilize a wide range of wearables, headsets, handhelds, or stationary systems (e.g., Makris et al., 2013; Metzger et al., 2018; Neges et al., 2015; X. Wang et al., 2016). Mirroring the wide range of explored application scenarios and utilized hardware and synthetic contents, an equally diverse range of ARSs have been developed. While most of these won't progress beyond their respective research and development projects, they are nonetheless a predictor of things to come. Understanding what is being explored, researched, and developed in the labs today means being better prepared for the product releases of tomorrow.

To understand the nature and possible impacts of contemporary ARSs, one useful perspective is their interaction with modern workflow management systems and their workflow execution support. The context-aware provision of information during workflow execution, i.e., providing the right information at the right time and in the right place, is a well-known challenge for organizations (Krcmar, 2006). When workflows are implemented as formalized models, they are processed by workflow management systems (WFMS). WFMSs define, interpret, instantiate, and manage the execution of workflows with software, integrate external applications if necessary, and interact with human workflow participants (Workflow Management Coalition, 1995b).

While clearly not all types of workflows are well suited for AR support, improved task efficiencies, i.e., reduced error rates, execution times, cognitive loads, and required training, have already been observed, e.g., in the domains of collaborative planning, assembly, service, and maintenance, warehouse picking, process training, or process modeling (Erkoyuncu et al., 2017; Hanson et al., 2017; Hofmann et al., 2019; Jetter et al., 2018; Lampen et al.; Seiger et al., 2021; X. Wang et al., 2016). As such, we argue that the research stream of *ARS-based workflow execution support* has successfully been established in the intersection of AR, workflows, and WFMSs.

To systematically characterize and gain deeper insight into the interplay of AR, workflows, and WFMSs, taxonomies can be utilized. A taxonomy can be defined as a set of dimensions, each containing a set of characteristics, which together exhaustively represent the possible expressions of their respective dimension (Nickerson et al., 2013). By abstracting the real complexity of objects to these dimensions and characteristics, taxonomies allow for an easier comparison of similarities and differences between objects. When analyzing groups of objects, the aggregated expressions of the taxonomy, i.e., the frequent common occurrence of characteristics or their common absence, can generate additional insights (Bailey, 1994). Further, taxonomies contribute to the IS knowledge base by providing a vocabulary of a domain and a set of defined constructs, thus establishing a foundation for future research efforts (Hevner et al., 2004; March & Smith, 1995).

Taxonomies are regularly used as support tools to structure a domain and ease and deepen its understanding. E.g., in the context of electronic markets, taxonomies have been developed to facilitate the understanding of FinTech start-ups (Gimpel et al., 2018), describe patterns in business models, or describe business models in the context of emergent technologies, e.g., blockchain technology, internet of thing, or predictive maintenance and internet of things (Hodapp et al., 2019; Passlick et al., 2021; Tönnissen et al., 2020; Weking, Hein, et al., 2020; Weking, Mandalenakis, et al., 2020).

To our knowledge, only a few taxonomies of AR, workflow, and WFMSs are presently available, which we further detail in Section 3. Of these, only two directly address the intersection of AR, workflows, and WFMS. First, Klinker et al. (2018) address both workflows and AR by providing a taxonomy of suitable use cases for AR-supported service workflows. Second, the framework by Fellmann et al. (2017) focuses on assistance systems for work processes in smart factories. The framework is not focused on workflow execution support but contains aspects of workflows and WFMS, e.g., the degree of human interaction control with the system.

While both studies are useful in their own right, we asses that the intersection of AR, workflows, and WFMSs could be described in much greater granularity and detail, e.g., regarding utilized workflow models or the specific type of AR task support. In the current status quo, a precise vocabulary and understanding of the possible descriptive constructs in this intersection of technologies are lacking. This, in turn, complicates the comparison between ARSs supporting workflow execution and the identification of patterns within the literature. Formally characterizing ARSs, identifying relevant literature and research gaps, and steering new research efforts become more difficult. Most importantly, however, R&D trends are complicated to identify. To enable those potential benefits, an extension and update of the currently existing taxonomies are necessary, which characterizes ARSs in terms of their integration with WFMS and details their specific contributions to supporting workflow execution. Consequently, we define our first research question (RQ 1):

RQ 1: What are the dimensions and characteristics of a taxonomy of augmented reality systems supporting workflow execution?

While taxonomies are valuable instruments, they are often difficult to interpret and utilize for practitioners. Also, taxonomies are tools to characterize objects but do not *per se* offer insights into the currently existing population of objects – in our case ARSs in support of workflow execution. To archive such insights, the taxonomy can be used to characterize existing objects, and methods of exploratory data analysis can then be utilized to identify patterns within the data and to develop archetypal patterns or *archetypes* (e.g., Arnold et al., 2022; Hodapp et al., 2019; Weking, Mandalenakis, et al., 2020). These archetypes thus concisely summarize the status quo. We, therefore, define our second research question (RQ 2) as follows:

RQ 2: Which characteristics define archetypes of augmented reality systems supporting workflow execution?

To answer RQ1, this study follows the well-known approach to taxonomy development of Nickerson et al. (2013), coupled with a systematic literature review following the methods of Vom Brocke et al. (2009) and Webster and Watson (2002). To address RQ2, we perform an exploratory cluster analysis, using quantitative and qualitative indices to triangulate a meaningful number of clusters and develop archetypes. The details of our research approach to developing the taxonomy are detailed in Section 2. In Section 3, we present the first main contribution of this paper, addressing RQ1: a novel taxonomy for classifying ARSs supporting workflow execution, introducing its four categories, 14 dimensions, and 83 characteristics. We address the evaluation of the taxonomy in Section 4. In Section 5, we detail our exploratory data analysis and present the second main contribution of this paper in Section 6: three archetypes of ARSs supporting workflow execution. In Section 7, we apply the taxonomy and archetypes to suggest three novel research streams, demonstrating the applicability of our contributions, which we further discuss in Section 8. In Section 9, we briefly summarize our key findings and reflect on the limitations of our approach.

Research Approach and Taxonomy Development Procedure

Our research approach is two-part. First, we developed the taxonomy by implementing steps 1-6, as shown in Figure 1and described in detail in this Section. Afterward, we utilized a 4-step approach to develop the archetypes, numbered steps 7-10, shown in Figure 1 and detailed in Section 5.

Figure 1: Overall research approach. Steps 1-6 adapted from Nickerson et al. (2013)

A taxonomy can be defined as a set of dimensions, each containing a set of characteristics, which together exhaustively represent the possible expressions of the respective dimension (Nickerson et al., 2013). From the perspective of IS theory building, taxonomies can be understood as theories about IS, which can be analyzed (Gregor, 2006). In a narrower sense, however, they are also design artifacts that enable the classification of existing and future objects (Nickerson et al., 2013). Thus, they represent an *organizational systematics* approach to systematize and better understand a specific problem space, e.g., ARS supporting workflow execution incorporating AR (McKelvey, 1978).

Our approach to developing a taxonomy for ARSs supporting workflow execution is based on the well-known method of Nickerson et al. (2013). As Kundisch et al. (2021, p. 2) point out in their analysis, about two-thirds of the taxonomies published in IS journals since 2013 follow this methodological approach. Our 6-step research approach for taxonomy development is illustrated in Figure 1.

Step 1 is to define a meta-characteristic, which serves as the most comprehensive characteristic at the highest level of abstraction and forms the basis for deriving dimensions and respective (sub)characteristics. For our taxonomy, we broadly define the meta-characteristic as *properties of ARSs supporting workflow execution.*

Step 2 is to define the taxonomy's purpose and target user group. The later are both general and specialized IS, AR, or workflow researchers, who want to understand the existing characteristics of ARSs in support of workflow execution, or who can use the taxonomy to formalize existing and identify novel research streams for such ARSs. To provide additional utility, e.g., for IS managers, we develop archetypes in Section 6.

Step 3 defines ending conditions that are used to determine when the resulting taxonomy is satisfactory. For this, we rely on the eight objective ending conditions (oec#) and five subjective ending conditions (sec#) proposed by Nickerson et al. (2013), shown in Table 1 and Table 2, respectively.

oec1	All objects or a representative sample of objects have been examined.
oec2	No object was merged with a similar object or split into multiple objects in the last iteration.
oec3	At least one object is classified under every characteristic of every dimension.
oec4	No new dimensions or characteristics were added in the last iteration.
oec5	No dimensions or characteristics were merged or split in the last iteration.
oec6	Every dimension is unique and not repeated.
oec7	Every characteristic is unique within its dimension.
oec8	Each cell is unique and is not repeated.

Table 1: Objective ending conditions (oec) by Nickerson et al., 2013, p. 344

sec1	Concise	Does the number of dimensions allow the taxonomy to be meaningful without being unwieldy or overwhelming?
sec2	Robust	Do the dimensions and characteristics provide for differentiation among objects sufficient to be of interest?
sec3	Comprehensive	Can all objects or a (random) sample of objects within the domain of interest be classified? Are all dimensions of the objects of interest identified?
sec4	Extendible	Can a new dimension or a new characteristic of an existing dimension be easily added?
sec5	Explanatory	What do the dimensions and characteristics explain about an object?

Table 2: Subjective ending conditions (sec) by Nickerson et al., 2013, p. 344

In **Step 4**, the taxonomy is iteratively constructed, with two approaches available: 1) the Empirical-to-Conceptual approach, where real objects – in our context ARSs – are identified, analyzed, and grouped by their dimensions and characteristics, and 2) the Conceptual-to-Empirical approach, where dimensions and characteristics are first conceptualized independently of real objects. The development of our taxonomy was initiated with the Empirical-to-Conceptual approach (Figure 1, Step 4). Since Nickerson et al. recommend conducting a literature review to identify real objects (cf. p. 345), we conducted a systematic literature review on relevant ARSs according to Vom Brocke et al. (2009). We chose the well-known methodology of Vom Brocke et al. (2009) as it allowed us to conduct a comprehensible, rigorous, and sound literature review. We chose it over alternative approaches, as it either incorporates them (Webster & Watson, 2002) or is more widely cited (e.g., Okoli (2015)).

To obtain a broad basis of search results, we searched five databases: ACM Digital Library, EBSCOHost, IEEE Xplore, ScienceDirect, and SpringerLink. Following the focus of our study, we used four search terms: 1) "augmented reality," 2) "system," 3) "app," and 4) "tool." Since we explicitly examine AR in our paper, we did not incorporate the term "mixed reality" as it describes the entire reality-virtuality continuum and thus denotes a superset of AR (Milgram & Kishino, 1994). Following Vom Brocke et al. (2009), the search results were subsequently selected in 5 steps: 1) duplicate removal, 2) title-based selection, 3) abstract-based selection, 4) full text-based selection, and 5) backward search.

The five selection steps were guided by four inclusion criteria. First, to ensure relevance and timeliness, articles must be published after 2010, coinciding with the release of relevant consumer products, e.g., Google Glass (2012) and Microsoft HoloLens (2015). Second, articles must be in English. Third, articles discussing ARS prototypes and designs were included if they were complete and specific enough, i.e., no articles about individual functions. Fourth, the described ARS must address a human-oriented workflow or workflow task in some capacity, e.g., no ARSs for purely educational purposes or enhanced situational awareness without specific relation to a workflow.

The resulting set of literature included 60 articles describing ARSs supporting workflow execution. To identify the characteristics and dimensions of relevant ARSs, we performed an author-centric analysis, as described by Webster and Watson (2002). In doing so, we noted that some articles describe the same ARS, reducing the set of real objects to be analyzed from 60 to 49. We then performed a backward search, yielding 905 results, of which 434 were published in English after 2010. After duplicate removal, 218 articles remained for full text-based selection, which yielded 93 relevant ARSs. We finally documented 142 ARSs in a concept matrix as Webster and Watson (2002) recommended, based on which we analyzed their characteristics and grouped them into dimensions (see Appendix A for the complete concept matrix). Figure 2 provides a summary of the literature search process. Following the comments on ex-ante evaluations by Pries-Heje et al. (2008), the eight objective ending conditions were already considered at this stage of development.

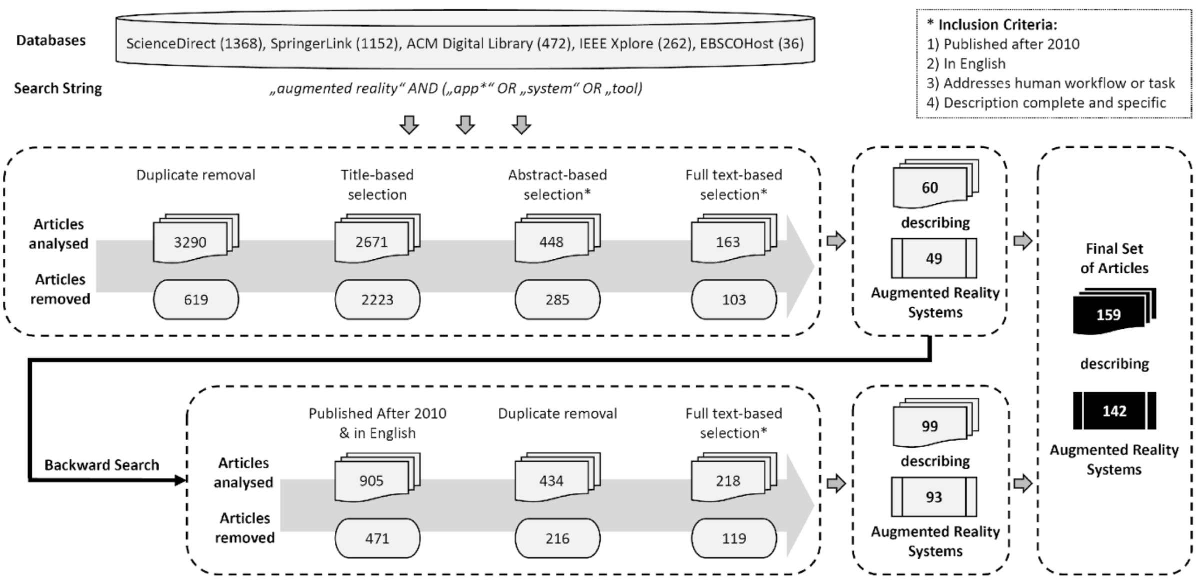


Figure 2: Literature Search Process

Step 5 served to verify that we met the objective ending conditions. Therefore, we continued the development procedure by implementing the Conceptual-to-Empirical approach (Nickerson et al., 2013).

The goal was to cross-check our taxonomy with existing taxonomies of ARSs and reference architectures for AR and WFMS for contradictions and additional characteristics.

In this context, we consulted the taxonomy proposed by Xiangyu Wang et al. (2013), which describes implementation-relevant characteristics of ARSs, i.e., a subset of our taxonomy without consideration of workflows. While generally in line with our own, their findings partly differ in the level of abstraction and wording, e.g., our taxonomy refers to “two-handed handhelds,” but they differentiate “tablets” and “laptops.” However, a more fine-grained breakdown of our characteristics, such as above, would unnecessarily inflate our taxonomy and, therefore, not be consistent with ending condition 2 (cf. Nickerson et al., 2013, p. 344). We also determined our implementation-oriented characteristics to align with van Krevelen and Poelman (2010), who describe possible technical implementations of ARSs. Furthermore, we cross-checked our taxonomy with the ID4AR framework by Limbu et al., describing 11 types of synthetic instructions, but without consideration of workflows or the underlying ARSs Limbu et al. (2019). The framework does not contradict our taxonomy, although we take a structured and more fine-grained approach. Additionally, we reviewed recent approaches by Bräker et al. (2021) and Hertel et al. (2021) to formalize the interaction techniques enabled by ARS and the resulting taxonomy. The taxonomy has a different focus than ours, i.e., their meta-characteristics (Nickerson et al., 2013) differ. Consequently, the selected set of ARSs and the set dimensions and characteristics differ markedly. In terms of content, we find the taxonomy by Hertel et al. (2021) in agreement with ours. Also, we reviewed the framework by Fellmann et al. (2017), which focusses on assistance systems for work processes in smart factories. The framework is not focused on workflow execution support but contains aspects of workflows and WFMS, e.g., the degree of human interaction control with the system. While dimensions and characteristics are named differently, we find no disagreement with our taxonomy.

Lastly, we found characteristics in the literature previously not identified in the analysis of the 142 ARSs, e.g., acoustic and mechanical tracking, smell and taste as output or various workflow management functions (Craig, 2013; MacWilliams et al., 2004; Milgram & Kishino, 1994; Workflow Management Coalition, 1995a). However, in line with oec3 (cf. Nickerson et al., 2013, p. 344), these characteristics were not considered during development as they have not yet been used to support workflow execution or have not yet characterized any identified ARSs.

Step 5, the Conceptual-to-Empirical approach as a second iteration, thus confirmed the identified dimensions and characteristics of the first iteration Empirical-to-Conceptual approach (step 4), and no modification of the taxonomy, i.e., insertion of new elements, renaming, swapping, splitting, merging, promotion or demotion of elements, was necessary (cf. Kundisch et al., 2021, p. 10). All eight objective ending conditions are, therefore, fulfilled. All objects were examined (oec1). No objects were merged or split (oec2). Only characteristics of real ARSs were incorporated (oec3). In the last iteration, no new dimensions or characteristics were added (oec4) or merged or split (oec5). The uniqueness of dimensions (oec6) and their respective characteristics (oec7) is ensured. Every cell of the taxonomy is unique (oec8).

Step 6, the evaluation of the taxonomy, is detailed in Section 4, in which we examined the five subjective ending conditions together with the perceived usefulness.

During the development of the taxonomy, it became clear that Nickerson et al.'s requirement of mutual exclusivity of characteristics within a dimension would collide with the reality of ARSs. To fulfill this requirement, most dimensions would include many combinations of characteristics for their cells. This would make the taxonomy highly unwieldy and thus collide with sec1, i.e., that the taxonomy should be concise (Nickerson et al., 2013, p. 344). Therefore, we decided to incorporate dimensions that contain non-mutually exclusive characteristics, in line with other works (Arnold et al., 2022; Jöhnk et al., 2017; Püschel et al., 2020; Seyffarth et al., 2017). The final taxonomy is shown in Figure 3 and detailed in the following Section.

A Taxonomy of Augmented Reality Systems Supporting Workflow Execution

	Dimension	Characteristics				
Device	Type	Wearable (10)	Head-mounted (70)			
		One-hand Handheld (22)	Two-hand Handheld (29)	Stationary Device (53)		
	Architecture	Single Device (70)	Connected Devices (40)	Integrated Devices (37)		
	User System*	Single-user (100)	Multi-user (42)			
	Output	Projector (15)	Optical See-through (15)	Video See-through (77)		
		Stationary Loudspeaker (3)	Mobile Loudspeaker (20)	Haptic Output(6)		
Tracking System	ARS Position Tracking	Image Targets (68)	Relative to Visual Feature-tracked Objects (43)	Spatial Map (13)		
		Position Tracking via Networked External Optical Sensors (4)	Inertial and Orientation (26)			
		GPS Position Tracking (3)	RFID Position Tracking(2)	None (27)		
	Object Tracking	Visual Marker-based (65)	Visual Feature-based Object Tracking(61)			
		Object Tracking via Networked External Optical Sensors (1)	GPS Object Tracking (1)	RFID Object Tracking(3)	Magnetic (5)	None (23)
	User Interaction Tracking	Hand Gestures (23)	Eye-tracking (6)	Body Pose (4)		
		Mechanical & Touch (60)	Speech (21)	Pointer (3)	None (52)	
Synthetic Content	Representation	Text (78)	Image (64)	Video (19)		
		2D Form (97)	3D Form (92)	Animation (23)	Acoustic (14)	Haptic Representation (6)
	Visual Alignment	Fixed (42)	Proximity (98)	Non-transparent Overlay (50)	Transparent Overlay (52)	
	User Interaction	None (83)	Selection (49)	Manipulation (29)		
	Content Control	Manual (6)	Automatic (51)	Hybrid (82)		
Workflow	Workflow Processing*	Implicit Workflow (96)	Implicit Workflow Task (36)			
		Modelled Workflow & Implicit Workflow Engine (10)				
	Workflow Management	None (105)	Instantiate Workflow (18)	Navigate to Next or Previous Workflow Task (20)		
		Cancel Workflow (2)	Change Workflow Path (8)			
		Workflow Task Overview (7)	Switch Workflow Task (4)			
	Workflow Task Support	Process Prescription (4)	Visualise Non-visible Real Objects (32)	Real-time Data (17)		
		Automatic Deviation Detection (10)	Instruction (61)	Demonstration (5)		
		Routing (6)	Telephone (2)	Remote Assistance (18)	Teleoperation (15)	
		Documentation (17)	Data Entry (13)	Data Scanning (3)		
		Process Modelling (1)	Synthetic Object Modelling (1)			
		Auxiliary Information (127)	Workflow Training (9)			

*Note: * = dimension with mutually exclusive characteristics. (#): quantity of characteristics identified in the analyzed 142 ARSs.*

Figure 3: Taxonomy of Augmented Reality Systems Supporting Workflow Execution

For clarity, we organized the dimensions into four groups: 1) device, 2) tracking system, 3) synthetic content, and 4) workflow. These are detailed in the following subsections. All characteristics are based on analyzed ARSs.

Group: Device

Some ARSs are implemented with multiple components or user-facing devices so that these ARSs express multiple characteristics in multiple dimensions.

The **dimension "type"** includes *wearables* which are worn on the body and are mainly implemented as smartwatches, *head-mounted* devices, e.g., AR headsets, *one-hand handhelds*, e.g., smartphones, *two-hand handhelds*, e.g., tablets, and *stationary devices*, which can only be used at predefined locations. The **dimension "architecture"** describes the physical makeup of an ARS. All components of an ARS can be physically integrated into a *single device*, e.g., an AR headset. Alternatively, the *connected devices* can be physically separate, e.g., headset and smartphone. If components are, however, (semi-)permanently connected, we refer to these *integrated devices*. The **exclusive dimension "user system"** describes how many persons can perceive the same synthetic content simultaneously, either one (*single-user)* or multiple *(multi-user)*. The **dimension "output"** could, in principle, address all human senses. However, we only identified visual, acoustic, and haptic as mediums. *Projectors* are stationary devices that project images locally onto surfaces and objects, while *optical see-through* devices use semi-transparent displays as projection surfaces. *Video see-through* devices overlay synthetic information on camera feeds. Acoustic output can be delivered either by (semi-)permanently installed *stationary loudspeakers* or *mobile loudspeakers,* e.g., headphones. *Haptic* output is delivered to worn devices via vibration.

Group: Tracking System

An ARS does not need to track objects, its own position, or user interaction to select the right synthetic content. Thus, all dimensions in this group are complemented by *None*. The **dimension "ARS position tracking"** describes how the ARS tracks its position with respect to the environment or specific objects in order to select, display, or align synthetic information with real objects. Many ARSs track their position only in relation to objects to display synthetic content in the correct perspective, as the ARS's relative position can be calculated from the distortion of tracked *image targets*, e.g., QR codes or images. Alternatively, *visual feature-based object tracking* calculates the ARS's relative position based on the known shape of an object. Similarly, an ARS can scan the local environment and create a *spatial map* to track its own position as well as "spatial anchors" within so that the user can fix synthetic objects on any real surface. *Networked external optical sensors*, e.g., a set of infrared cameras, can track visual markers on objects and infer their spatial orientation from the combined data. Specifically designed *inertial and orientation* sensors consist of accelerometers, gyroscopes, or magnetometers. Position information can also be obtained by using network-oriented sensors like *GPS* or *RFID* tags and sensors. The **dimension "object**

tracking" includes similar *characteristics: **visual marker**- and **visual feature**-based tracking, **networked external optical sensors**, **GPS**, and **RFID**.* Additionally, objects can be tracked ***magnetically***, which is especially utilized for medical devices. The **dimension "user interaction tracking"** includes predefined ***hand gestures***, which are usually recognized via optical sensors. *Eye-tracking* tracks the direction of gaze via pupil movements or visibility. Also, the general *body pose* of the user can be used for interaction, e.g., tilting the head. Using mechanical and tactile sensors (e.g., buttons or touch screens), *mechanical & touch* can be performed. Finally, microphones enable *speech* control, and *pointers* can be used for interaction, e.g., a laser pointer tracked an ARS's cameras.

Group: Synthetic Content

All ARSs utilize some form of synthetic content; otherwise, we do not consider it an object of interest for our taxonomy. The **dimension "representation"** correlates with the dimension "output" but describes a different aspect of the synthetic content. Consequently, we differentiate between *text*, *images*, *videos*, *2D forms*, *3D forms*, *animations*, *acoustic*, and *haptic* representations. The **dimension "visual alignment"** describes the alignment of synthetic visual content with the environment from the user's perspective. It can be *fixed* in place, stay in *proximity* to an object or marker, or congruently overlay it, either as a *non-transparent overlay* or *transparent overlay*. In the analyzed ARSs, all acoustics were aligned as user-centric, although this could theoretically be different. The **dimension "user interaction"** broadly describes how the user interacts with the synthetic content during workflow task execution, either not at all (*none*), *selecting* content (e.g., menu items), or *manipulating* synthetic content, e.g., changing the color, shape, scaling, position, orientation or inserting and deleting objects into and from the scene. The **dimension "content control"** specifies how synthetic content during workflow task execution is instantiated. *Manual* control requires user input for every single instantiation, while *automatic* requires none. In *hybrid* approaches, some content is triggered automatically, others manually.

Group: Workflow

In this group, we take a broad approach and include some edge cases of the usual definitions of workflows and WFMS. The **exclusive dimension of "workflow processing"** describes the formal representation and processing of workflows. An *implicit workflow* exists when the sequence of synthetic contents presented by an ARS is structured by logical stages, phases, triggers, or conditions, i.e., not all synthetic content is presented all the time. For example, in Metzger et al. (2018), synthetic instructions are ordered in a workflow and become visible after appropriate voice commands. Vice versa, in an *implicit workflow task*, all content is always presented, e.g., in Ferrari et al. (2016), medical instruments are always visualized during a surgical workflow task. A modeled workflow describes the structure of the synthetic content in some formalized notation, e.g., Petri nets or XML schemas. In this case, the ARS utilizes a *modeled workflow and implicit workflow engine*, which interprets the model and controls the presentation of the appropriate synthetic content. However, no analyzed ARS explicitly mentioned a workflow engine or WFMS.

The **dimension "workflow management"** describes a user's possibilities to control and manage workflow instances. Most analyzed ARSs offer *none*. Some ARSs allow the user to *instantiate a workflow* deliberately, to *navigate to the next or previous workflow task*, or to *cancel a workflow instance*, e.g., via a visual menu. When the workflow is branched, some ARSs can *change the workflow path* based on the user's input. Some ARSs can manage multiple active tasks and present the user with a *task overview*, i.e., showing running and/or assigned tasks, or let the user *switch workflows tasks*, i.e., execute a task from another workflow instance.

The **dimension "workflow task support"** specifies how synthetic content supports the user during workflow execution. *Process prescription* can be utilized to select the next best task to reach the workflow's goals. This requires an active complex processing of the relevant context to reason about the next best task, usually involving some form of process prediction and/or process simulation. For example, in Makris et al. (2013), an ARS supports a machine disassembly workflow by simulating the possible motions of parts and then selects the next best part to remove by the number of possible motions.

Passive workflow guidance is provided by *visualizing non-visible real objects*, e.g., visually occluded but magnetically tracked medical instruments during surgery. Also, *real-time data* can provide guidance, e.g., data from handheld measuring devices or database queries. Such data can also present the results of an *automatic deviation detection*, which detects if a workflow task is being performed incorrectly, has not yet been completed, or is completed erroneously, e.g., a medical instrument's deviation from the proper insertion angle.

More active guidance is provided by *instructions*, which signal to the user what should be done and can include visual guidance on how to perform a task or handle. In a *demonstration,* this guidance is contextually specific and animated, e.g., showing where to attach and how to turn a wrench to screw in a specific bolt. Similarly, contextually specific in regards to an ARS's real-world location is dynamically *routing* a user to a specific location.

For collaborative forms of workflow guidance, experts can be called in via *telephone* or more complex *remote assistance*, which enhances video telephony by simultaneously granting access to the user's field of view and other sensor inputs. This allows the remote experts to create guiding synthetic content, e.g., draw annotations in the user's field of view.

An ARS can provide the user with new AR-based ways to execute workflows and tasks. Quasi the reverse of remote assistance, *teleoperation* allows the programming, controlling, and general interaction with machines or robots via an AR UI. The ARSs sensor inputs during a workflow task can be recorded as *documentation*, e.g., videos of the users' field of view. Going beyond the use of navigation and administrative menus, the user can perform manual *data entry* via text input, speech recognition, or multiple-choice selections. A semi-automatic variant of data entry is *data scanning,* in which the user directs the ARS's sensors in a specific way to collect some specific data, e.g., scanning a barcode. Also, a kind of data entry, *process modeling* encompasses a set of special synthetic contents and functions to document a workflow or process in a formal model, e.g., in the Event-driven Process Chain (EPC) notation. Similarly, *synthetic object modeling* describes the modeling, construction, stacking, assembly, etc., of synthetic objects during a computer-aided design (CAD) workflow. All supportive synthetic content that cannot be classified more specifically in the above characteristics is termed *auxiliary information,* e.g., highlighting interesting real objects. Finally, while all workflow execution, in principle, can serve as an instrument of training and many ARSs are developed and tested in artificial demonstration scenarios, *workflow training* refers to special kinds of synthetic content and functions to explicitly facilitate training or is developed explicitly for training scenarios, e.g., the user needs to repeat a training task until some execution speed is reached or a workflow is executed on a virtual training object.

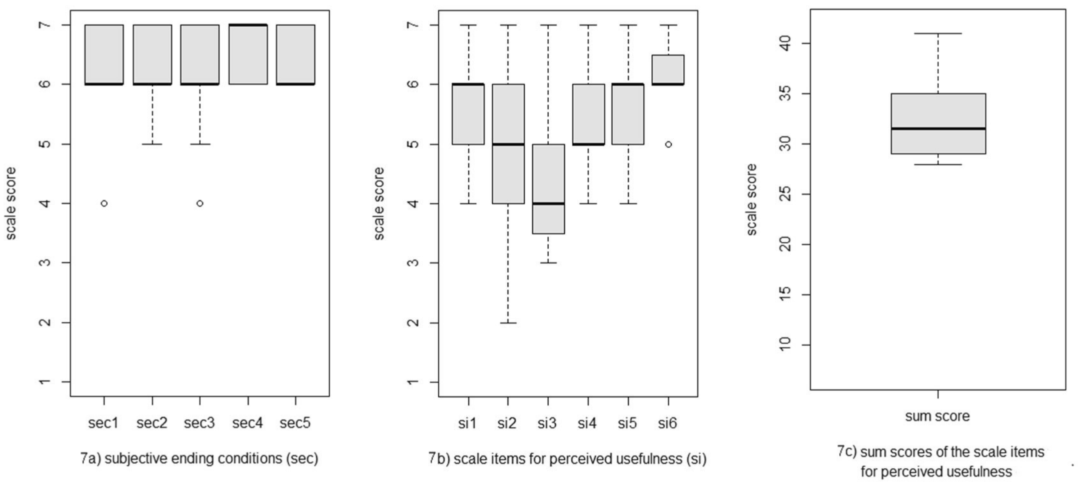
Evaluation of the Taxonomy

The evaluation strategy of our work comprises three steps: step 1) an ex-ante evaluation of the objective ending conditions, step 2) an ex-post evaluation of the subjective ending conditions, and step 3) a summative evaluation of the perceived usefulness of our taxonomy. Following Pries-Heje et al. (2008), the first step, the ex-ante evaluation, was performed during iterations 1 and 2 of the taxonomy development process, in which we already considered the objective ending conditions (cf. Section 2).

Regarding the second step of the evaluation, Nickerson et al. (2013) highlight the importance of the subjective ending criteria (sec) (cf. Table 2). To assess these conditions and to realize a summative evaluation of the perceived usefulness of our taxonomy –the third step– we conducted an expert survey. The assessment of perceived usefulness is directly recommended by Nickerson et al. for summative evaluations and is also one of the most commonly used evaluation criteria for taxonomies (Nickerson et al., 2013, p. 346f.; Szopinski et al., 2019). Since the perceived usefulness is a construct that is not directly measurable, we relied on the six well-known scale items (si) by Davis (1989) as part of our summative evaluation: quickness (si1), performance (si2), productivity (si3), effectiveness (si4), ease (si5), and overall utility (si6). We specified both sec and si for our application context, i.e., for a taxonomy for classifying ARSs supporting workflow execution (sec) and for applying the taxonomy for task accomplishment (si), such as for ARS selection.

The initial questionnaire included an introductory text about the research project, the taxonomy itself, a short explanation of each dimension and characteristic, and associated questions/statements on the sec and si. For data collection, we used interval-scaled verbal-numeric 7-point Likert-style scales. In a pretest, we provided the initial questionnaire to five experienced testers and received feedback that additional information about the taxonomy and context of use would be helpful in answering the questions. Therefore, we supplemented the questionnaire with short examples and a comprehensive handout. For reasons of scientific rigor and comprehensibility, the final questionnaire can be found in Appendix B.

In choosing the sample size, we followed the so-called "10±2 rule" (Hwang & Salvendy, 2010), which states that 8 to 12 respondents are sufficient for usefulness evaluations. Based on an expected response rate of 50%, we sent the questionnaire to a total of 24 experts and received 11 completed questionnaires (actual response rate: 46%). The respondents included a senior manager, an IT project manager, an AR engineer, a software and solution engineer, a multimedia designer, a software developer, two heads of research, two research associates, and one postdoctoral researcher), all working in the ARS and workflow domain. Among the experts, six work in large, 3 in medium-sized, and 2 in micro-companies/organizations.



Note. sec1 = conciseness, sec2 = robustness, sec3 = comprehensiveness, sec4 = extendibility, sec5 = explanatory power, si1 = quickness, si2 = performance, si3 = productivity, si4 = effectiveness, si5 = ease, si6 = overall utility.

Figure 4: Box Plots of Evaluation Results for the Taxonomy

The results of the expert survey are shown as boxplots in Figure 4. The y-axis of each boxplot corresponds to the interval-scaled verbal-numeric 7-point Likert-style scales from the questionnaire. On the x-axis, the scale items of the sec (4a), the perceived usefulness (4b), and the sum score of the scale items of the perceived usefulness (4c) are plotted. Each boxplot is composed of the same elements. The median of the data is shown with a bold line. The grey box represents 50% of the data and starts at the 25% quantile (Q1) and ends at the 75% quantile (Q3). The minimum and maximum of the data, both excluding outliers, are marked above and below the grey box with a thin line connected to the box with a dashed line. The outliers are shown as circles and are defined as those data which lie either 1.5 interquartile ranges (Q3-Q1) above Q3 or below Q1. The underlying data for the boxplots can be found in Appendix C.

The median (m) of the results for sec1, sec2, sec3, and sec5 is, in each case m=6, and the median of the results for sec4 is even m=7. In the evaluation of sec1 and sec3, outliers show up at the level of 4 (partial agreement). However, the overall results show a very high level of agreement, indicating the subjective ending conditions to be fulfilled. Consequently, our taxonomy can be considered concise, robust, comprehensive, extendible, and explanatory.

We also received high levels of agreement for si1, si5, and si6, each with a median of m=6. The median of si4 is m=5, with the voting results fluctuating between 4 (partial agreement) and 7 (strong agreement). The median of si2 is also m=5 and, thus, above the scale level of a partial agreement but shows a greater fluctuation than si4 (scale levels 2 to 7). This results from two respondents scoring below the level of partial agreement. The median of si3 is m=4 (partial agreement). Here, too, the voting results fluctuate quite strongly between the scale levels of 3 and 7. Looking at the medians alone, si1, si2, si4, si5, and si6 show a rating above partial agreement, from which we conclude that the perceived usefulness of the taxonomy was generally rated positively. In particular, the high rating of si6 with m=6 can be seen as a confirmation of the overall usefulness of the taxonomy. This interpretation is also supported by the boxplot of the sum scores of the perceived usefulness calculated from the sums of the scale items of the questionnaire responses. In this boxplot, on a scale of 7-42, the mean is 32.5, and the median is 31.5.

Due to the large fluctuations in the voting results for si2 and si3, we contacted the experts again and offered the possibility to justify results below the scale level of 4 in order to identify possible adaptation potentials for our taxonomy. Three participants responded to this follow-up question. Based on the responses, it appeared that the use of taxonomies is not widespread in practice, which makes it difficult to assess their impact on work performance (si2) and productivity (si3). However, in our opinion, this feedback does not limit the overall usefulness of our taxonomy. Nevertheless, we aim to use the feedback in future research to establish a closer transfer between science and research, e.g., as part of meaningful use cases of our taxonomy.

Exploratory Data Analysis via Identification of Clusters

Overall approach

Cluster analysis is a part of *exploratory data analysis*. While the general aim remains to analyze sets of data objects to identify interesting characteristics, the goal of cluster analysis is to facilitate this by developing meaningful subgroups (*clusters*) from a set of data objects. These clusters are based on similarities – in the widest sense – among objects and are not predefined, i.e., the cluster analysis identifies clusters in the first place (Hair et al., 2009). The precise definition of a cluster is a debated topic within the literature, including notions that the criterion for a "good" *clustering*, i.e., a set of clusters resulting from an applied *clustering algorithm*, is ultimately subjective (Bonner, 1964). From a large number of available cluster algorithms, the appropriate algorithm often needs to be chosen experimentally (Estivill-Castro, 2002). That choice depends on the goals of the cluster analysis but also on the inherent subjectivity in choosing "good" clusterings (Bonner, 1964; Estivill-Castro, 2002).

Ultimately, in order to define archetypes for easy interpretation, we utilize the k-modes algorithm. This algorithm, however, can produce *k* clusterings for any given integer *k*. Therefore, we could generate clusterings for all reasonable numbers of clusters, e.g., k=2-15, and then choose a good clustering based on interpretability and meaningfulness based on our real-world observations (Jick, 1979). To first reduce the number of analyzed clusterings and second, to inform our final decision, we, therefore, utilize *triangulation*, i.e., the combination of quantitative and qualitative methods (Jick, 1979).

More generally, criteria to determine the number of clusters can be ***external*** or ***internal criteria***. External criteria use an independently obtained partition, which is defined a priori to the clustering process (Milligan, 1981). However, external criteria are often not available for empirical data sets, as is the case for our data. Therefore, we utilize *internal criterion analysis*, which determines the "goodness" of a fit between input data and clustering results by using information from the clustering process itself (Milligan & Cooper, 1985). The quantitative and qualitative indicators in our triangulation approach require choices for a specific distance metric and distance measurement method, which define and measure the distances between data objects, i.e., characterized ARSs. We discuss these in the next Section.

Coding and Dimensionality of Data

The choice of distance metric depends on the coding of the data. In our data, we utilize a **binary coding of characteristics** to interpret the expression of the nominally scaled characteristics in our taxonomy, i.e., 1 = ARS has this characteristic; 0 = ARS does not have this characteristic.

The **dimensionality of our *data vector space*** suggests itself as either the number of dimensions (14) or the number of characteristics (83) of our taxonomy. The related works of Püschel et al. (2020) and Arnold et al. (2022) chose the number of dimensions of their taxonomy as the dimensionality of their binary data. To treat all dimensions equally, they normalized the value range to [0;1] for each dimension, i.e., for a taxonomy dimension with n characteristics, the value range is $[0, i/n, \ldots, 1]$ and $i = 1, \ldots, n$.

For our taxonomy, however, this would mean that two ARSs, each offering five different sets of workflow task support functions, would both be positioned at 5/17 on the corresponding workflow task support dimensions of the 14-dimensional data vector space. This would then only describe and compare ARSs by the number of supported workflow task support functions and thus lessen the distinctiveness between ARSs. Applying this example to the rest of our taxonomy, which contains multiple dimensions with high numbers of characteristics, would mean greatly reducing the distinctiveness between ARSs in the data vector space and a consequent loss of information.

We, therefore, opt for an 83-dimensional data vector space, with each dimension corresponding to a characteristic in the taxonomy and a binary value range of [0,1]. Table 3 shows an excerpt from our data.

Characteristic / ARS ID	1	2	3	4	5	6	7	8	9	…	142
Type: Wearable	0	0	0	0	0	0	0	0	0	…	0
Type: Head-mounted	1	0	1	1	1	1	1	0	0	…	0
Type: One-hand Handheld	1	1	0	0	0	0	1	1	1	…	1
Type: Two-hand Handheld	0	0	0	0	0	0	1	0	0	…	1
Type: Stationary Device	0	0	1	0	0	0	0	0	0	…	0
…	…	…	…	…	…	…	…	…	…	…	…
Workflow Task Support: Workflow Training	0	0	0	0	0	0	0	0	0	….	0

Table 3. Example of binary coded data vector space

Distance Metric and Distance Measurement

Since our data is binary, the standard Euclidian distance metric is not appropriate. Two well-known alternative distance metrics for binary data are the Manhattan distance and Jaccard's distance (e.g., Arnold et al., 2022; Püschel et al., 2020). The ***Manhattan distance*** for two objects A and B, is defined as the sum of differing dimensions (Guendouzi & Boukra, 2018, p. 483). For our 81-dimensional data, this means that the distance is an integer between 0 and 81. ***Jaccard's distance*** defines the distance between two objects A and B as the ratio of 1) the sum of different dimensions to 2) the sum of the different dimensions plus those dimensions which are positive for both objects (Jaccard, 1912; Teknomo, 2015). Thus, the distance is a real number between 0 and 1.

To measure the distance between the clusters and select the next two clusters to merge, multiple well-known approaches are available for binary data (Reddy & Vinzamuri, 2014, 101 ff.). One group of approaches compares individual members of clusters. The two clusters, A and B, with the minimum distance between any two of their members $\mathrm{d(a,b)}$ can be chosen, also known as ***single-linkage*** or *single link clustering* (McQuitty, 1957; Sneath & Sokal. R. R., 1962). This approach gives more importance to the regions where the clusters as closest and thus neglects the overall cluster structures, thus making it a *local* similarity-based approach (Reddy & Vinzamuri, 2014). The reverse approach is the merging of the two clusters with the maximum distance between any two of their members, also known as ***complete-linkage*** or *complete link clustering* (King, 1967). This method also considers the overall shapes of the clusters and generally leads to more compact clusters. It is, however, also sensitive to outliers (Reddy & Vinzamuri, 2014).

A second group of approaches considers cluster averages. The distance between two clusters can be measured by calculating the average pair-wise distances for all members of the clusters. This can be done via the ***unweighted pair-group method using arithmetic averages*** (UPGMA), which simply calculates the average distance between the cluster (Sokal & Michener, 1958). This method can be extended by considering the average distances of previously merges clusters, known as the ***weighted pair-group method using an arithmetic average*** (WGPMA) (Sokal & Michener, 1958). Another approach is to measure the distances between the centroids between two clusters, in its simple form known as the ***unweighted pair-group method using centroids*** (UPGMC) (Sokal & Michener, 1958). For this approach, the distance between the centroids of previously merged clusters can also be considered, known as the ***weighted pair-group method using centroids*** (WPGMC) (Gower, 1967). The key formulas for the distance metrics and distance measurements are available in Appendix D.

#

Number of clusters: Quantitative Methods

A great variety of indices are available to calculate the ideal number of clusters for a data set. E.g., the well-known *R* package *NbClust* implements 30 such indices (Charrad et al., 2014) (See Appendix E for the key formulas of the indices). However, as Dimitriadou et al. (2002) find in a comparison of clustering indices for different binary data sets, the reliability of available indices to find good clusterings depends heavily on the underlying data set

(Dimitriadou et al., 2002, pp. 10–19). Therefore, the resulting clusterings can only be a supportive factor in the final decision for the appropriate clustering. As our data does not suggest otherwise, we utilized all 30 indices from the *R* package *NbClust*, each with the Manhattan distance and Jaccard's distance, as well as the distance measuring methods single-linkage, complete-linkage, UPGMA, WPGMA, UPGMC, and WPGMC. The utilized indices of the *NbClust* package are detailed in Charrad et al. (2014). Some indices did not work for our data as there where to many zeros, though. The Hubert Index and D Index are qualitative methods and are discussed later. To ensure a degree of interpretability and meaningfulness of the clustering, we chose an upper limit of 15 clusters for the indices. The complete results for the 19 remaining indices are available in Appendix F, and a summary of the prescribed number of clusters for each pair of distance metrics and the measurement methods is available in Appendix G.

Number of Clusters: Qualitative Methods

As part of our triangulation approach (Jick, 1979), we oriented ourselves methodically on established works (Arnold et al., 2022; Püschel et al., 2020) and utilized a number of qualitative approaches, detailed below. Where applicable, we implemented the methods for all combinations of distance metrics and measurement methods.

One graphical indicator is the calculation of the **within-cluster sum of squares** (WSS) (also known as the *(total) intra-cluster variance)*, which measures the compactness of the clusters and produces a graph that monotonically declines with the number of clusters. An appropriate number of clusters is then indicated with an "elbow" in the graph, i.e., the number of clusters from where onwards a significant, roughly elbow-shaped flattening of the decrease appears (Tibshirani et al., 2001). For implementation, we utilize *R* via the *fviz_nbclust()* function of the *factoextra* package. As a clustering algorithm, we use *Partitioning Around Medoids* (PAM, "cluster::pam") (also known as *k-medoids*) as it is more robust to outliers than the standard *k-means* algorithm and measures dissimilarities instead of summed Euclidian squares, suited for our binary data (Kaufman & Rousseuw, 1990, pp. 68–72). See Appendix H for the plots. For our data, this flattening is not very distinct, but four (main) clusters mostly fulfill these criteria, with a possibility of eight sub-clusters contained therein.

An approach to formalize the "elbow heuristic" and support the decision-making process is **gap statistics**. These compare the WSS for each number of clusters k with their expected values under a null reference distribution of the data. The gap statistic then indicates the "gaps" between the clusterings with k clusters and a random uniform distribution of points (Tibshirani et al., 2001). We implemented the gap statistics test in *R* with the *fviz_nbclust()* function from the *factoextra* package. We used the *PAM* clustering method. See Appendix I for the plots.

Following the interpretation of gap statistics by Tibshirani et al. (2001), the plots indicate four well-separated clusters and eight less-separated sub-clusters within. Even smaller, less defined clusters are indicated as well.

Another criterion for deciding on a good number of clusters is the **average silhouette** approach. This method measures the quality of clusterings with *k* clusters by how well the objects lie within their respective clusters, with high values indicating good fits (Kaufman & Rousseeuw, 1990). We again use *R* for implementation, using the *fviz_nbclust()* function from the *factoextra* package. We again used the *PAM* clustering method. The plots indicate two clusters as the best choice. See Appendix J for the plots.

The plots of the **dendrograms** are available in Appendix K. For both distance metrics, the centroid methods UPGMC and WPGMC did not lead to a *monotone distance* measure, i.e., the resulting dendrograms exhibited so-called inversions or reversals and thus yielded no insightful interpretation. The single-linkage method produced a stairway-formed dendrogram, i.e., each cluster contained approximately one less object than the previous. The interpretation of the remaining dendrograms suggested two, three, five, or six clusters.

The **Hubert Index** and the **D Index** are graphical indices contained in the *NbClust* package. The plots are depicted in Appendix L and M. For both indices, a good number of clusters is indicated by a significant "knee" in the plot, corresponding to a significant peak in the plot of the second differences (right-hand side of the plots) (Charrad et al., 2014). The indices suggest mostly three but also four to seven clusters.

Combination of results

The quantitative and qualitative results show a strong tendency towards 2-4 clusters, but other clusterings are also suggested. Appendix F provides an overview of the results of the quantitative indices, Appendix N for the qualitative indices, and Appendix O for the combined results. Table 4 shows an excerpt from Appendix O for the dominant results of two to four clusters.

	Manhattan distance						Jaccard's distance					
No. of clusters	Single-linkage	Complete-linkage	UPGMA	WPGMA	UPGMC	WPGMC	Single-linkage	Complete-linkage	UPGMA	WPGMA	UPGMC	WPGMC
2	13	5	13	3	2	2	2	10	10	3	10	10
3	14	3-4	3	8	2-3	2-5	1	1	2-4	9-10	2	4
4	2	3-5	3-4	2	2	2-3	3	2	4-5	4	5	2

Table 4: Combined suggested cluster numbers from qualitative and quantitative indications

We subsequently utilized the K-Modes algorithm via the *R* function *kmodes()*of the *klaR* package to produce 2-4 archetypes and discussed these among the authors in light of their interpretability and meaningfulness based on our real-world observations (Jick, 1979). Based on these criteria, ***three archetypes*** were the most meaningful and interpretable. The alternative two and four archetype solutions are shown in Appendix P and Q, and the three archetypes are profiled in Table 5 and discussed in the next Section below.

Archetypes of ARS in support of workflow execution

	Archetype 1 „Advanced HMD“	Archetype 2 „Simple HMD“	Archetype 3 „ Installation“
Type	Head-mounted	*	Stationary Device
Architecture	Single Device	Single Device	*
User System	Single-user	Single-user	Multi-user
Output	Optical See-through	Video See-through	Video See-through
ARS Position Tracking	Relative to Visual Feature-tracked Objects	Image Targets	*
Object Tracking	Visual Feature-based Object Tracking	Visual Marker-based Object Tracking	*
User Interaction Tracking	*	Mechanical & Touch	None
Representation	Text, Image, 2D Form, 3D Form	Text, Image, 2D Form, 3D Form	2D Form, 3D Form
Visual Alignment	Proximity	Proximity	*
User Interaction	Selection	None	None
Content Control	Hybrid	Hybrid	Automatic
Workflow Processing	Implicit Workflow	Implicit Workflow	Implicit Workflow Task
Workflow Management	None	None	None
Workflow Task Support	Instruction, Auxiliary Information	Auxiliary Information	Auxiliary Information

*** = archetype is not strongly specified, i.e., exhibits no strong characteristic in this dimension.**

Table 5: Archetypes

The **first ARS archetype (*Advanced HMD*)** utilizes a head-mounted, single device for a single user, presenting information with an optical see-through display, e.g., a Microsoft HoloLens. Objects are tracked via visual features, and the ARS calculates its position relative to these objects. AR support for workflows is provided by instructions for tasks and auxiliary information. These are visualized via text, image, 2D, and 3D forms and presented in proximity to tracked objects. The user can select certain synthetic content, e.g., items in an AR menu, and the content is controlled hybrid. However, the first archetype is not characterized by a dominant mode of user interaction tracking. The ARS internal representation of workflows is implicit, and no workflow management functions are provided.

The **second ARS archetype (*Simple HMD*)** is also a single-user, single-device system but utilizes see-through video technology, similar to VR headsets. The ARS calculates its position via recognition of image targets and tracks objects similarly with visual markers. User interaction is tracked via mechanical and touch inputs, also utilized for hybrid content control. However, the archetype is also characterized by offering no user interaction with the synthetic content itself, i.e., the user can control which AR content is presented but can not interact with it actively. This content is auxiliary information in support of task execution, presented in the proximity of recognized visual markers, and can be text, images, 2D and 3D forms. The internal representation of workflows is implicit, and no workflow management functions are provided.

The **third ARS archetype (*Installation*)** is a stationary device for multiple simultaneous users. The synthetic content takes the form of 2D and 3D forms, viewed through a display of sorts, i.e., video see-through, explaining how multiple users can see the same content. The information displayed is auxiliary information aimed at supporting specific workflow tasks rather than entire workflows, i.e., a series of tasks. No user interaction is possible, and consequently, no user interaction tracking takes place, and the synthetic content is controlled automatically. The third archetype is not characterized by an ARS position or object tracking method. Unsurprisingly, the archetype also does not utilize visual alignment.

The defined three archetypes do not represent every ARS in the literature but provide an overview and condense the state-of-the-art of ARS in support of workflow execution, management, and control. In this regard, the archetypes represent the underlying data well in that none of them use explicit workflow modeling or offer workflow management functions. Also, the provided workflow task support is very limited, i.e., instructions and generally auxiliary information. In our opinion, this represents clear opportunities for research and development projects for ARSs supporting more numerous and complex workflow management and control functionalities and workflow execution support. Especially when further exploring the underlying dataset, it is clear that most analyzed ARSs focus on specific application scenarios and singular functions. Proof of concepts and demonstrations of innovative approaches to specific problems are clearly valuable for the IS knowledge base. However, it is probable that significant challenges and research opportunities would arise through the integration of multiple different approaches and the consideration of multiple application scenarios ARS simultaneously.

The general lack of workflow management and control functions as well as workflow execution support in the analyzed ARSs may be explained by the lack of formal workflow modeling. Only 10 ARSs use some kind of formal modeling for the logical structure of the synthetic content, none used BPMN, and none explicitly mentioned a workflow engine or WFMS to process these workflow models. Therefore, one promising avenue of research seems to be the integration of ARSs with well-known concepts of workflow management, i.e., workflow management systems (c.f. Workflow Management Coalition (1995b)) and workflow modeling via BPMN.

Applying the Taxonomy for the Design of Novel Augmented Reality Systems

Based on the defined archetypes and the underlying dataset of the 142 analyzed ARSs, we utilize the taxonomy to propose three novel types of ARSs, which – in our opinion – represent promising avenues for research. Two of the proposed ARS are *advanced HMDs,* and one is an *installation*.

First, we envision an *advanced HMD* that addresses the lack of workflow management functions in ARSs. This ARS would implement all functions for WFMS front ends as defined in the well-known WFMS reference architecture by the Workflow Management Coalition, extending the sparse and individual functions identified in the 142 analyzed ARSs (Workflow Management Coalition, 1995b). This ARS would be designed for modeled workflows and explicitly incorporate a WFMS, for which it would act as a front end. Thus, a user could interact with a WFMS while benefiting from other AR-based workflow task support functions, eliminating the need for additional devices and media brakes. This research project would serve as a foundation for future research into the integration of advanced workflow task support functionality. A key challenge of this research project would be how to, in principle, connect the WFMS and ARS, as well as the user interface design of the ARS, in order to ensure usability, i.e., user satisfaction, efficiency, and effectiveness (ISO, 2018).

Second, we propose another *advanced HMD* that focuses on harnessing the potential of more complex workflow-based functions like context-aware workflow path steering and process prescription. This ARS would be designed to support complex, knowledge-intensive workflows, e.g., the repair of an industrial machine. The underlying workflow would be modeled in a standard notation like BPMN to integrate easily with an organization's existing workflow management infrastructure. Each workflow task could be associated with a physical state of the machine, recognized, e.g., via visual feature-based object recognition or internal sensors. Based on past workflow instances and present context information, the ARS would use process prescription to recommend the next best task to the human operator while ensuring their correct execution via automatic deviation detection. A major research question for this type of ARS could be how to model the in-principle infinite complex reality to account for a high percentage of possible error states in a repair workflow and, thus, provide value to an organization while not getting overwhelmed with real-world complexity and incurring prohibitive costs.

Third, we propose a novel type of *installation*. Even though the concepts of ambient or spatial AR are well known (e.g., Bimber & Raskar, 2005), only relatively few ARSs utilize projectors and stationary loudspeakers (cf. Figure

3). In combination with eye-tracking, body pose recognition, and general position tracking, e.g., via RFID, an ARS could generate a seamless yet individual workflow support experience for users in predefined locations. This would be particularly beneficial in settings where workflow participants are not willing or able to use additional wearable, head-mounted, or handheld devices, e.g., for medical reasons or because of necessary equipment or protective gear. A potential application scenario could be care facilities and collaborative workflows for caregivers and people in need of care alike. Such an ARS could project real-time data of ambient sensors only when someone is looking in that direction and provide animated and acoustic warning marks, e.g., for still hot stove tops or when a patient is injured. Routing functions could guide lost objects, people, or specific rooms. These different functions could be modeled as workflows, and a WFMS could integrate the different applications, input sensors, and output devices to facilitate workflow execution support.

In general, interesting research questions for all three proposed research projects include the elements of a design theory for the ARS types (Jones & Gregor, 2007), the UI design, a reference architecture (ISO, 2011), or the application scenarios in which the ARS can provide usability, i.e., user satisfaction, efficiency, and effectiveness (ISO, 2018).

Contributions and Implications to Theory and Practise

As Benbasat and Zmud (2003) point out, it is important to consider the possible use and impact of IT artifacts in order to adequately reflect the interdisciplinary nature of the IS discipline.

From a **theoretical perspective**, our taxonomy contributes a novel analytical lens for existing ARSs, focusing on support for workflows execution, in contrast to related taxonomies and frameworks (Fellmann et al., 2017; Klinker et al., 2018; MacWilliams et al., 2004; Milgram & Kishino, 1994; van Krevelen & Poelman, 2010; Xiangyu Wang et al., 2013). Our taxonomy, thus, not only utilizes different dimensions and characteristics but is also more detailed in some respects, especially regarding the integration with workflow management systems, the modeling of workflows, and the type of workflow support. Our taxonomy, therefore, contributes to the IS knowledge base as an exaptation (Gregor & Hevner, 2013).

More generally, taxonomies contribute to the IS knowledge base by providing a vocabulary of a domain and a set of defined constructs and, thus, establishing a foundation for future research efforts (Hevner et al., 2004; March & Smith, 1995). Taxonomies cannot only be utilized to describe and classify phenomena but can also function as a foundation for sensemaking (Gregor & Hevner, 2013) and theory building (Doty & Glick, 1994). In reference to the theory types defined by Gregor (2006), taxonomies can be utilized as theories for analysis. These represent the most basic forms of theory (Gregor, 2006) and have been termed *taxonomic theories* (Muntermann et al., 2015; Nickerson et al., 2017). Taxonomic theories can serve as a foundation to develop other theories, e.g., explanatory theories or design theories, as the dimensions and characteristics of the taxonomies provide fundamental constructs and relationships (Gregor, 2006; Muntermann et al., 2015; Whetten, 1989). In this context, the taxonomic theory implicitly presented in this article not only serves as an underlying theory for the analysis of the 142 ARSs but also as a foundation for the definition of the ARS archetypes. Further, the proposed research projects for novel ARSs in Section 7 should include the development of design theories, which then would be grounded in the taxonomic theory.

In the context of **research applications**, the developed taxonomy can be used to classify ARSs and consequently apply cluster analysis techniques to the resulting dataset, yielding meaningful and expressive archetypes. These archetypes encapsulate the contemporary state-of-the-art in an easily understandable format. Additionally, the taxonomy and archetypes can be used to design novel artifacts or identify promising avenues of research, as also demonstrated within this article. Therefore, we believe that researchers and developers in the fields of ARS and workflow management can benefit from our taxonomy by steering their efforts in promising directions. Additionally, existing and future ARSs can be formally described via the taxonomy, thus providing an easily comprehensible way to understand the characteristics of an ARS.

For practice, both the taxonomy and archetypes offer value: the taxonomy describes what can be done, and the archetypes describe what has been done. Therefore, organizations designing and developing ARSs can save time and effort by better understanding the problem space and development alternatives. Organizations comparing ARSs during a make-or-buy decision can improve the quality of their decision-making by utilizing the taxonomy to better compare ARSs. In both cases, possible characteristics might be overlooked without the taxonomy. As the analysis of ARSs showed, few ARSs offer complex workflow execution support, but still, these research streams exist and are actively pursued. The taxonomy, therefore, shows a possible–or probable–feature set of future ARSs and thus provides value to long-term IT strategies. While the taxonomy's value for practitioners stems from its details, the archetypes are valuable for their brevity. Theses three types of ARSs serve as a summary of the state-of-the-art tools to enhance communication within organizations when discussing ARSs and their application, esp. in regard to supporting workflow execution. More generally, both the archetypes and taxonomy serve as tools to improve understanding and communication about ARSs by providing a clearly defined vocabulary and concepts.

Conclusion and Outlook

In this work, we present a taxonomy to characterize ARSs supporting workflow execution. Following the methodology of Nickerson et al., we conducted a systematic literature review and consequently identified and classified 142 relevant ARSs in a concept matrix, from which we derived a taxonomy consisting of 14 dimensions and 83 characteristics. We positively evaluated our taxonomy ex-ante with objective ending conditions and ex-post with subjective ending conditions proposed by Nickerson et al., as well as a summative evaluation of the perceived usefulness (Nickerson et al., 2013). Building on this dataset, we performed exploratory data analysis and present three archetypes, summarising the contemporary state-of-the-art of ARSs in support of workflow execution. Based on our findings, we finally propose three novel research avenues.

For an adequate interpretation of our results, the following limitations should be considered. First, we base our taxonomy on the relevant literature we identified with our systematic literature review. Although comprehensive, it is possible that we missed relevant ARSs and consequently relevant characteristics and dimensions, as we did not include all theoretically possible characteristics but only those identified in the analyzed ARSs. However, the amount of ARSs reduces the probability of missing relevant characteristics. This also means that the taxonomy will require updating as AR technology advances. Second, an inherent weakness of any taxonomy development is the subjectivity of the underlying design decisions. As the comparison with the related work showed, other divisions of characteristics are possible (Kalawsky et al., 2000; Klinker et al., 2018; Milgram & Kishino, 1994; Xiangyu Wang et al., 2013). However, our design choices are underpinned by the objective and subjective ending conditions of Nickerson et al. (2013) and the evaluation of our taxonomy with experts. Third, the descriptions of the ARSs were often difficult to interpret in the context of our taxonomy. Therefore, some ARSs might have been classified erroneously. Forth, cluster analysis and the choice of clusterings are inherently subjective. While we based our clustering with three archetypes on both quantitative and qualitative indices, other clusterings are possible. Some indices, for example, suggest sub-archetypes as well. Additionally, the k-means algorithm is only a heuristic and can, in principle, yield different archetypes. These limitations notwithstanding, we do believe that our methodological approach yielded useful contributions, as outlined in Section 8.

Finally, our taxonomy was developed with the rule to only contain characteristics that are actually implemented and not only described in the literature (see oec3, Section 2). Future developments, therefore, might necessitate an update of the taxonomy. Known but hitherto not implemented features might be finally realized, e.g., utilization of the sensory channel of smell. Also, some characteristics suggested themselves and might become interesting in the future but were not taken up for the taxonomy yes since ARSs lacked a detailed description of them, e.g., the operation system (e.g., Windows, Android, iOS, etc.) or the specific device (e.g., Microsoft HoloLens, Varjo XR-3, etc.). Of course, new, hitherto unsuspected characteristics may emerge that are important for an effective overview of ARSs in support of workflow execution. Therefore, to adequately reflect the contemporary market, the taxonomy and archetypes presented herein need to be updated regularly – or discarded eventually. Our future work will strive to ensure the former and avoid the latter.

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Appendix F: Appendix of the article "Understanding Augmented Reality Systems for Workflow Support – A Taxonomy and Archetypical Patterns"

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The original version of this appendix was published as electronic supplementary material to the article "*Understanding Augmented Reality Systems for Workflow Support – A Taxonomy and Archetypical Patterns*", which was submitted to the journal *Electronc* Markets (Springer Nature) and currently awaits a decision.

Understanding Augmented Reality Systems for Workflow Support – A Taxonomy and Archetypical Patterns Appendix

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Appendix A Concept Matrix

Dimension		Characteristic	[2]	[10, 11]	[12]	[13]	[19]	[20]	[25]	[37]	[41]	[28, 29, 48]	[53]	[61]	[99]
			Augmented Reality Systems												
Device	Type	Wearable													
		Head-mounted	X		X	X	X	X	X			X	X	X	X
		One-hand Handheld	X	X					X	X	X				
		Two-hand Handheld							X						
		Stationary Device			X							X			X
	Architecture	Single Device				X	X		X	X	X	X		X	X
		Connected Devices	X	X	X			X							X
		Integrated Devices										X	X		
	User System*	Single-user	X		X		X	X		X	X	X	X		X
		Multi-user				X			X			X		X	
	Output	Projector										X			
		Optical See-through	X		X	X	X		X			X	X	X	X
		Video See-through		X				X	X	X	X				
		Stationary Loudspeaker													
		Mobile Loudspeaker	X			X	X	X	X	X				X	
		Haptic													
Tracking System	ARS Position Tracking	Image Targets	X	X	X	X			X		X	X			X
		Visual Feature-based Object Tracking			X					X				X	
		Spatial Map													
		Networked External Optical Sensors													X
		Inertial and Orientation			X				X					X	
		GPS					X	X							
		RFID							X						
		None											X		
	Object Tracking	Visual Marker-based	X			X			X		X	X			
		Visual Feature-based		X	X					X		X	X	X	X
		Networked External Optical Sensors													
		GPS													
		RFID							X						
		Magnetic													
		None					X	X							
	User Interaction Tracking	Hand Gestures										X	X		
		Eye-tracking	X												
		Body Pose													
		Mechanical & Touch							X	X	X	X			
		Speech	X				X	X	X				X		
		Pointer													
		None		X	X	X								X	X
Synthetic Content	Representation	Text	X			X	X	X	X	X		X		X	X
		Image	X			X	X	X	X	X		X		X	X
		Video								X			X	X	
		2D Form	X			X		X	X	X		X		X	X
		3D Form		X	X	X			X		X		X		X
		Animation		X		X					X	X	X		
		Acoustic	X			X	X	X							
		Haptic													
	Visual Alignment	Fixed					X	X					X		
		Proximity	X						X	X	X	X		X	X
		Non-transparent Overlay	X	X					X	X					
		Transparent Overlay			X	X			X						
	User Interaction	None	X	X	X	X	X	X	X	X				X	X
		Selection										X	X		
		Manipulation									X		X		
	Content Control	Manual													
		Automatic		X	X								X	X	
		Hybrid	X			X	X	X	X	X	X	X			X
Workflow	Workflow Processing*	Implicit Workflow Task			X						X				
		Implicit Workflow	X	X		X	X		X	X		X	X	X	X
		Modelled Workflow & Implicit Workflow Engine						X							
	Workflow Management	None	X	X	X	X	X		X		X		X	X	
		Instantiate Workflow						X		X		X			
		Navigate to Next or Previous Task						X				X			X
		Cancel Workflow								X					
		Change Workflow Path						X							
		Tasklist Overview													
		Switch Workflow Task													
	Workflow Task Support	Process Prescription													
		Visualize Non-visible Real Objects							X						
		Real-time Data				X	X		X			X			
		Automatic Deviation Detection							X						X
		Instruction					X	X	X			X			X
		Demonstration													
		Routing					X								
		Telephone					X								
		Remote Assistance				X			X					X	
		Teleoperation											X		
		Documentation						X	X	X					
		Data Entry						X							
		Data Scanning					X	X							
		Process Modelling													
		Synthetic Object Modelling													
		Auxiliary Information	X	X	X	X	X	X	X	X	X	X		X	X
		Workflow Training													

* = Dimensions with mutually exclusive characteristics

Dimension		Characteristic	Augmented Reality Systems												
			[69]	[81]	[3]	[101]	[106]	[111]	[116]	[118]	[121]	[123]	[126]	[127, 128]	[129]
Device	Type	Wearable													
		Head-mounted			X		X		X			X	X		X
		One-hand Handheld		X		X									
		Two-hand Handheld						X	X						
		Stationary Device	X							X	X				
	Architecture	Single Device		X	X	X	X		X			X		X	
		Connected Devices	X					X		X			X		X
		Integrated Devices									X				
	User System*	Single-user			X	X	X		X	X		X	X		X
		Multi-user	X	X							X			X	
	Output	Projector	X												
		Optical See-through			X		X		X			X	X	X	X
		Video See-through		X		X		X	X	X	X				
		Stationary Loudspeaker	X												
		Mobile Loudspeaker		X										X	
		Haptic												X	
Tracking System	ARS Position Tracking	Image Targets					X			X	X		X	X	X
		Visual Feature-based Object Tracking		X				X							
		Spatial Map			X	X			X			X	X	X	
		Networked External Optical Sensors													
		Inertial and Orientation										X	X	X	
		GPS													
		RFID													
		None	X												
	Object Tracking	Visual Marker-based	X							X	X		X	X	X
		Visual Feature-based		X		X	X	X				X	X	X	
		Networked External Optical Sensors													
		GPS													
		RFID													
		Magnetic									X				
		None			X				X						
	User Interaction Tracking	Hand Gestures					X					X		X	
		Eye-tracking					X							X	
		Body Pose													
		Mechanical & Touch	X			X			X	X	X		X		
		Speech					X		X						
		Pointer													
		None		X	X			X							X
Synthetic Content	Representation	Text	X			X	X		X			X	X	X	
		Image	X		X			X		X		X		X	
		Video			X			X						X	
		2D Form	X	X			X	X				X	X	X	X
		3D Form	X			X		X	X		X	X	X	X	X
		Animation									X			X	
		Acoustic	X				X							X	
		Haptic												X	
	Visual Alignment	Fixed						X	X			X		X	
		Proximity	X	X	X	X			X		X	X	X	X	X
		Non-transparent Overlay						X		X			X	X	X
		Transparent Overlay						X						X	
	User Interaction	None	X	X	X	X		X		X					X
		Selection					X		X			X		X	
		Manipulation									X		X	X	
	Content Control	Manual							X						
		Automatic		X	X			X		X					
		Hybrid	X			X	X				X	X	X	X	X
Workflow	Workflow Processing*	Implicit Workflow Task			X			X					X		
		Implicit Workflow	X	X		X	X		X	X	X	X		X	X
		Modelled Workflow & Implicit Workflow Engine													
	Workflow Management	None		X	X	X	X	X	X	X	X		X		X
		Instantiate Workflow							X			X		X	
		Navigate to Next or Previous Task	X									X		X	
		Cancel Workflow													
		Change Workflow Path													
		Tasklist Overview												X	
		Switch Workflow Task													
	Workflow Task Support	Process Prescription													
		Visualize Non-visible Real Objects						X							
		Real-time Data			X	X		X				X	X		
		Automatic Deviation Detection									X		X		X
		Instruction	X	X			X	X	X	X				X	
		Demonstration	X											X	
		Routing										X			
		Telephone													
		Remote Assistance		X										X	
		Teleoperation								X					
		Documentation							X					X	
		Data Entry							X			X			
		Data Scanning													
		Process Modelling													
		Synthetic Object Modelling													
		Auxiliary Information	X		X	X	X	X	X	X	X	X	X	X	X
		Workflow Training									X				

* = Dimensions with mutually exclusive characteristics

Dimension		Characteristic	Augmented Reality Systems												
			[132]	[140]	[146]	[149]	[152]	[155]	[158]	[161, 162]	[164, 166]	[171, 172]	[179]	[186]	[189]
Device	Type	Wearable	X		X										
		Head-mounted	X	X	X		X	X	X	X	X	X	X	X	
		One-hand Handheld			X			X							X
		Two-hand Handheld				X				X					
		Stationary Device								X					
	Architecture	Single Device		X	X	X	X	X	X	X	X		X		X
		Connected Devices	X							X		X			
		Integrated Devices								X				X	
	User System*	Single-user	X	X	X	X	X	X	X	X	X	X	X	X	X
		Multi-user													
	Output	Projector													
		Optical See-through	X	X	X			X	X	X	X	X	X		
		Video See-through			X	X	X	X						X	X
		Stationary Loudspeaker													
		Mobile Loudspeaker											X		
		Haptic													
Tracking System	ARS Position Tracking	Image Targets	X		X			X	X		X		X	X	
		Visual Feature-based Object Tracking							X	X					
		Spatial Map							X			X			X
		Networked External Optical Sensors											X		
		Inertial and Orientation							X	X		X	X		
		GPS													
		RFID													
		None		X		X	X								
	Object Tracking	Visual Marker-based	X		X	X		X			X	X		X	
		Visual Feature-based				X			X	X					X
		Networked External Optical Sensors													
		GPS													
		RFID													
		Magnetic													
		None		X			X						X		
	User Interaction Tracking	Hand Gestures							X	X		X			
		Eye-tracking													
		Body Pose													
		Mechanical & Touch	X		X	X	X								X
		Speech		X			X				X		X		
		Pointer													
		None						X						X	
Synthetic Content	Representation	Text	X	X	X	X			X	X	X				
		Image	X	X		X			X	X	X		X		
		Video								X	X				
		2D Form	X		X				X	X		X	X		
		3D Form	X		X	X		X	X	X		X		X	X
		Animation	X					X							
		Acoustic											X		
		Haptic													
	Visual Alignment	Fixed	X	X		X					X				
		Proximity	X		X			X	X			X			X
		Non-transparent Overlay	X		X	X		X				X	X		X
		Transparent Overlay	X			X		X		X		X	X	X	
	User Interaction	None	X		X			X		X	X		X	X	
		Selection				X	X		X			X			X
		Manipulation		X					X						X
	Content Control	Manual		X											X
		Automatic						X					X	X	
		Hybrid	X		X	X	X		X	X	X	X			
Workflow	Workflow Processing*	Implicit Workflow Task													
		Implicit Workflow	X	X			X	X	X	X	X	X	X	X	X
		Modelled Workflow & Implicit Workflow Engine			X	X									
	Workflow Management	None						X		X	X	X	X	X	X
		Instantiate Workflow	X	X	X		X								
		Navigate to Next or Previous Task					X		X						
		Cancel Workflow													
		Change Workflow Path				X									
		Tasklist Overview	X												
		Switch Workflow Task			X										
	Workflow Task Support	Process Prescription													
		Visualize Non-visible Real Objects						X				X			X
		Real-time Data										X			
		Automatic Deviation Detection								X					
		Instruction	X		X	X	X		X	X					
		Demonstration							X	X					
		Routing							X			X			
		Telephone													
		Remote Assistance													
		Teleoperation	X									X			
		Documentation			X		X		X	X	X				
		Data Entry			X	X	X		X						X
		Data Scanning													
		Process Modelling		X											
		Synthetic Object Modelling													
		Auxiliary Information	X		X	X	X	X	X	X	X	X	X	X	X
		Workflow Training								X					

* = Dimensions with mutually exclusive characteristics

Dimension		Characteristic	Augmented Reality Systems												
			[190]	[191, 192]	[36, 194]	[196]	[197]	[198, 199]	[200]	[18, 202]	[165]	[206]	[1]	[4]	[5]
Device	Type	Wearable				X	X								X
		Head-mounted	X		X	X		X	X	X	X		X	X	X
		One-hand Handheld												X	
		Two-hand Handheld					X					X			
		Stationary Device		X	X					X	X				X
	Architecture	Single Device	X		X			X	X	X		X	X		
		Connected Devices		X		X	X				X			X	
		Integrated Devices													X
	User System*	Single-user	X	X	X	X		X	X		X	X	x	x	
		Multi-user					X			X					x
	Output	Projector		X							X				
		Optical See-through	X		X			X	X	X	X		x	x	x
		Video See-through				X	X			X	X	X			
		Stationary Loudspeaker								X					
		Mobile Loudspeaker	X							X					x
		Haptic				X	X								
Tracking System	ARS Position Tracking	Image Targets		X		X	X	X	X	X			x	x	
		Visual Feature-based Object Tracking	X		X	X		X				X			
		Spatial Map													
		Networked External Optical Sensors													
		Inertial and Orientation	X		X									x	
		GPS													
		RFID													
		None									X				x
	Object Tracking	Visual Marker-based	X	X		X	X	X	X	X	X		x	x	
		Visual Feature-based			X	X						X			
		Networked External Optical Sensors													
		GPS													
		RFID													
		Magnetic													
		None													x
	User Interaction Tracking	Hand Gestures	X			X		X							x
		Eye-tracking	X											x	
		Body Pose												x	
		Mechanical & Touch		X			X			X	X				
		Speech	X					X						x	x
		Pointer													
		None			X				X			X	x		x
Synthetic Content	Representation	Text		X		X	X		X	X	X			x	
		Image		X		X	X	X	X	X	X		x	x	
		Video						X							
		2D Form		X	X	X	X	X	X	X	X		x		
		3D Form			X		X	X	X	X		X	x		x
		Animation					X		X		X	X			
		Acoustic													x
		Haptic				X	X								
	Visual Alignment	Fixed					X	X	X		X			x	x
		Proximity	X	X	X	X	X	X	X	X	X		x		
		Non-transparent Overlay	X	X	X		X	X				X			
		Transparent Overlay	X		X		X	X	X		X	X			
	User Interaction	None		X	X				X	X	X		x	x	x
		Selection	X			X	X	X							
		Manipulation				X	X			X	X				
	Content Control	Manual													
		Automatic										X	x		x
		Hybrid	X	X	X	X	X	X	X	X	X			x	
Workflow	Workflow Processing*	Implicit Workflow Task			X								x		
		Implicit Workflow	X	X			X	X	X	X		X		x	x
		Modelled Workflow & Implicit Workflow Engine				X					X				
	Workflow Management	None	X	X	X				X	X	X	X	x		x
		Instantiate Workflow				X					X			x	
		Navigate to Next or Previous Task				X		X							
		Cancel Workflow													
		Change Workflow Path									X				
		Tasklist Overview													
		Switch Workflow Task													
	Workflow Task Support	Process Prescription													
		Visualize Non-visible Real Objects	X		X										
		Real-time Data				X									
		Automatic Deviation Detection			X	X			X						
		Instruction		X		X	X	X	X	X	X				
		Demonstration										X			
		Routing													
		Telephone													
		Remote Assistance					X			X					x
		Teleoperation													
		Documentation					X							x	
		Data Entry	X					X						x	
		Data Scanning													
		Process Modelling													
		Synthetic Object Modelling													
		Auxiliary Information	X	X	X	X	X	X	X	X	X	X	x	x	x
		Workflow Training	X				X								

* = Dimensions with mutually exclusive characteristics

Dimension		Characteristic	Augmented Reality Systems												
			[6]	[7]	[21]	[22]	[26]	[30]	[34]	[39]	[44]	[135]	[52]	[56]	[60]
Device	Type	Wearable													
		Head-mounted			X				X	X	X	X			X
		One-hand Handheld		X					X					X	
		Two-hand Handheld					X		X						
		Stationary Device	X	X		X		X		X			X		
	Architecture	Single Device			X		X			X	X	X		X	X
		Connected Devices		X		X			X						
		Integrated Devices	X	X				X					X		
	User System*	Single-user	X		X	X		X			X	X		X	X
		Multi-user		X			X		X	X			X		
	Output	Projector		X		X		X					X		
		Optical See-through			X				X	X	X	X			X
		Video See-through	X						X					X	
		Stationary Loudspeaker													
		Mobile Loudspeaker									X				
		Haptic													
Tracking System	ARS Position Tracking	Image Targets				X	X		X		X				X
		Visual Feature-based Object Tracking	X	X	X				X	X		X			
		Spatial Map													
		Networked External Optical Sensors													
		Inertial and Orientation		X						X				X	X
		GPS												X	
		RFID													
		None						X					X		
	Object Tracking	Visual Marker-based				X			X		X				X
		Visual Feature-based	X	X	X			X	X	X		X	X		
		Networked External Optical Sensors													
		GPS												X	
		RFID													
		Magnetic													
		None					X							X	
	User Interaction Tracking	Hand Gestures						X		X					X
		Eye-tracking													
		Body Pose													
		Mechanical & Touch		X					X					X	
		Speech								X	X				
		Pointer		X	X										
		None	X			X						X	X		
Synthetic Content	Representation	Text					X			X	X			X	X
		Image					X	X	X	X	X				
		Video						X							
		2D Form	X	X		X	X	X	X	X	X	X	X	X	X
		3D Form	X		X	X			X		X			X	X
		Animation											X		
		Acoustic													
		Haptic													
	Visual Alignment	Fixed					X	X		X				X	
		Proximity	X	X			X	X	X	X	X		X	X	X
		Non-transparent Overlay					X		X						
		Transparent Overlay			X	X	X	X	X		X	X	X		X
	User Interaction	None	X			X						X	X		
		Selection			X			X	X	X	X			X	X
		Manipulation		X					X						
	Content Control	Manual													
		Automatic				X						X	X		
		Hybrid	X	X	X		X	X	X	X	X			X	X
Workflow	Workflow Processing*	Implicit Workflow Task													
		Implicit Workflow	X	X	X	X	X	X	X	X	X	X	X	X	X
		Modelled Workflow & Implicit Workflow Engine													
	Workflow Management	None	X	X	X	X	X	X	X			X	X	X	
		Instantiate Workflow								X	X				
		Navigate to Next or Previous Task									X				X
		Cancel Workflow													
		Change Workflow Path													
		Tasklist Overview								X					X
		Switch Workflow Task													X
	Workflow Task Support	Process Prescription													
		Visualize Non-visible Real Objects		X		X			X			X			
		Real-time Data													
		Automatic Deviation Detection													
		Instruction	X					X	X		X			X	X
		Demonstration													
		Routing												X	
		Telephone													
		Remote Assistance					X		X						
		Teleoperation		X											
		Documentation					X			X					
		Data Entry								X					
		Data Scanning													
		Process Modelling													
		Synthetic Object Modelling													
		Auxiliary Information	X	X	X	X		X	X	X	X	X	X	X	X
		Workflow Training													

* = Dimensions with mutually exclusive characteristics

Dimension		Characteristic	Augmented Reality Systems												
			[62–65]	[67]	[72, 73]	[79]	[83]	[84]	[86]	[89]	[93]	[94]	[96]	[97]	[98]
Device	Type	Wearable							X						X
		Head-mounted						X	X		X	X			X
		One-hand Handheld					X								X
		Two-hand Handheld			X		X						X	X	
		Stationary Device	X	X		X				X					
	Architecture	Single Device			X		X				X	X	X	X	
		Connected Devices				X				X					X
		Integrated Devices	X					X	X						
	User System*	Single-user			X		X		X		x	X	X	X	X
		Multi-user	X	X		X		X		X	X				
	Output	Projector				X				X					
		Optical See-through							X		X	X			
		Video See-through	X	X	X		X	X					X	X	X
		Stationary Loudspeaker													
		Mobile Loudspeaker									X			X	
		Haptic													
Tracking System	ARS Position Tracking	Image Targets	X		X		X	X		X					
		Visual Feature-based Object Tracking							X				X		
		Spatial Map					X		X		X				
		Networked External Optical Sensors						X							X
		Inertial and Orientation					X		X		X				
		GPS													
		RFID													
		None		X		X								X	
	Object Tracking	Visual Marker-based	X		X		X	X							
		Visual Feature-based				X			X				X		
		Networked External Optical Sensors						X							
		GPS													
		RFID													
		Magnetic		X											
		None								X	X	X		X	X
	User Interaction Tracking	Hand Gestures				X					X				
		Eye-tracking							X						
		Body Pose							X						
		Mechanical & Touch	X		X		X							X	X
		Speech													
		Pointer													
		None		X			X	X		X		X	X		
Synthetic Content	Representation	Text	X				X		X	X	X	X	X	X	X
		Image					X		X		X	X	X	X	X
		Video												X	
		2D Form	X	X	X	X	X		X	X	X	X	X	X	X
		3D Form	X		X			X			X		X	X	X
		Animation											X	X	X
		Acoustic									X				
		Haptic													
	Visual Alignment	Fixed	X				X							X	X
		Proximity	X		X	X	X	X	X	X	X	X	X		X
		Non-transparent Overlay		X				X							X
		Transparent Overlay	X		X						X	X	X		
	User Interaction	None	X	X		X	X	X	X			X	X		
		Selection			X						X			X	X
		Manipulation			X						X				
	Content Control	Manual													
		Automatic	X	X				X				X	X	X	
		Hybrid			X	X	X		X	X	X				X
Workflow	Workflow Processing*	Implicit Workflow Task		X										X	
		Implicit Workflow	X		X	X	X	X		X	X	X	X		X
		Modelled Workflow & Implicit Workflow Engine							X						
	Workflow Management	None	X	X	X	X	X	X	X	X	X	X	X	X	X
		Instantiate Workflow													
		Navigate to Next or Previous Task													
		Cancel Workflow													
		Change Workflow Path													
		Tasklist Overview													
		Switch Workflow Task													
	Workflow Task Support	Process Prescription													
		Visualize Non-visible Real Objects		X											X
		Real-time Data													
		Automatic Deviation Detection													
		Instruction				X			X	X	X	X	X		X
		Demonstration													
		Routing					X								
		Telephone													
		Remote Assistance								X	X				
		Teleoperation			X									X	
		Documentation													
		Data Entry													
		Data Scanning													
		Process Modelling													
		Synthetic Object Modelling													
		Auxiliary Information	X			X	X	X	X	X	X	X	X	X	X
		Workflow Training													

* = Dimensions with mutually exclusive characteristics

Dimension		Characteristic	Augmented Reality Systems												
			[103]	[102]	[107]	[109]	[110]	[113]	[114]	[117]	[119]	[122]	[125]	[130]	[131]
Device	Type	Wearable			X										
		Head-mounted						X	X		X				
		One-hand Handheld						X							
		Two-hand Handheld						X				X			
		Stationary Device	X	X		X	X		X	X			X	X	X
	Architecture	Single Device			X			X			X	X			
		Connected Devices	X	X			X		X				X	X	
		Integrated Devices				X							X		X
	User System*	Single-user		X	X	X		X	X		X	X			X
		Multi-user	X				X			X			X	X	
	Output	Projector											X		
		Optical See-through			X			X		X	X				X
		Video See-through	X	X		X	X	X	X			X	X	X	
		Stationary Loudspeaker													
		Mobile Loudspeaker										X			
		Haptic													
Tracking System	ARS Position Tracking	Image Targets	X	X					X		X		X	X	X
		Visual Feature-based Object Tracking					X	X				X			
		Spatial Map													
		Networked External Optical Sensors													
		Inertial and Orientation													
		GPS													
		RFID													
		None			X	X				X			X		
	Object Tracking	Visual Marker-based	X	X					X	X	X		X	X	X
		Visual Feature-based				X	X	X		X		X			
		Networked External Optical Sensors													
		GPS													
		RFID													
		Magnetic													
		None			X										
	User Interaction Tracking	Hand Gestures									X				
		Eye-tracking													
		Body Pose													
		Mechanical & Touch	X	X		X									
		Speech													
		Pointer													
		None			X		X	X	X	X			X	X	X
Synthetic Content	Representation	Text	X	X	X			X				X	X		
		Image	X					X				X	X		
		Video					X						X		
		2D Form	X	X						X		X	X	X	X
		3D Form	X	X		X			X		X	X		X	X
		Animation										X			
		Acoustic										X			
		Haptic													
	Visual Alignment	Fixed			X					X					
		Proximity	X	X			X	X	X		X	X		X	
		Non-transparent Overlay				X									X
		Transparent Overlay				X									
	User Interaction	None	X	X	X		X	X	X	X		X	X	X	X
		Selection				X					X				
		Manipulation				X					X				
	Content Control	Manual		X											
		Automatic			X		X	X	X	X			X	X	X
		Hybrid	X			X					X				
Workflow	Workflow Processing*	Implicit Workflow Task			X		X			X					X
		Implicit Workflow	X			X		X	X		X		X	X	
		Modelled Workflow & Implicit Workflow Engine		X								X			
	Workflow Management	None	X		X	X	X	X		X	X		X	X	X
		Instantiate Workflow													
		Navigate to Next or Previous Task		X											
		Cancel Workflow													
		Change Workflow Path							X			X			
		Tasklist Overview													
		Switch Workflow Task													
	Workflow Task Support	Process Prescription							X						
		Visualize Non-visible Real Objects					X								X
		Real-time Data			X								X		
		Automatic Deviation Detection							X						
		Instruction	X	X				X	X			X			
		Demonstration													
		Routing													
		Telephone													
		Remote Assistance										X			
		Teleoperation									X				
		Documentation													
		Data Entry													
		Data Scanning													
		Process Modelling													
		Synthetic Object Modelling													
		Auxiliary Information	X	X	X	X	X	X	X	X	X	X	X	X	X
		Workflow Training		X											

* = Dimensions with mutually exclusive characteristics

Dimension		Characteristic	Augmented Reality Systems												
			[133, 173]	[134]	[137]	[141]	[145, 147]	[148]	[150]	[153]	[156]	[159]	[160]	[163]	[167]
Device	Type	Wearable													
		Head-mounted		X		X						X	X	X	X
		One-hand Handheld		X			X								
		Two-hand Handheld				X				X					
		Stationary Device	X	X	X	X		X	X		X				
	Architecture	Single Device				X	X			X			X	X	X
		Connected Devices				X			X						
		Integrated Devices	X	X	X			X			X	X			
	User System*	Single-user	X	X	X	X	X		X	X	X	X	X	X	X
		Multi-user						X							
	Output	Projector			X										
		Optical See-through		X									X	X	X
		Video See-through	X	X		X	X	X	X	X	X	X			
		Stationary Loudspeaker			X										
		Mobile Loudspeaker					X								
		Haptic							X						
Tracking System	ARS Position Tracking	Image Targets		X	X	X	X		X			X	X	X	
		Visual Feature-based Object Tracking	X					X		X	X				
		Spatial Map													X
		Networked External Optical Sensors													
		Inertial and Orientation										X			X
		GPS													
		RFID													
		None													
	Object Tracking	Visual Marker-based		X	X	X	X		X			X	X	X	
		Visual Feature-based	X					X		X	X				X
		Networked External Optical Sensors													
		GPS													
		RFID													
		Magnetic													
		None													
	User Interaction Tracking	Hand Gestures										X			X
		Eye-tracking													
		Body Pose													X
		Mechanical & Touch		X	X	X	X		X	X					
		Speech													X
		Pointer										X			
		None	X					X			X	X	X	X	
Synthetic Content	Representation	Text		X	X	X	X				X		X		X
		Image		X			X						X		
		Video													
		2D Form			X	X	X	X			X			X	X
		3D Form	X	X		X	X	X	X	X	X	X		X	X
		Animation					X								X
		Acoustic			X		X								
		Haptic							X						
	Visual Alignment	Fixed		X		X									
		Proximity	X	X	X	X	X	X	X		X	X	X	X	X
		Non-transparent Overlay	X	X		X		X		X		X			
		Transparent Overlay	X	X				X		X					X
	User Interaction	None	X	X	X			X			X	X	X	X	
		Selection		X		X	X		X	X					X
		Manipulation								X					X
	Content Control	Manual													
		Automatic	X					X			X			X	
		Hybrid		X	X	X	X		X	X					X
Workflow	Workflow Processing*	Implicit Workflow Task						X						X	
		Implicit Workflow		X		X	X		X	X	X	X	X		X
		Modelled Workflow & Implicit Workflow Engine	X		X										
	Workflow Management	None		X	X	X		X	X	X	X	X	X	X	X
		Instantiate Workflow													
		Navigate to Next or Previous Task													
		Cancel Workflow													
		Change Workflow Path	X				X								
		Tasklist Overview													
		Switch Workflow Task					X								
	Workflow Task Support	Process Prescription	X				X								
		Visualize Non-visible Real Objects	X					X		X				X	
		Real-time Data									X				
		Automatic Deviation Detection													
		Instruction	X			X	X						X		
		Demonstration													
		Routing													
		Telephone										X			
		Remote Assistance													
		Teleoperation		X	X				X		X				X
		Documentation													
		Data Entry					X								
		Data Scanning													
		Process Modelling													
		Synthetic Object Modelling													
		Auxiliary Information	X	X	X	X	X	X	X	X	X	X	X	X	X
		Workflow Training													

* = Dimensions with mutually exclusive characteristics

Dimension		Characteristic	Augmented Reality Systems												
			[168]	[169]	[176]	[177]	[181]	[184]	[185]	[193]	[195]	[201]	[203]	[204]	[205]
Device	Type	Wearable												x	x
		Head-mounted												x	x
		One-hand Handheld										x			
		Two-hand Handheld				x		x			x	x			
		Stationary Device	x	x	x		x		x	x			x		
	Architecture	Single Device				x					x	x			
		Connected Devices			x			x							
		Integrated Devices	x	x			x		x	x			x	x	x
	User System*	Single-user	x	x		x		x				x		x	x
		Multi-user			x		x		x	x	x		x		
	Output	Projector			x										
		Optical See-through							x					x	x
		Video See-through	x	x		x	x	x		x	x	x	x		
		Stationary Loudspeaker													
		Mobile Loudspeaker													x
		Haptic													
Tracking System	ARS Position Tracking	Image Targets	x	x		x		x	x		x	x			
		Visual Feature-based Object Tracking				x							x	x	x
		Spatial Map													
		Networked External Optical Sensors													
		Inertial and Orientation												x	x
		GPS													
		RFID												x	
		None			x		x			x					
	Object Tracking	Visual Marker-based	x	x		x			x		x	x			
		Visual Feature-based		x		x		x					x	x	x
		Networked External Optical Sensors													
		GPS													
		RFID												x	
		Magnetic								x					
		None			x		x								
	User Interaction Tracking	Hand Gestures		x											
		Eye-tracking													
		Body Pose													
		Mechanical & Touch	x	x	x	x		x			x	x		x	x
		Speech													
		Pointer													
		None					x		x	x			x		
Synthetic Content	Representation	Text	x	x		x		x			x	x		x	x
		Image	x					x				x		x	x
		Video					x								x
		2D Form	x	x	x	x		x		x	x	x	x	x	x
		3D Form	x	x		x		x	x		x	x	x	x	x
		Animation			x										
		Acoustic													x
		Haptic													
	Visual Alignment	Fixed	x								x	x		x	x
		Proximity	x	x		x	x	x			x	x		x	x
		Non-transparent Overlay							x	x			x		x
		Transparent Overlay			x				x				x		
	User Interaction	None	x		x		x		x	x	x	x	x		x
		Selection		x		x		x						x	
		Manipulation		x				x							
	Content Control	Manual													
		Automatic	x				x		x	x			x		
		Hybrid		x	x	x		x			x	x		x	x
Workflow	Workflow Processing*	Implicit Workflow Task					x	x	x	x			x		
		Implicit Workflow	x	x	x	x					x	x		x	x
		Modelled Workflow & Implicit Workflow Engine													
	Workflow Management	None	x	x			x	x	x	x	x		x		x
		Instantiate Workflow													
		Navigate to Next or Previous Task	x		x	x						x			
		Cancel Workflow													
		Change Workflow Path												x	
		Tasklist Overview													
		Switch Workflow Task													
	Workflow Task Support	Process Prescription													x
		Visualize Non-visible Real Objects					x		x	x					
		Real-time Data											x		
		Automatic Deviation Detection													
		Instruction	x	x	x	x					x	x		x	x
		Demonstration													
		Routing													
		Telephone													
		Remote Assistance					x				x				
		Teleoperation						x							
		Documentation										x			
		Data Entry													
		Data Scanning													
		Process Modelling													
		Synthetic Object Modelling													
		Auxiliary Information	x	x	x	x	x	x	x		x	x	x	x	x
		Workflow Training								x					x

* = Dimensions with mutually exclusive characteristics

Dimension		Characteristic	Augmented Reality Systems												
			[82]	[8]	[9]	[14]	[24]	[27]	[31]	[32]	[38]	[40]	[42]	[43]	[157]
Device	Type	Wearable													
		Head-mounted		X	X	X		X			X		X		X
		One-hand Handheld													
		Two-hand Handheld	X				X								
		Stationary Device							X	X		X		X	
	Architecture	Single Device	X	X	X	X	X	X							X
		Connected Devices									X				
		Integrated Devices							X	X		X	X	X	
	User System*	Single-user	X	X	X	X	X		X	X	X		X		X
		Multi-user						X				X		X	
	Output	Projector													
		Optical See-through		X				X	X	X	X				X
		Video See-through	X		X	X	X		X			X	X	X	
		Stationary Loudspeaker													
		Mobile Loudspeaker													
		Haptic	X												
Tracking System	ARS Position Tracking	Image Targets	X		X			X							
		Visual Feature-based Object Tracking				X	X		X	X		X	X		X
		Spatial Map													
		Networked External Optical Sensors													
		Inertial and Orientation					X								
		GPS													
		RFID													
		None		X			X				X			X	
	Object Tracking	Visual Marker-based	X		X			X							
		Visual Feature-based			X	X	X		X	X		X	X		X
		Networked External Optical Sensors													
		GPS													
		RFID													
		Magnetic												X	
		None		X							X				
	User Interaction Tracking	Hand Gestures			X										
		Eye-tracking													
		Body Pose													
		Mechanical & Touch	X		X		X		X	X			X		X
		Speech		X											
		Pointer													
		None				X		X			X	X		X	
Synthetic Content	Representation	Text	X	X	X		X						X		X
		Image	X	X			X								
		Video									X				
		2D Form		X	X	X	X	X	X			X	X	X	
		3D Form			X	X		X	X	X		X	X		X
		Animation											X		
		Acoustic													
		Haptic	X												
	Visual Alignment	Fixed		X							X				X
		Proximity	X			X	X	X					X		
		Non-transparent Overlay			X	X			X	X		X		X	X
		Transparent Overlay				X	X		X	X		X			X
	User Interaction	None		X		X		X			X	X	X	X	
		Selection	X		X		X								
		Manipulation			X				X	X					
	Content Control	Manual							X	X					
		Automatic		X		X		X			X	X		X	
		Hybrid	X		X		X						X		X
Workflow	Workflow Processing*	Implicit Workflow Task		X		X		X	X	X	X	X		X	
		Implicit Workflow	X		X		X						X		X
		Modelled Workflow & Implicit Workflow Engine													
	Workflow Management	None		X	X	X		X	X	X	X	X		X	
		Instantiate Workflow					X								
		Navigate to Next or Previous Task	X												
		Cancel Workflow													
		Change Workflow Path													
		Tasklist Overview	X										X		
		Switch Workflow Task													X
	Workflow Task Support	Process Prescription													
		Visualize Non-visible Real Objects				X			X	X		X		X	X
		Real-time Data									X				
		Automatic Deviation Detection													
		Instruction	X			X							X		
		Demonstration													
		Routing													
		Telephone													
		Remote Assistance													
		Teleoperation					X								
		Documentation		X											
		Data Entry													
		Data Scanning													
		Process Modelling													
		Synthetic Object Modelling			X										
		Auxiliary Information	X			X	X	X	X	X	X	X	X		X
		Workflow Training	X					X							

* = Dimensions with mutually exclusive characteristics

Dimension		Characteristic	Augmented Reality Systems											
			[47]	[49]	[51]	[58]	[59]	[66]	[68]	[70]	[71]	[76]	[78]	[80]
Device	Type	Wearable												
		Head-mounted		x			x	x		x				
		One-hand Handheld										x		x
		Two-hand Handheld	x			x	x		x			x		x
		Stationary Device			x				x		x		x	
	Architecture	Single Device	x	x		x		x						x
		Connected Devices					x		x	x		x	x	
		Integrated Devices			x						x			
	User System*	Single-user		x		x	x	x		x	x			x
		Multi-user	x		x				x			x	x	
	Output	Projector							x				x	
		Optical See-through		x			x	x						
		Video See-through	x		x	x	x		x	x	x	x		x
		Stationary Loudspeaker												
		Mobile Loudspeaker										x		
		Haptic							x					
Tracking System	ARS Position Tracking	Image Targets					x		x	x				x
		Visual Feature-based Object Tracking	x	x	x	x	x							
		Spatial Map												
		Networked External Optical Sensors												
		Inertial and Orientation				x								
		GPS												
		RFID												
		None						x			x	x	x	
	Object Tracking	Visual Marker-based					x	x		x				x
		Visual Feature-based	x	x	x	x	x							
		Networked External Optical Sensors												
		GPS												
		RFID					x							
		Magnetic									x			
		None							x			x	x	
	User Interaction Tracking	Hand Gestures								x				
		Eye-tracking												
		Body Pose							x					
		Mechanical & Touch	x	x	x	x	x	x	x			x		
		Speech		x								x		
		Pointer												
		None									x		x	x
Synthetic Content	Representation	Text		x	x	x	x	x				x		x
		Image		x		x	x	x					x	x
		Video		x		x							x	
		2D Form				x	x		x	x	x	x	x	x
		3D Form	x		x	x	x		x	x	x			x
		Animation												x
		Acoustic												
		Haptic							x					
	Visual Alignment	Fixed		x		x	x	x				x		
		Proximity	x	x		x	x		x	x	x	x	x	x
		Non-transparent Overlay	x		x	x					x			
		Transparent Overlay	x		x	x							x	
	User Interaction	None			x						x		x	x
		Selection	x	x		x	x	x	x	x		x		
		Manipulation	x			x			x	x				
	Content Control	Manual												
		Automatic	x		x						x		x	x
		Hybrid		x		x	x	x	x	x		x		
Workflow	Workflow Processing*	Implicit Workflow Task	x		x		x		x	x	x	x		x
		Implicit Workflow		x		x		x					x	
		Modelled Workflow & Implicit Workflow Engine												
	Workflow Management	None	x		x				x	x	x	x	x	x
		Instantiate Workflow		x				x						
		Navigate to Next or Previous Task				x	x							
		Cancel Workflow		x										
		Change Workflow Path												
		Tasklist Overview				x								
		Switch Workflow Task												
	Workflow Task Support	Process Prescription												
		Visualize Non-visible Real Objects	x		x	x					x			
		Real-time Data					x							
		Automatic Deviation Detection												
		Instruction				x	x						x	
		Demonstration												
		Routing												
		Telephone												
		Remote Assistance		x					x			x		
		Teleoperation												
		Documentation		x										
		Data Entry												
		Data Scanning						x						
		Process Modelling								s				
		Synthetic Object Modelling												
		Auxiliary Information			x	x	x			x	x		x	x
		Workflow Training												

* = Dimensions with mutually exclusive characteristics

Appendix B Questionaire

Questionnaire on the Perceived Usefulness of a Taxonomy for Augmented Reality Systems Supporting Workflow Execution

Recently, several approaches have emerged that support workflow execution with augmented reality systems (ARS) and address the challenge of providing contextual information to users. Although there have been some efforts to systematise existing ARSs, to the best of our knowledge there is no holistic taxonomy addressing the dimensions and properties of ARSs in the context of workflow execution support. The purpose of our research is to identify these dimensions and properties, which can be used to classify existing ARS and identify potentials for new systems as well as research gaps. The result of our study is a taxonomy consisting of 4 categories, 14 dimensions and 83 characteristics. The taxonomy is intended to–inter alia–help practitioners in the selection and comparison of ARSs to support workflow execution, and system developers and researchers in the categorization and analysis of ARSs as well as in the identification of new ARS topics and issues.

In this questionnaire, we aim to evaluate the perceived usefulness of the taxonomy addressed. Please complete the following questionnaire.

All questions will be collected completely anonymously and will only be used for the purpose of evaluating the taxonomy. The data will be aggregated for the purpose of evaluation and used in particular within the framework of descriptive evaluations. It is not possible to draw any conclusions about your personal response behaviour from these evaluations.

After completion of the research project, your data will be deleted immediately. Answering all questions is completely voluntary, i.e. you are welcome to refrain from answering individual questions or the entire questionnaire. If you are interested in the results of the survey, please reach out via e-mail. The questionnaire will take about 10 minutes to complete. Thank you for your willingness to participate in our survey!

Yours sincerely,

Johannes Damarowsky, Stephan Kühnel, Tobias Seyffarth and Stefan Sackmann.

Please answer the questions below with one of the following scenarios in mind:

Scenario for practitioners:

Imagine that you're tasked selecting an ARS to support the execution of your organizations workflows. Multiple ARSs are available and a discussion among management has started, which ARS to select. To support your decision-making, you can use all your existing prior knowledge. Additionally, you're provided with the taxonomy above.

Scenario for researchers and developers:

Imagine that you're tasked with designing and conceptualizing an ARS, which should support workflow execution. You are at the very beginning of your design and conceptualization process. You can use all your existing prior knowledge and are additionally provided with the taxonomy above.

Statements on the Perceived Usefulness of a Taxonomy for Augmented Reality Systems Supporting Workflow Execution

	Strongly disagree			Partly agree			Strongly agree	Not specified
(1) The taxonomy enables me to accomplish tasks more quickly (i.e., choosing the right ARS for workflow support or identifying new AR issues).	☐	☐	☐	☐	☐	☐	☐	☐
(2) Using the taxonomy improves my job performance (i.e., choosing the right ARS for workflow support or identifying new AR issues).	☐	☐	☐	☐	☐	☐	☐	☐
(3) Using the taxonomy increases my productivity (i.e., choosing the right ARS for workflow support or identifying new AR issues).	☐	☐	☐	☐	☐	☐	☐	☐
(4) Using the taxonomy enhances my effectiveness on the job (i.e., choosing the right ARS for workflow support or identifying new AR issues).	☐	☐	☐	☐	☐	☐	☐	☐
(5) Using the taxonomy makes it easier to do my job (i.e., choosing the right ARS for workflow support or identifying new AR issues).	☐	☐	☐	☐	☐	☐	☐	☐
(6) Overall, I find the taxonomy useful in my job.	☐	☐	☐	☐	☐	☐	☐	☐

Conciseness, Robustness, Comprehensiveness, Extendability and Explanatory Power of the Taxonomy

	Strongly disagree			Partly agree			Strongly agree	Not specified
(7) Conciseness Does the number of dimensions allow the taxonomy to be meaningful without being unwieldy or overwhelming?	☐	☐	☐	☐	☐	☐	☐	☐
(8) Robustness Do the dimensions and characteristics provide for differentiation among objects (i.e., ARSs) sufficient to be of interest?	☐	☐	☐	☐	☐	☐	☐	☐
(9) Comprehensiveness Can all objects (i.e., ARSs) or a (random) sample of objects within the domain of interest be classified?	☐	☐	☐	☐	☐	☐	☐	☐
(10) Extendability Can a new dimension or a new characteristic of an existing dimension be easily added?	☐	☐	☐	☐	☐	☐	☐	☐
(11) Explanatory Power Are the dimensions and characteristics of objects (i.e., ARSs) sufficiently explained?	☐	☐	☐	☐	☐	☐	☐	☐

Socio-demographic Data

For reasons of data analysis we would be pleased to receive some voluntary socio-demographic data from you.

(12) What sex are you?

☐ male ☐ female ☐ Diverse

(13) How old are you?

__________________ years

(14) How much professional experience do you have?

__________________ years

(15) What industry do you work in?

☐ Consulting
☐ Finance
☐ Research and Development
☐ IT services
☐ Insurance
Other: ________________________

(16) To which category can the company or institution in which you work be assigned?

☐ Micro enterprise (fewer than 9 employees and up to 2 Mio. Euro annual revenue)
☐ Small enterprise (fewer than 9 employees and up to 10 Mio. Euro annual revenue)
☐ Medium-sized enterprise (fewer than 249 employees and up to 50 Mio. Euro annual revenue)
☐ Large enterprise (more than 249 employees and more than 50 Mio. Euro annual revenue)

(17) What is your current job role?

____

You are welcome to leave further comments on the perceived usefulness of the taxonomy.

____

____

Thank you very much for your time and participation in the survey!

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Appendix C Dataset of Questionnaire Responses

Question No.	Items	Questionnaire Response No.					
		1	2	3	4	5	6
1	si1	7	6	6	6	5	4
2	si2	7	2	3	4	5	NA
3	si3	7	3	3	3	5	4
4	si4	7	6	5	5	5	NA
5	si5	6	5	6	5	7	5
6	si6	7	6	6	6	7	6
7	sec1	7	6	6	4	6	6
8	sec2	7	6	5	5	6	6
9	sec3	7	6	6	6	4	5
10	sec4	7	7	6	6	7	6
11	sec5	7	7	6	6	6	7
12	sd1	m	m	m	w	m	m
13	sd2	34	53	30	27	34	31
14	sd3	7.5	25	4	4	9	5
15	sd4	R&D	R&D	R&D	R&D	R&D	Consulting, R&D, IT-Services
16	sd5	large	large	micro	micro	large	medium
17	sd6	PostDoc	Head of Research	Software Developer	Multimedia Design	Research Associate	Software & Solution Engineer

Note. si = scale items by Davis [46]
sec = subjective ending criteria by Nickerson et al. [151]
sd = socio-demographic questions

Question No.	Items	Questionnaire Response No.				
		7	**8**	**9**	**10**	**11**
1	**si1**	5	6	5	7	5
2	**si2**	7	5	6	5	5
3	**si3**	5	4	5	5	4
4	**si4**	7	4	5	6	5
5	**si5**	7	4	6	6	5
6	**si6**	7	5	6	6	6
7	**sec1**	6	NA	6	7	7
8	**sec2**	7	7	6	7	6
9	**sec3**	7	7	6	7	7
10	**sec4**	7	7	6	7	7
11	**sec5**	6	7	6	7	6
12	**sd1**	m	d	m	m	m
13	**sd2**	25	36	31	34	31
14	**sd3**	4	13	10	10	4.5
15	**sd4**	Consulting, R&D	IT-Services, R&D	Consulting, R&D	Consulting, IT-Services	Consulting, IT-Services
16	**sd5**	large	large	large	medium	medium
17	**sd6**	AR-Engineer, Research Associate	Research Associate	Research Associate	Senior Manager	IT-Project Manager

Note. si = scale items by Davis [46]
sec = subjective ending criteria by Nickerson et al. [151]
sd = socio-demographic questions

Appendix D Distance Metrics and Distance Measurements

The ***Manhattan distance*** (dm_{AB}) for two objects A and B is defined as [88]:

$$dm_{AB} = \sum_{i=1}^{n} |A_i - B_i| \tag{1}$$

$i \in \mathbb{N}$,
$n = number\ of\ dimensions\ in\ vector\ space$
$A = (a_1, \dots, a_n)$
$B = (b_1, \dots, b_n)$

Jaccard's distance (dj_{AB}), which is derived from Jaccard's index s_{AB} for similarity of two objects A and B [108, 187] is defined as:

$$dj_{AB} = 1 - s_{AB} = 1 - \frac{q+r}{p+q+r} = \frac{q+r}{p+q+r} \tag{2}$$

p = number of variables that are positive for both objects
q = number of variables that are positive for object A and negative for object B
r = number of variables that are positive for object B and negative for object A

$d_{single-linkage}(A,B) := \min_{a \in A, b \in B} \{d(a,b)\}$	[139, 182]
$d_{complete-linkage}(A,B) := \max_{a \in A, b \in B} \{d(a,b)\}$	[115]
$d_{UPGMA}(A,B) := \frac{1}{\lvert A \rvert \cdot \lvert B \rvert} \sum_{a \in A, b \in B} d(a,b)$ $d_{UPGMA}(A \cup B, C) := \frac{1}{\lvert A \cup B \rvert \cdot \lvert C \rvert} \sum_{x \in A \cup B, c \in C} d(x,c)$	[183]
$d_{WPGMA}(A \cup B, C) := \frac{D(A,C) + D(B,C)}{2} = \frac{d_{UPGMA}(A,C) + d_{UPGMA}(B,C)}{2}$ $A \cup B = clusters\ A\ and\ B\ merged\ in\ a\ previous\ step$	[183]
$d_{UPGMC}(A,B) := d(\vec{a}, \vec{b})$ $\vec{a} = centroid\ of\ cluster\ A$ $\vec{b} = centroid\ of\ cluster\ B$	[183]
$d_{WPGMC}(A,B) := d(\overrightarrow{A \cup B}, \vec{C})$ $A \cup B = clusters\ A\ and\ B\ merged\ in\ a\ previous\ step$ $\overrightarrow{A \cup B} = \frac{1}{2}(\vec{A} + \vec{B}) = mean\ of\ centroids\ of\ clusters\ A\ and\ B$ $\vec{C} = centroid\ of\ cluster\ C$	[87]

Appendix E Key Formulas of the Indices in the *R* package *NbClust*

Also known as	Name in NbClust	Key Equation in the nomenclature of 35 [35]	Associated sources
Ball Index	ball	Ball = $\frac{W_q}{q}$	[16], [144], [50]
Beale Index	beale	$Beale = F \equiv \frac{\left(\frac{W_m - W_k - W_l}{W_k + W_l}\right)}{\left(\left(\frac{n_m - 1}{n_m - 2}\right) 2^{\frac{2}{p}} - 1\right)}$	[17], [85]
Cubic Clustering Criterion	ccc	$CCC = \ln\left[\frac{1 - E(R^2)}{1 - R^2}\right] * \frac{\sqrt{\frac{np^*}{2}}}{(0.001 + E(R^2))^{1.2}}$	[178], [144]
Caliński-Harabasz Index, CH Index	ch	$CH\ (q) = \frac{\frac{trace(B_q)}{(q-1)}}{\frac{trace(W_q)}{(n-q)}}$	[33]
C-Index	cindex	$Cindex\ = \frac{S_w - S_{min}}{S_{max} - S_{min}}, S_{min}\ \neq\ S_{max}\ Cindex\ \in\ (0,1)$	[105], [85], [144]
Davies-Bouldin Index, DB Index	db	$DB(q) = \frac{1}{q}\sum_{k=1}^{q} \max_{k \neq l}\left(\frac{\delta_k + \delta_l}{d_{kl}}\right)$	[45], [144]
Duda–Hart, Duda Index, $\mathrm{Je}(2)/\mathrm{Je}(1)$ Criterion	duda	$Duda = \frac{Je(2)}{Je(1)} = \frac{W_k + W_l}{W_m}$	[54], [85], [144]
Dunn Index	dunn	$Dunn = \frac{\min_{1 \leq i < j \leq q} d(C_i, C_j)}{\max_{1 \leq k \leq q} diam(C_k)}$	[55]
Dindex	dindex	$w(P^q) = \frac{1}{q}\sum_{k=1}^{q} \frac{1}{n_k} \sum_{x_i \in C_k} d(x_i, c_k)$	[124]
Friedman Index	friedman	Friedman = $trace(W_q^{-1} B_q)$	[75]
Frey Index	frey	$Frey = \frac{\bar{S}_{b_{j+1}} - \bar{S}_{b_j}}{\bar{S}_{w_{j+1}} - \bar{S}_{w_j}}$	[74], [144]
Gamma Index	gamma	$Gamma = \frac{s(+) - s(-)}{s(+) + s(-)}$	[15], [85], [144]
Gap Index	gap	$Gap(q) = \frac{1}{B}\sum_{b=1}^{B} \log W_{qb} - \log W_q$	[188]
$\mathrm{G}(+)$	gplus	$Gplus = \frac{2s(-)}{N_t(N_t - 1)}$	[174], [143], [144]
Hartigan Index	hartigan	$Hartigan = \left(\frac{trace(W_q)}{trace(W_{q+1})} - 1\right)(n - q - 1)$	[95], [144]
Hubert's Γ statistic	hubert	$\Gamma(P, Q) = \frac{1}{N_t}\sum_{i=1, i<j}^{n-1} P_{ij} Q_{ij}$	[104], [23], [90]
KL Index	kl	$KL(q) = \left\lvert\frac{DIFF_q}{DIFF_{q+1}}\right\rvert$	[120]

Marriot Index	marriot	$Marriot = q^2 \det(W_q)$	[136], [144]
McClain Index, McClain and Rao Index,	mcclain	$McClain = \frac{\bar{S}_w}{\bar{S}_b} = \frac{\frac{S_w}{N_w}}{\frac{S_b}{N_b}}$	[138]
Point-Biserial Correlation	ptbiserial	$Ptbiserial = \frac{[\overline{S_b} - \overline{S_w}]\left[\frac{N_w N_b}{N_t^2}\right]^{\frac{1}{2}}}{s_d}$	[142], [143], [144]
Pseudo t^2	pseudot2	$Pseudot2 = \frac{V_{kl}}{\frac{W_k + W_l}{n_k + n_l - 2}}$	[54], [85]
Ratkowsky-Lance Index	ratkowsky	Ratkowsky = $\frac{\bar{S}}{q^{0,5}}$	[170], [144], [100]
Rubin Index	rubin	Rubin = $\frac{\det(T)}{\det(W_q)}$	[75]
SDindex	sdindex	$SDindex(q) = Scat(q) + Dis(q)$	[92]
SDbw calidity index	sdbw	$SDbw(q) = Scat(q) + Density.bw(q)$	[91]
Scott Index	scott	Scott = $n \log \frac{\det(T)}{\det W_q}$	[180], [144]
Silhouette Index	silhouette	$Silhouette = \frac{\sum_{i=1}^{n} S(i)}{n}, Silhouette \in [-1,1]$	[175], [112]
τ Index	tau	Tau = $\frac{s(+) - s(-)}{\left[\left(\frac{N_t(N_t-1)}{2-t}\right)\left(\frac{N_t(N_t-1)}{2}\right)\right]^{0,5}}$	[174], [143], [144]
$trace(COV(W_q))$	trcovw	Trcovw = $trace(COV(W_q))$	[144], [50]
$trace(W_q)$	tracew	Tracew = $trace(W_q)$	[144], [57], [75], [154], [77]

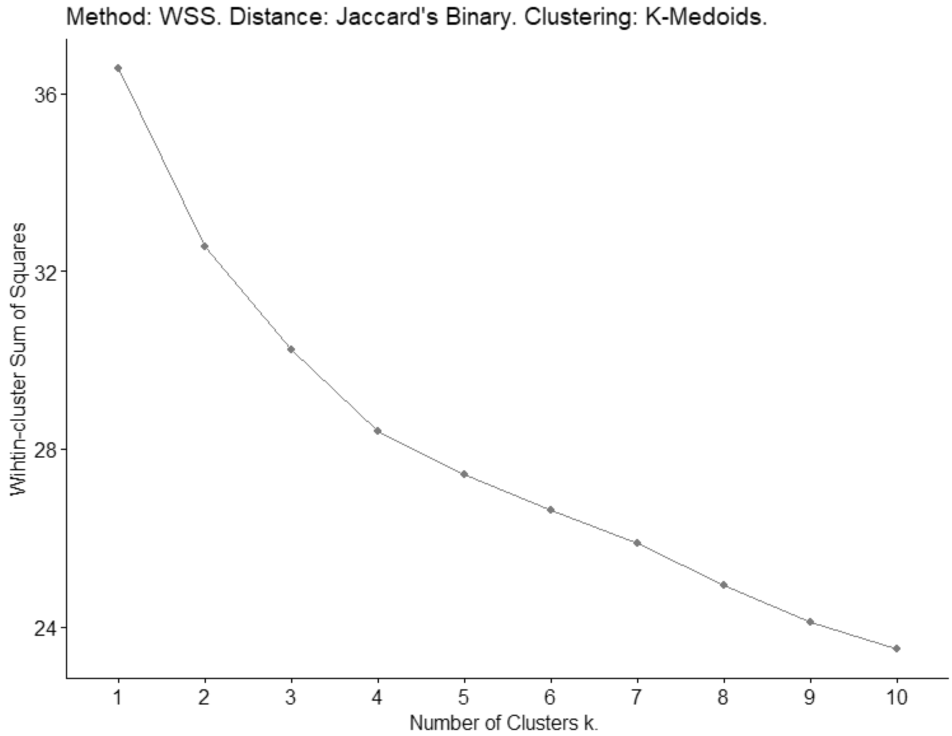
Appendix F Results of Quantitative Indices via *R*'s *NbClust* package

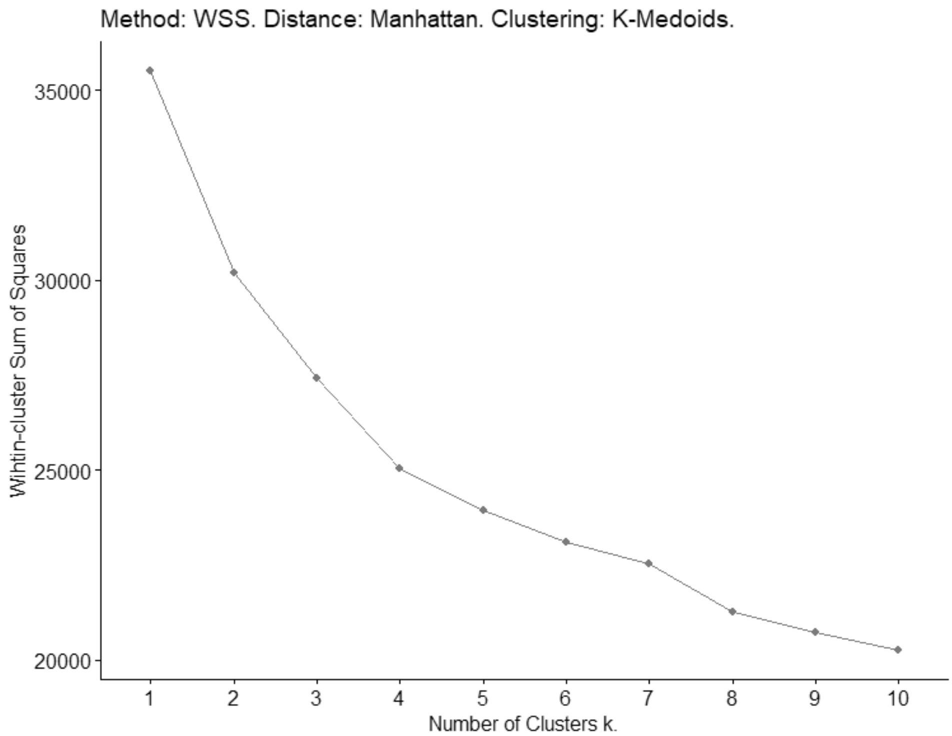
Also known as	Name in NbClust	Manhattan distance						Jaccard's distance					
		Single-linkage	Complete-linkage	UPGMA	WPGMA	UPGMC	WPGMC	Single-linkage	Complete-linkage	UPGMA	WPGMA	UPGMC	WPGMC
Ball Index	ball	3	3	3	3	3	3	3	3	3	3	3	3
Caliński-Harabasz Index, CH Index	ch	2	3	6	3	2	2	8	2	4	3	4	7
C-Index	cindex	15	2	15	8	15	15	15	7	15	15	15	14
Davies-Bouldin Index, DB Index	db	2	15	2	2	2	2	2	15	2	15	4	2
Duda–Hart, Duda Index, $Je(2)/Je(1)$ Criterion	duda	2	5	2	3	2	2	2	2	2	4	2	2
Dunn Index	dunn	2	2	2	2	2	2	2	13	2	12	2	2
Frey Index	Frey	1	1	3	2	9	5	2	2	2	1	1	3
Gamma Index	gamma	2	15	2	2	2	2	6	15	15	15	2	2
Gap Index	gap	2	2	2	2	2	2	2	2	2	2	2	2
$G(+)$	gplus	2	15	2	2	2	2	2	15	2	15	2	2
Hartigan Index	hartigan	3	3	4	3	10	3	13	7	3	3	8	7
KL Index	kl	2	14	13	3	10	12	2	2	9	3	2	3
McClain Index, McClain and Rao Index,	mcclain	2	2	2	2	2	2	2	2	2	2	2	2
Point-Biserial Correlation	ptbiserial	10	11	15	14	15	12	13	6	8	9	15	14
Pseudo t^2	pseudot2	2	5	2	3	2	2	2	2	2	4	2	2
Ratkowsky-Lance Index	ratkowsky	10	5	6	9	10	10	13	7	6	3	14	11
SDindex	sdindex	10	11	2	2	14	15	8	13	2	9	13	14
SDbw validity index	sdbw	15	15	2	2	15	15	12	15	13	15	15	15
Silhouette Index	silhouette	2	2	2	2	2	2	2	2	15	3	2	2
2τ Index	tau	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	2	∞

Appendix G Number of Clusters prescribed by *NbClust* indices

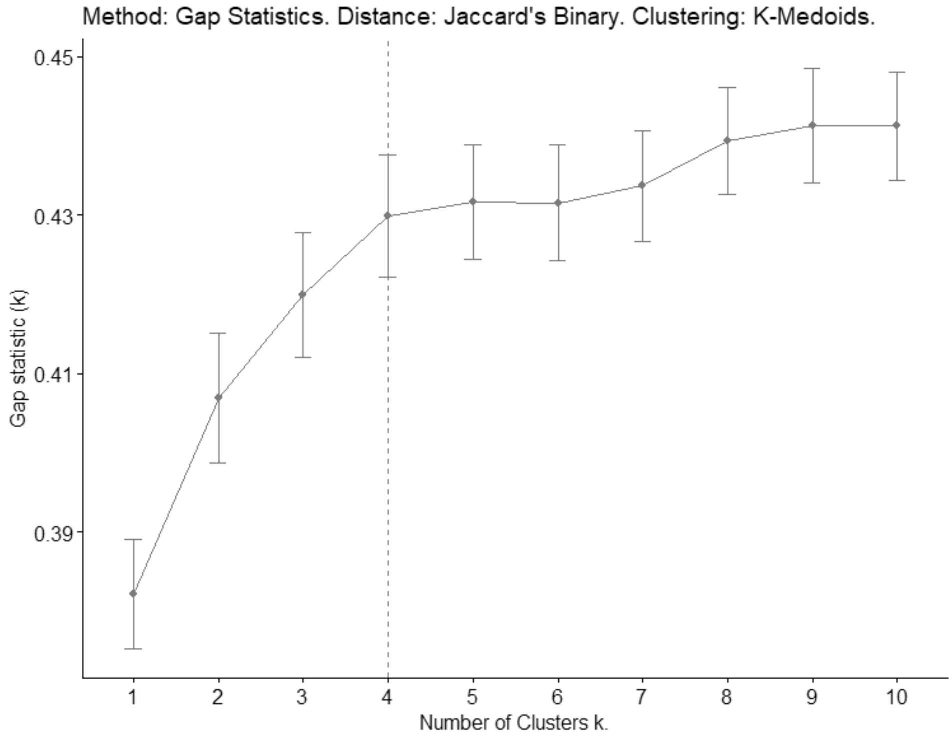
Number of clusters	The number of indices prescribing the number of clusters, depending on distance metric and measurement method. All indices are limited to 15 clusters maximum.											
	Manhattan distance						Jaccard's distance					
	Single-linkage	Complete-linkage	UPGMA	WPGMA	UPGMC	WPGMC	Single-linkage	Complete-linkage	UPGMA	WPGMA	UPGMC	WPGMC
1	1	1								1	1	
2	11	5	11	1	1	1	1	8	9	2	9	9
3	2	3	2	6	1	2	1	1	2	6	1	3
4			1						1	2	2	
5		3				1						
6			2				1	1	1			
7								3				2
8				1			2		1		1	
9				1	1				1	2		
10	3				3	1						
11		2										1
12						2	1			1		
13			1				3	2	1		1	
14		1		1	1						1	3
15	2	4	2		3	3	1	4	3	5	3	1

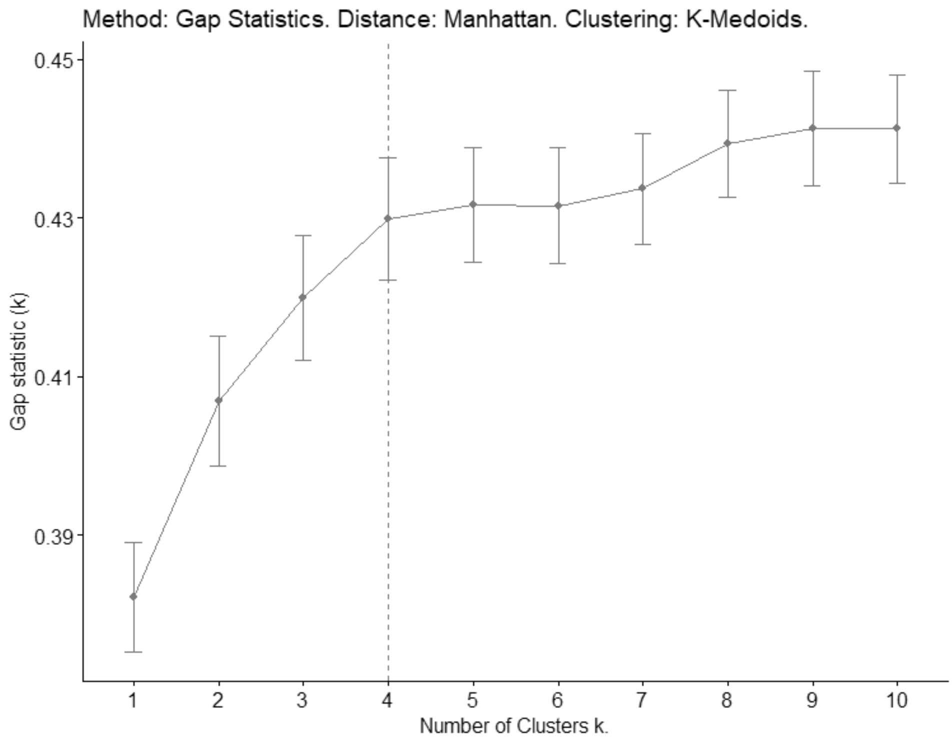
Appendix H Plots for Within-Cluster Sum of Squares



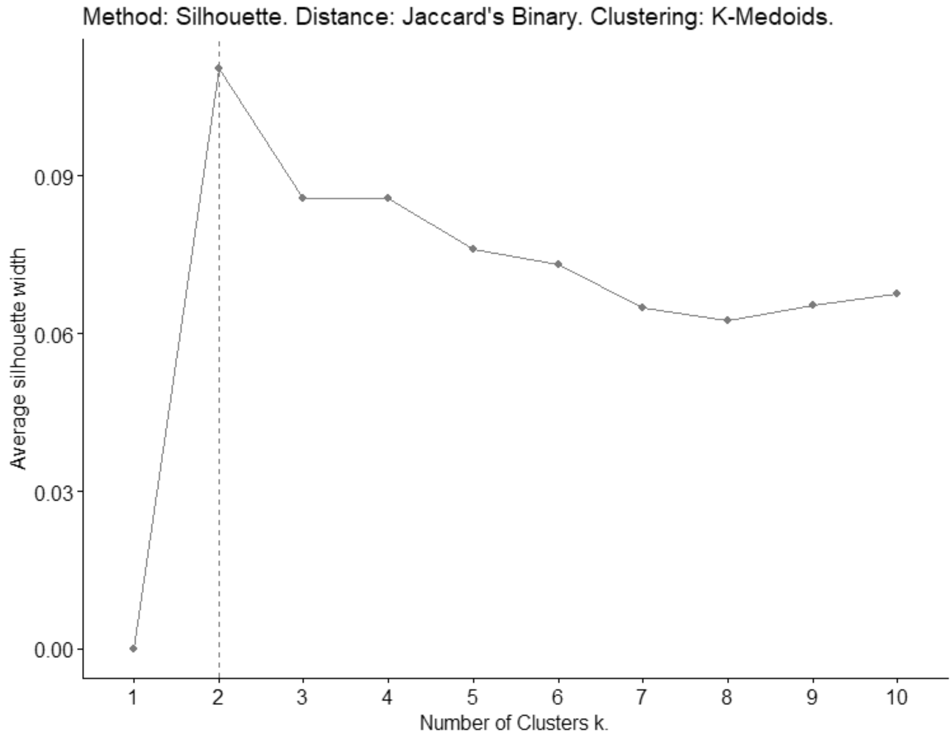


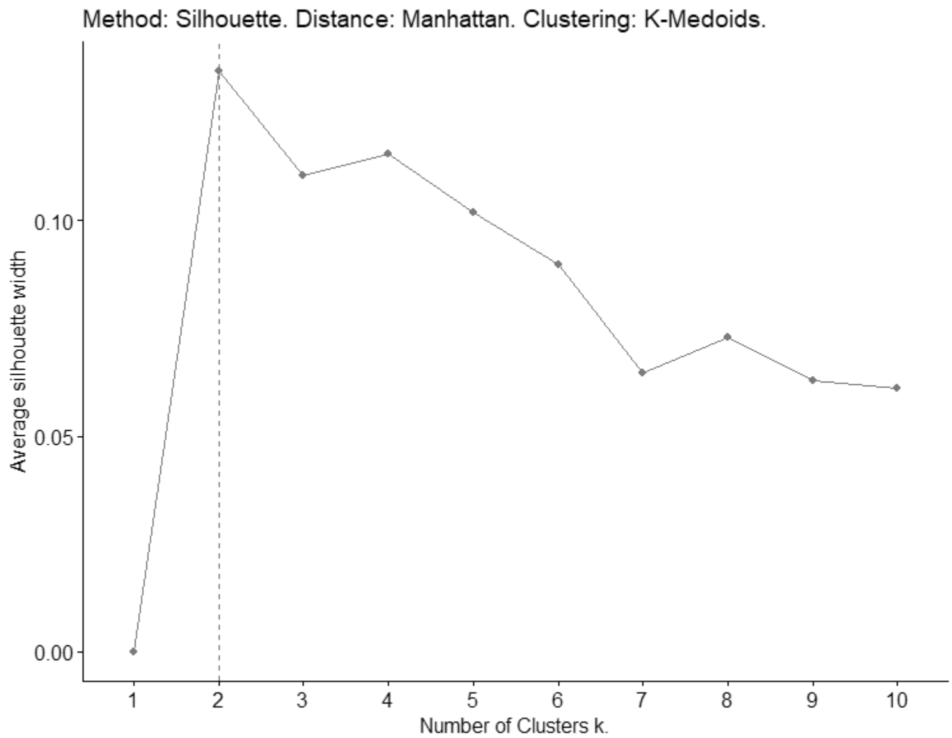
Appendix I Plots for Gap Statistic



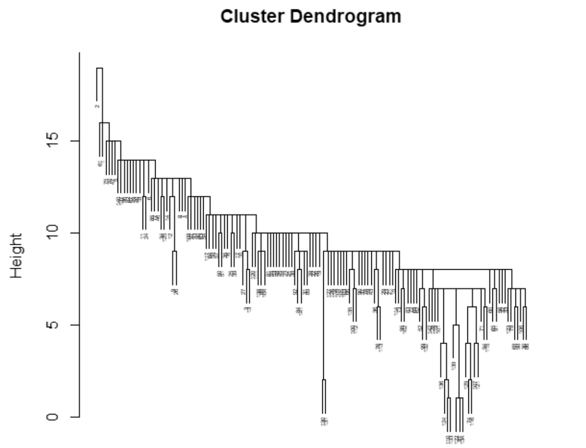


Appendix J Plots of Shilouette

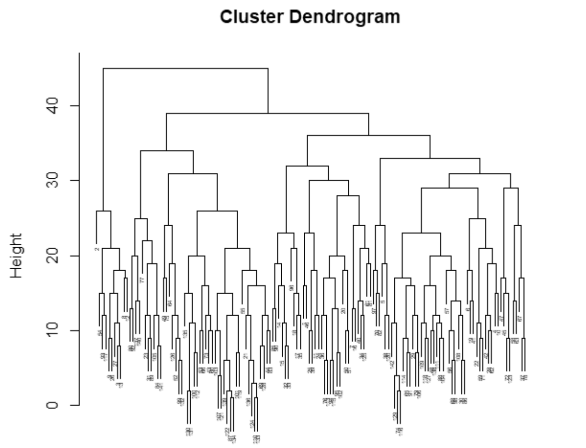




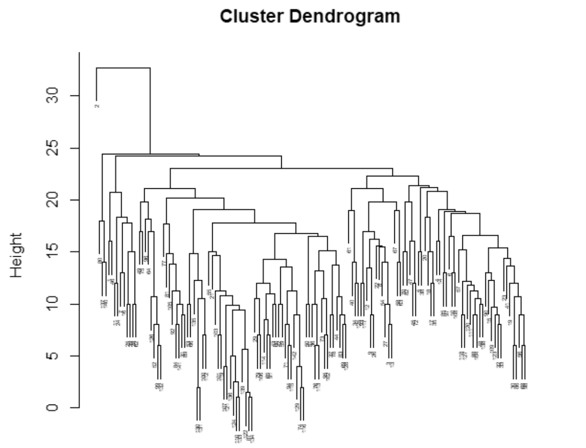
Appendix K Dendograms



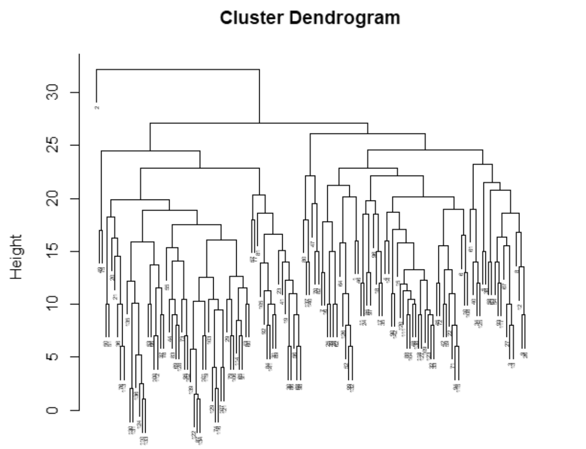
Manhattan Distance, Single-linkage



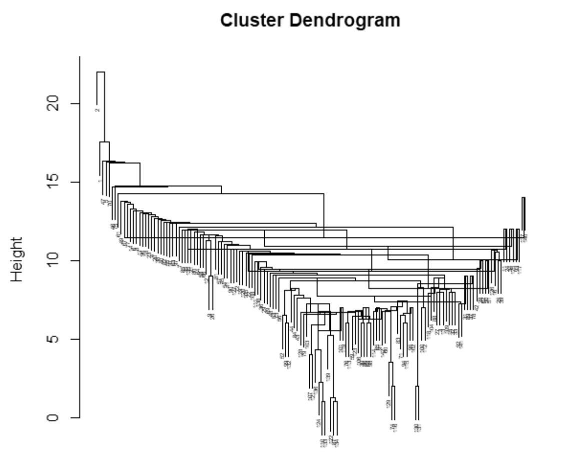
Manhattan Distance, Complete -linkage



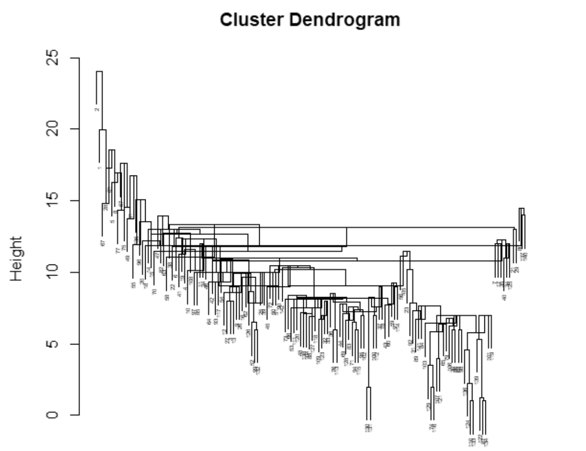
Manhattan Distance, UPGMA



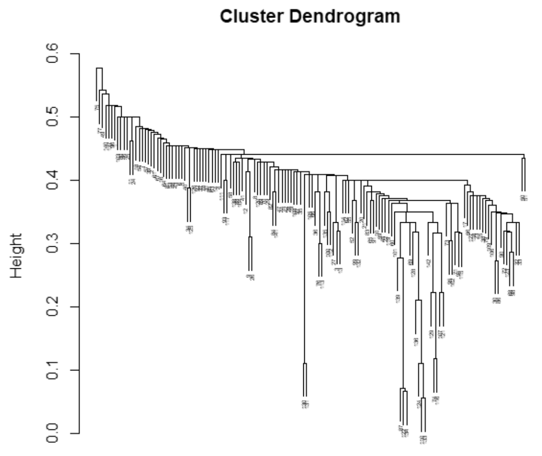
Manhattan Distance, WPGMA



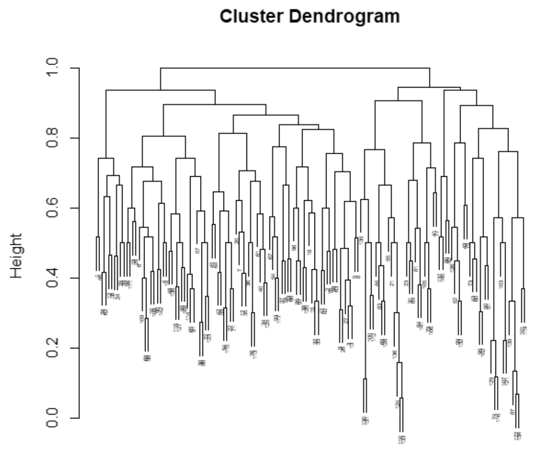
Manhattan Distance, UPGMC



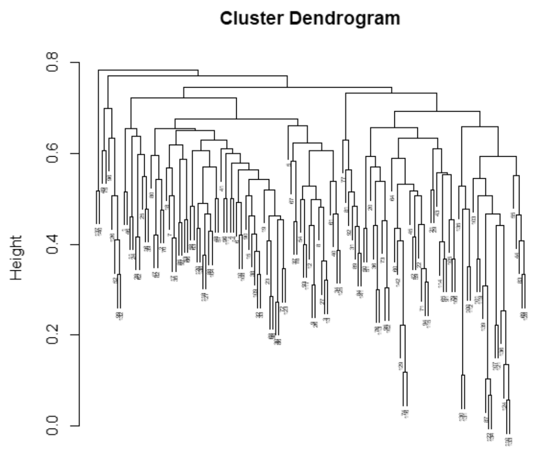
Manhattan Distance, WPGMC



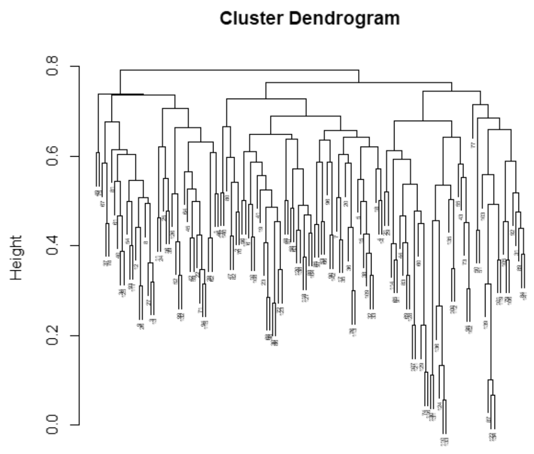
Jaccard´s Binary Distance, Single-linkage



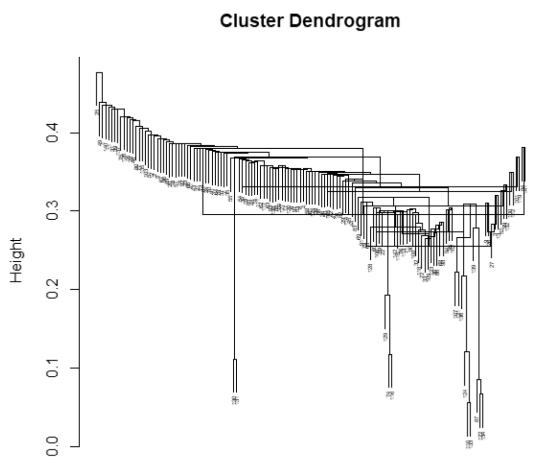
Jaccard´s Binary Distance, Complete-linkage



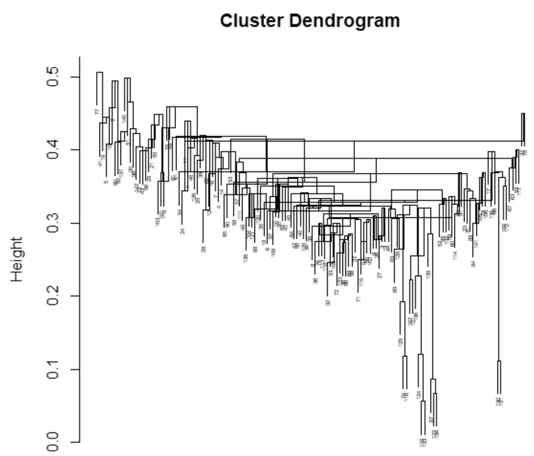
Jaccard´s Binary Distance, UPGMA



Jaccard´s Binary Distance, WPGMA



Jaccard´s Binary Distance, UPGMC



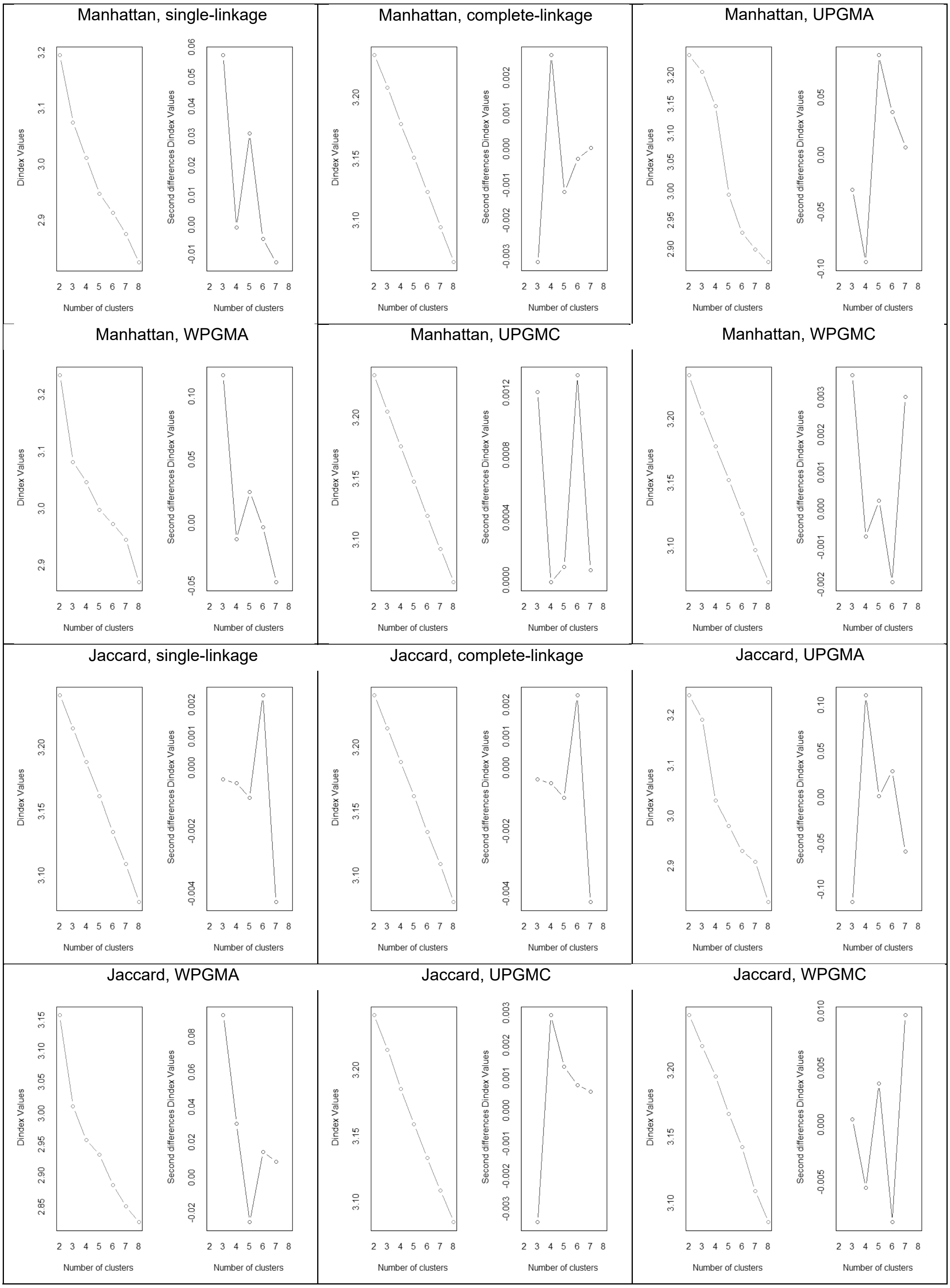
Jaccard´s Binary Distance, WPGMC

Interpretation of Dendograms

Distance Metric	Distance Measurement	Indicated Number Cluster
Manhattan distance	Single-linkage	*Not suited for interpretation*
	Complete-linkage	3 or 4
	UPGMA	3
	WPGMA	2
	UPGMC	*Not suited for interpretation*
	WPGMC	*Not suited for interpretation*
Jaccard's binary distance	Single-linkage	*Not suited for interpretation*
	Complete-linkage	2
	UPGMA	3 or 4
	WPGMA	3
	UPGMC	*Not suited for interpretation*
	WPGMC	*Not suited for interpretation*

Appendix L Plots of D Index

Manhattan distance: single-linkage (1st left), complete-linkage (1st center), UPGMA (1st right), WPGMA (2nd, left), UPGMC (2nd, center), WPGMC (2nd, right).
Jaccard's binary distance: single-linkage (3rd, left), complete-linkage (3rd, center), UPGMA (3rd, right), WPGMA (4th, left), UPGMC (4th, center), WPGMC (4th, right).

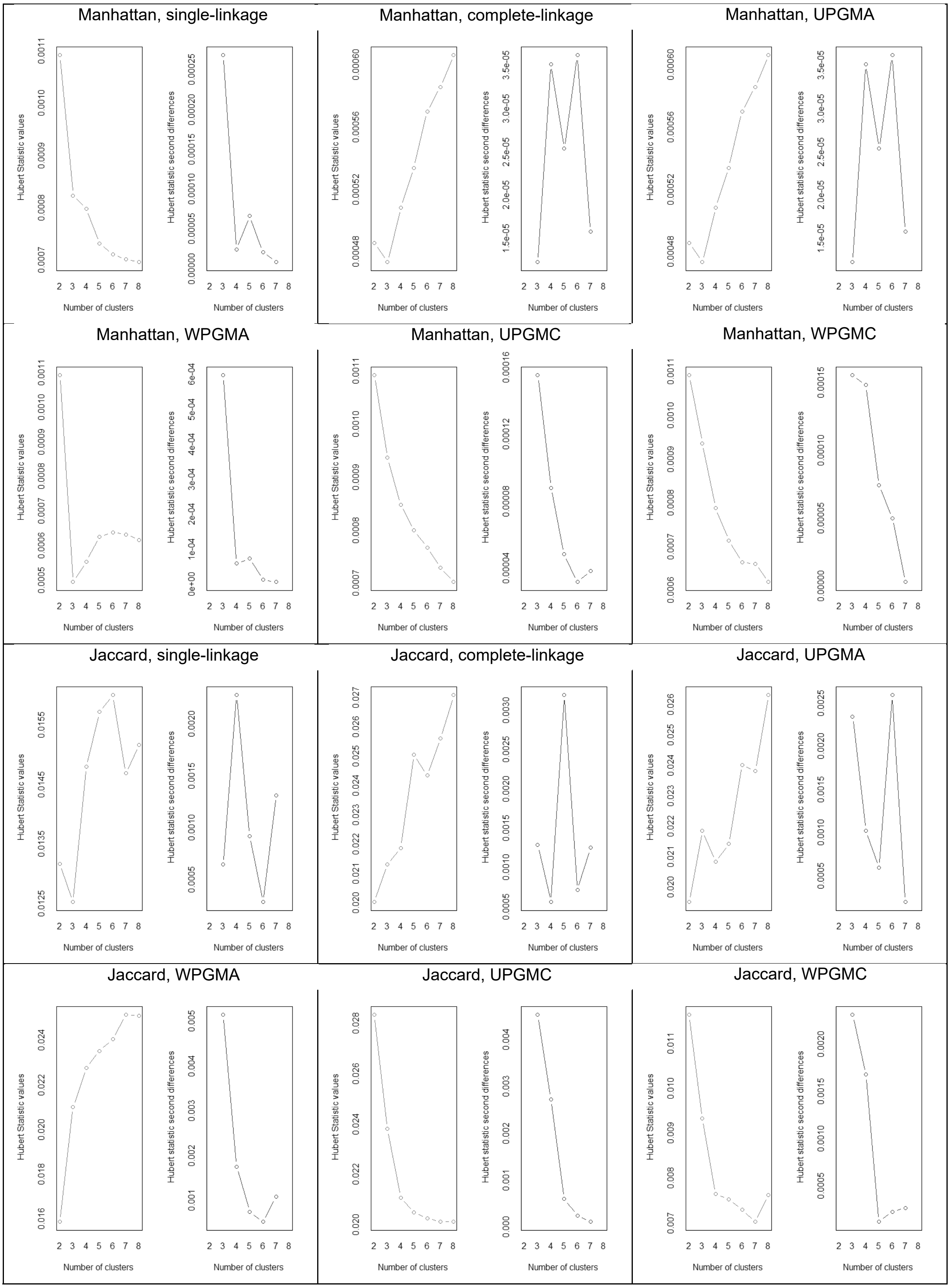


Interpretation of D Index

Distance Metric	Distance Measurement	Indicated Number Cluster
Manhattan distance	Single-linkage	3
	Complete-linkage	4
	UPGMA	5
	WPGMA	3
	UPGMC	3 or 6
	WPGMC	3 or 7
Jaccard's binary distance	Single-linkage	6
	Complete-linkage	6
	UPGMA	4
	WPGMA	3
	UPGMC	4
	WPGMC	7

Appendix M Plots of Hubert Index

Manhattan distance: single-linkage (1st left), complete-linkage (1st center), UPGMA (1st right), WPGMA (2nd, left), UPGMC (2nd, center), WPGMC (2nd, right).
Jaccard's binary distance: single-linkage (3rd, left), complete-linkage (3rd, center), UPGMA (3rd, right), WPGMA (4th, left), UPGMC (4th, center), WPGMC (4th, right).



Interpretation of Hubert Index		
Distance Metric	**Distance Measurement**	**Indicated Number Cluster**
Manhattan distance	Single-linkage	3
	Complete-linkage	4 or 6
	UPGMA	4 or 6
	WPGMA	3
	UPGMC	3
	WPGMC	3 or 4
Jaccard's binary distance	Single-linkage	4
	Complete-linkage	5
	UPGMA	3 or 6
	WPGMA	3
	UPGMC	3
	WPGMC	3

Appendix N Overview of Results of Qualitative Indices

Strength	Indicator	Manhattan distance: Single-linkage	Manhattan distance: Complete-linkage	Manhattan distance: UPGMA	Manhattan distance: WPGMA	Manhattan distance: UPGMC	Manhattan distance: WPGMC	Jaccard's distance: Single-linkage	Jaccard's distance: Complete-linkage	Jaccard's distance: UPGMA	Jaccard's distance: WPGMA	Jaccard's distance: UPGMC	Jaccard's distance: WPGMC
+	Dendogram Interpretation	*n/s*	3-4	3	2	*n/s*	*n/s*	*n/s*	2	3-4	3	*n/s*	*n/s*
-	Within-Cluster Sum of Squares Interpretation	4 main clusters, 8 sub clusters						4 main clusters, 8 sub clusters					
0	Gap Statistic Interpretation	4 main clusters, 8 sub clusters						4 main clusters, 8 sub clusters					
+	Shilouette Interpretation	2	2	2	2	2	2	2	2	2	2	2	2
+	Hubert Index Interpretation	3	4 or 6	4 or 6	3	3	3 or 4	4	5	3 or 6	3	3	3
+	D Index Interpretation	3	4	5	3	3 or 6	3 or 7	6	6	4	3	4	7

Appendix O Combined Number of Clusters prescribed by qualitative and quantitative Indicators

	Manhattan distance						Jaccard's distance					
No. of clusters	Single-linkage	Complete-linkage	UPGMA	WPGMA	UPGMC	WPGMC	Single-linkage	Complete-linkage	UPGMA	WPGMA	UPGMC	WPGMC
1	1	1								1	1	
2	13	5	13	3	2	2	2	10	10	3	10	10
3	14	3-4	3	8	2-3	2-5	1	1	2-4	9-10	2	4
4	2	3-5	3-4	2	2	2-3	3	2	4-5	4	5	2
5		3	0-1			1		1				
6		1	2-3		0-1		2	2	1-2			
7						0-1		3				3
8				1			2		1		1	
9				1	1				1	2		
10	3				3	1						
11		2										1
12						2	1			1		
13			1				3	2	1		1	
14		1		1	1						1	3
15	2	4	2		3	3	1	4	3	5-6	3	1

Appendix P Extracted Archetypes from two Clusters

	Archetype 1	Archetype 2
Type	Head-mounted	Stationary Device
Architecture	Single Device	*
User System	Single-user	Single-user
Output	Optical See-through, Video See-through	Video See-through
ARS Position Tracking	Image Targets	*
Object Tracking	Visual Marker-based Object Tracking	
User Interaction Tracking	Mechanical & Touch	None
Representation	Text, Image, 2D Form, 3D Form	2D Form, 3D Form
Visual Alginment	Proximity	Proximity, Fixed
User Interaction	Selection	*
Content Control	Hybrid	Automatic
Workflow Processing	Implicit Workflow	Implicit Workflow
Workflow Management	None	None
Workflow Task Support	Instruction, Auxiliary Information	Auxiliary Information

* = archetype is not strongly specified, i.e., exhibits no strong characteristic in this dimension.

Appendix Q Extracted Archetypes from four Clusters

	Archetype 1	Archetype 2	Archetype 3	Archetype 4
Type	Head-mounted	Stationary Device	Head-mounted	*
Archi-tecture	Single Device	Integrated Device	Single Device	*
User System	Single-user	Multi-user	Single-user	Single-user
Output	Optical See-through	Video See-through	Optical See-through	Video See-through
ARS Position Tracking	Relative to Visual Feature-tracked Objects	Relative to Visual Feature-tracked Objects	*	Image Targets
Object Tracking	Visual Feature-based Object Tracking	Visual Feature-based Object Tracking	*	Visual Marker-based Object Tracking
User Interaction Tracking	*	None	None	Mechanical & Touch
Represen-tation	Text, Image, 2D Form, 3D Form	2D Form, 3D Form	Text, Image,	Text, 2D Form, 3D Form
Visual Alignment	Proximity, Transparend Overlay	Non-transparent Overlay, transparend Overlay, Fixed	Fixed	Proximity, Fixed
User Interaction	Selection	*	*	*
Content Control	Hyrid	Automatic	Automatic	Hybrid
Workflow Processing	Implicit Workflow	Implicit Workflow Task	Implicit Workflow	Implicit Workflow
Workflow Management	*	None	None	None
Workflow Task Support	Instruction, Auxiliary Information	Instruction, Auxiliary Information, Non-visible Real Objects	Instruction, Auxiliary Information	Instruction, Auxiliary Information

* = archetype is not strongly specified, i.e., exhibits no strong characteristic in this dimension.

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Appendix G: Author's statement on the work shares in the article "Conceptualization and Design of a Workflow Management System Front End for Augmented Reality Headsets"

The article *"Conceptualization and Design of a Workflow Management System Front End for Augmented Reality Headsets"* was co-authored. The following table gives an overview of the authors' contributions to the article.

Authors:

Johannes Damarowsky JD
Stephan Kühnel SK

Aspect	Author(s)
Research concept	SK, JD
Research methodology	SK, JD
Problem and objective	SK, JD
Literature review	JD
Conceptualisation of the topic	JD, SK
Conducting and analysing the qualitative studies	JD
Definition of the design theory	JD
Development of a user interface design	JD
Qualitative and formal evaluation	JD, SK
Discussion and conclusion	JD, SK
Preparation of the manuscript	JD, SK
Review and revision before submission	JD, SK
Revision after review	JD, SK

Appendix H: Full text of the article "Conceptualization and Design of a Workflow Management System Front End for Augmented Reality Headsets"

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CONCEPTUALIZATION AND DESIGN OF A WORKFLOW MANAGEMENT SYSTEM FRONT END FOR AUGMENTED REALITY HEADSETS

Research in Progress

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Abstract

A currently discussed approach to increase efficiency during task execution, inter alia to reduce error rates and execution times, is the utilization of headset-based augmented reality systems (HARS). Additional to direct task support, HARSes can offer workflow management and control functions. However, these are only covered very limitedly by existing design-oriented approaches. Thus, users have to resort to additional devices, decreasing efficiency, and usability. Based on a three-step systematic literature analysis and two focus groups, we present a novel tentative design theory for HARSes supporting the full range of workflow management and control functions. Our design theory consists of four design requirements and nine design principles and is the basis for a software artifact prototype. Both our tentative design theory and software artifact are formatively evaluated by a third focus group. Our contributions add to the prescriptive knowledge base of the community and may be adapted by researchers and practitioners.

Keywords: Augmented Reality, Workflow Management System, Workflow, Design Science Research, Design Theory.

1 Introduction

A well-known tool for the management and (partial) automation of workflows is the workflow management system (WFMS) (Reijers et al. 2016). A WFMS defines, interprets, instantiates, and manages the execution of workflows with software, integrates external applications, and interacts with human workflow participants (Workflow Management Coalition 1995). Many types of devices can be utilized to interact with WFMSes to archive workflow management and control, e.g., desktop PCs, tablets, and smartphones. However, we here focus on a currently discussed approach to increase efficiency during task execution, i.e., to reduce error rates, execution times, cognitive loads, or required training, which is the utilization of augmented reality (AR). AR combines and aligns real and virtual objects in real environments, runs interactively, and in real-time (Azuma et al. 2001). A frequent implementation is as headset-based AR systems (HARS), which offer versatile sensors and advanced modes of interaction like tracking hand gestures and eye movements (e.g., Microsoft HoloLens). During workflow task execution, HARSes support users in manifold ways, e.g., by providing task descriptions and instructions with text and images, visually highlighting important objects, marking spots for tool placement, or demonstrating handles (Berkemeier et al. 2019; Mourtzis et al. 2019; Makris et al. 2013). While clearly not all workflows are well suited for AR-based support, improved task efficiencies, i.e., reduction of error rates, execution times, cognitive loads, or required training, have been observed in the domains of, e.g., collaborative planning, assembly, service, maintenance, warehouse picking, process training and process modeling (Hanson et al. 2017; Lampen et al.; Seiger et al. 2021; Jetter et al. 2018; Sääski et al.; Hofmann et al. 2019; Wang et al. 2016).

Besides directly supporting the execution of workflow tasks, HARSes are also utilized to enable workflow control and management. However, the currently supported functions are very limited and are provided in isolation, e.g., advancing backward and forward through a workflow's tasks or switching to a task of a different workflow (Berkemeier et al. 2019; Mourtzis et al. 2019; Makris et al. 2013). In contrast, the well-known WFMS reference architecture (RA) by the Workflow Management Coalition (WFMC) describes a much greater variety of functions for workflow control and management, e.g., instantiating, pausing, canceling, and generating filtered lists of workflow instances (Workflow Management Coalition 1995). However, to the best of our knowledge, no conceptualized HARS in the literature enables or aims at such holistic workflow management and control. Therefore, users wishing to control and manage workflows during task execution have to resort to additional devices. This creates media breaks and decreases efficiency and usability. It also diminishes or neutralizes one of the primary strengths of HARSes: enabling hands-free modes of use. Also, the use of additional devices for workflow management and control is not even possible in many cases, e.g., when using tools. The challenge then is how to simultaneously provide HARS users with both AR-based workflow execution support and associated efficiency gains, as well as workflow management and control capabilities, while ensuring usability, i.e., enabling users to achieve their workflow goals effectively, efficiently, and satisfactorily (ISO 9241-11:2018). As this challenge is as of yet unaddressed within the research literature, there is no guiding design knowledge available for information system (IS) architects, developers, and researchers. To address this research gap, we define our research question (RQ) as:

RQ: *What are the design requirements and design principles of a workflow management system front end for augmented reality headsets, providing the full range of workflow user interactions?*

To answer the question, we apply a design science research (DSR) approach to generate a design theory (DT) for a workflow management system front end for augmented reality headsets (HoloWFM), whose methodical foundations are described in Section 2. In Section 3, we describe the process for deriving design requirements (DR), based on both a three-step structured literature review (SLR) (Cooper 1988; Vom Brocke et al. 2009) and two focus groups (Morgan 1997) with IS researchers specializing in workflow management, AR practitioners and users. In Section 4, we present corresponding design principles (DP) and a tentative DT as the main contribution of this paper, answering the RQ. Section 5 describes the first development stage of a HoloWFM prototype, and Section 6 evaluates both this prototype and underlying DT with two reconvened focus groups (Morgan et al. 2008) and the DT framework by Gregor and Jones (2007). Section 7 discusses related work, and Section 8 summarizes our findings and next steps in research.

2 Research Method

To structure our procedure and ensure scientific rigor while designing HoloWFM, we applied a DSR approach based on the well-known work of Vaishnavi and Kuechler (2015), which involves five steps: awareness of problem, suggestion, development, evaluation, and conclusion. Our multi-cyclical research design follows Meth et al. (2015) and at least one further cycle is currently planned (Figure 1). As of now, the first cycle has been completed, which was dedicated to an initial conceptualization of our DT and includes a set of tentative DRs and DPs. A complete DT has two necessary elements: requirements and components, which together embody a general design solution for a class of problems (Baskerville and Pries-Heje 2010). The DRs describe the general objectives of the DT and function as meta-requirements for the software artifact (Baskerville and Pries-Heje 2010; Walls et al. 1992). The DPs can be descriptive or–as in our case–prescriptive, stating how an artifact should be instantiated to fulfill the DRs (Fu et al. 2016). In the next sections, we present the results of each phase of the first DSR cycle.

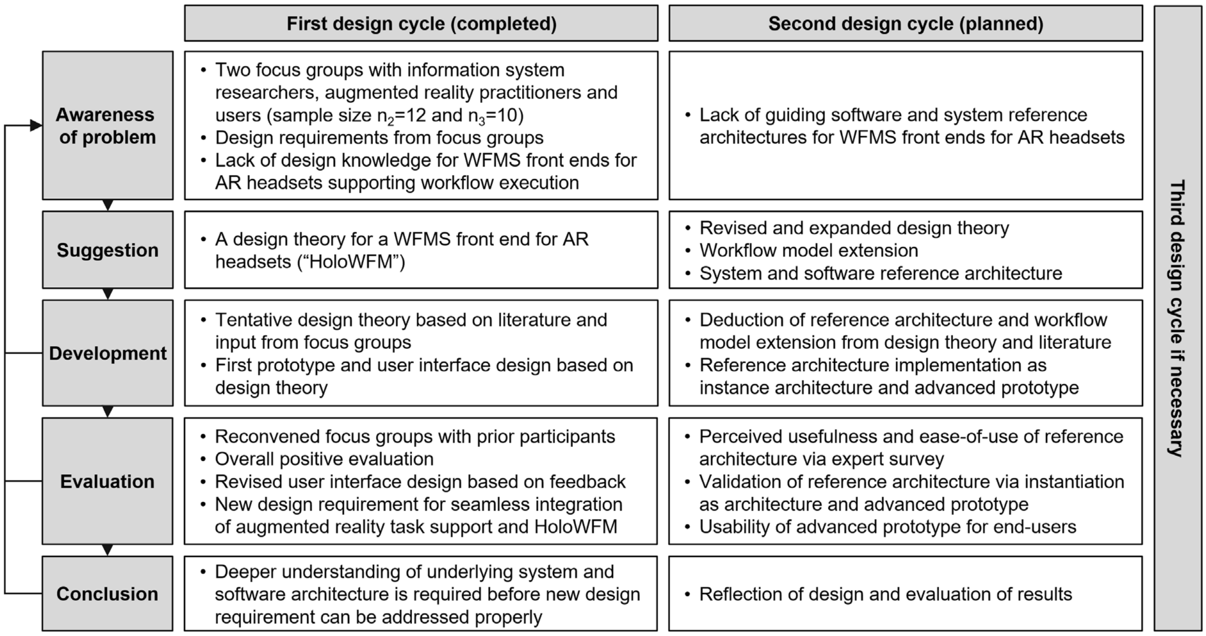


Figure 1. Design science research cycles for HoloWFM

3 Awareness of Problem

In the first phase of design cycle 1, we conducted a total of three SLRs, detailed in Table 1. In terms of the taxonomy by Cooper (1988) our SLRs can be characterized as focusing on research outcomes with SLR 3 additionally considering applications. The audience is specialized and general scholars. The coverage is representative for SLR 1-2 and exhaustive & selective for SLR 3. All SLRs have the goal to integrate the literature, organize it conceptually, and represent it in a neutral perspective.

	SLR 1	SLR 2	SLR 3
Search string	("workflow management" OR "process management") AND ("architect*" OR "ontology")	("augmented reality" OR "mixed reality") AND ("architect*" OR "ontology")	("augmented reality" OR "mixed reality") AND ("business process" OR "workflow")
Search fields	title	title	all search fields
Databases	ScienceDirect, ACM Digital Library, AIS electronic Library, SpringerLink, IEEE Xplore, Web of Science, EBSCOhost (Business Source Premier/Academic Search Premier)		
O/TA/F/BF	1.465 / 171 / 3 / 5	1.018 / 30 / 1 / 1	9.016 / 85 / 0 / 0

Note. O = original hits, TA = after title & abstract filter, F = after full text evaluation, BF = after backward & forward search.

Table 1. Details and characteristics of the structured literature reviews

From the respective hits, we first selected the literature by title and abstract, and second by analyzing the content, complementing the results with backward and forward searches. To ensure our state-of-the-art understanding of the involved technologies, we conducted SLRs on the RAs of AR and WFMSes. RAs are reference models for architectures that capture the essence of existing architectures and provide blueprints and guidance for the design of concrete architectures (Cloutier et al. 2009). In SLR 1, we searched for RAs of WFMSes and finally identified five relevant results: Lin et al. (2008), Rodriguez and Buyya (2017), Pourmirza et al. (2019), Workflow Management Coalition (1995), and Grefen and Vries (1998). With 23 mentions in 171 reviewed documents, the RA of the Workflow Management Coalition (1995) is currently the most representative RA for WFMS. In SLR 2, we searched for RAs of AR and first identified Reicher et al. (2003) and with a forward search MacWilliams et al. (2004), who fully include and extend the former, describing subsystems of AR systems and the relationships between the concepts and components involved. With our understanding thus grounded in the state-of-the-art, we conducted SLR 3, reviewing approaches to developing WFMS front ends providing the full range of a workflow client application (WCA) as defined by Workflow Management Coalition (1995). However, we could not identify any such approaches, but only some HARSes that complementarily offer very limited WCA functions, which we discuss in section 7.

To rigorously establish the DRs for HoloWFM, we conducted two moderated focus groups (MFG). An MFG is a qualitative research method where a moderator guides a group discussion and which relies on the interaction between participants to generate insights (Morgan 1997). As the number of MFGs necessary for reliable results is highly debated in the literature we follow the empirical findings of Guest et al. (2017), suggesting that two to three MFGs are sufficient. Therefore, we conducted two MFGs to identify DRs and two further MFGs as part of our evaluation (see Section 6). All groups consisted of a mix of workflow and AR researchers, AR practitioners, and AR users, all having several years of experience. The first group (n=12) included 6 IS researchers, 2 AR user interface (UI) and user experience (UX) designers, 1 AR engineer, and 3 HARS end-users. The second group (m=10) included 4 IS researchers, 3 AR engineers, and 3 HARS end-users. The MFG procedure consisted of four steps: 1) motivating the research topic, 2) discussing the problem context, 3) protocolling, and 4) evaluating the protocols through manual DR clustering. In both groups, the topic was approached by discussing the previously identified RAs of WFMSes and AR to establish a common understanding of the topic.

To systematize the statements by the participants, we took on the thoughts of Gioia et al. (2012) to distill first-order concepts and second-order themes from the verbalized statements of the subjects but adapted the method to our DSR approach. Thus, we clustered the statements of our subjects (concepts) and derived seven important themes for HoloWFM, shown in Table 2.

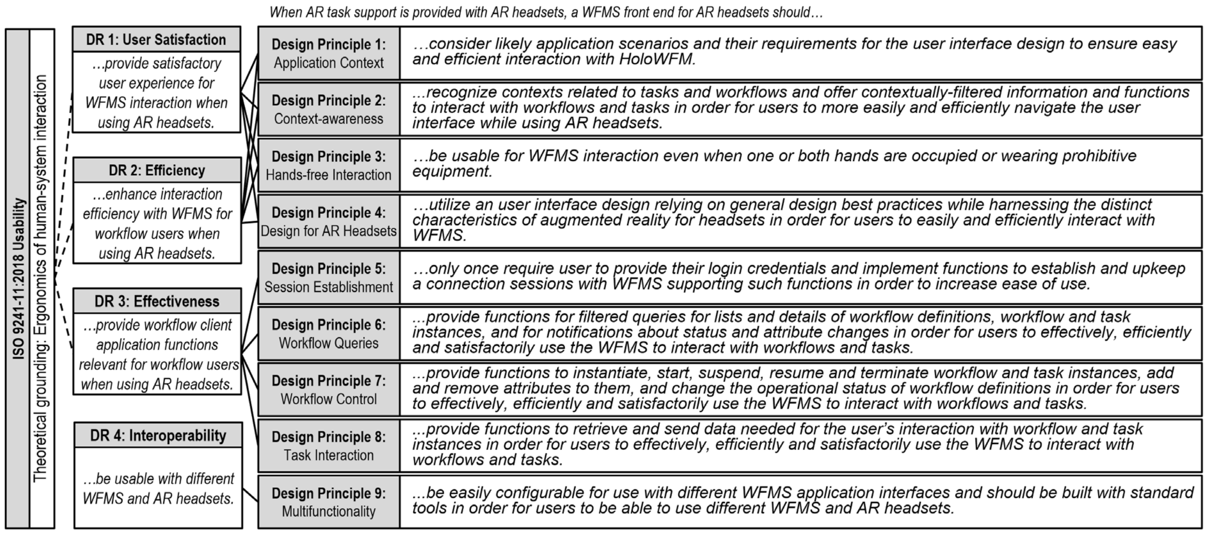
1st order concepts: clustered verbalized statements	2nd order themes
• AR can generally be utilized as an interaction format for all tools and human interfaces to the workflow engine, i.e., process definition tools (interface 1), administration & monitoring tools (interface 5), and especially workflow client applications (interface 2).	1) Applicability for workflow management system interfaces
• The user experience should be a focus of HoloWFM since adaption by employees is very important. • Many AR systems have poor usability and are thus hard to use. • HoloWFM should focus on use cases where conventional devices cannot be utilized well.	2) User Experience & Usability
• HoloWFM must be useful and offer the same functions as non-headset-based workflow client applications. • HoloWFM must be completely interoperable with existing workflow management systems as it were a “normal” workflow client application.	3) Effectiveness & Interoperability
• Scenarios and processes where users perform some manual labor are generally well suited. • Industrial processes are generally well suited for HoloWFM, including assembly, service, maintenance, and warehouse picking. • Utilizing real 3D experiences during, collaborative planning and design is a well-suited application scenario.	4) Application Scenarios
• HoloWFM should offer context-aware functions to fully utilize HARS sensors.	5) Context-awareness
• Application scenarios where only one or no hands can be utilized are well suited to fully realize the potential of HoloWFM.	6) Single-hand & hands-free interaction
• AR has great potential for user experience, but needs special user interface design. • Using web browsers in HARSes as workflow management system front ends is very user-unfriendly. • HoloWFM should be designed as an AR-native workflow client application. • Spatial AR (Bimber and Raskar 2005), is not well suited for many application scenarios, especially in the field.	7) Design for HARS

Note. AR = augmented reality, HARS = headset-based AR system

Table 2. Clustered statements of participants of the moderated focus groups.

4 Suggestion of a Tentative Design Theory for HoloWFM

To methodically underpin the development of the DPs and DT, we oriented ourselves on the supportive approach of Möller et al. (2020). Following this approach, DPs aim to provide design knowledge before the design process takes place. The DRs and DPs are derived in advance from the literature, case studies, focus groups, expert interviews, or other suitable sources of design knowledge (Möller et al. 2020).



Note. AR = augmented reality, WFMS = workflow management system.

Figure 2. Tentative design requirements and design principles for HoloWFM

After evaluating the distilled concepts and themes, we were able to cluster a total of 4 essential DRs for HoloWFM, which we addressed with 9 DPs as part of our DSR suggestion phase (Figure 2, cf. Figure 1). We divided the requirement "usability" into its components according to ISO 9241-11:2018: user satisfaction (**DR1**), efficiency (**DR2**), and effectiveness (**DR3**). To address interoperability, we defined **DR4**. DPs 1-4 address DR1 and DR2 respectively and must, therefore, be implemented considering both requirements. We define **DP1** to ensure that HoloWFM is designed for relevant scenarios, as suggested by the MFGs and discussed in the literature (e.g., Ganapathy 2013; Berkemeier et al. 2019). To increase the artifact's usability in relevant scenarios, we define **DP2** and **DP3**. Taking up the statements of the MFGs, the sensors of the HARS should be utilized to implement context-aware filtering of tasks and workflows and present appropriate interaction options to the user (**DP2**) (Dey 2001). To address scenarios where conventional devices are unusable or poorly suited, HoloWFM should be usable with one and without hands (**DP3**). While general design guidelines for UIs and UX apply, AR has distinct features that should be used to improve UI and UX (Dünser et al. 2007). Hence, HoloWFM should be natively designed for HARS (**DP4**). For DR3, we defined **DP5-DP8**, whose articulations are based on the functional requirements of a WCA as defined by the Workflow Management Coalition (1995), but were specified due to their relevance for HARSes. To address DR4, we define **DP9** to specify and constrain the software architecture and development toolset for HoloWFM.

5 Development of HoloWFM

In the first design cycle, we focus on a general design direction rather than on implementation details (Vaishnavi and Kuechler 2004). We understand our multi-cyclical DSR approach as an iterative-formative process in which design details of HoloWFM may change in later DSR cycles, although we are guided by the literature on UI design for AR (e.g., Dünser et al. 2007). We design HoloWFM as a software artifact consisting of four UI components: a heads-up display (HUD), a quick-access menu (QM), a main menu (MM), and a context-aware mode (CM). Figure 3 shows the UI design and the associated DPs. To illustrate the UI, we chose a fictional radio tower inspection workflow as an application scenario. In this, an engineer has already powered down the radio tower and climbed it, and now has to check a data logging unit before finally powering the tower back up.

Figure 3. The user interface design of HoloWFM

The HUD addresses DP4 and presents key information: the currently active task and subtask, the parent workflow, time remaining, and priority. The QM is associated with DP3-4 and DP8 and is anchored to the hand. It is minimized by default to minimize interference with the user's activities. The QM displays more detailed information about the currently active task than the HUD while minimizing the user's interaction with HoloWFM. In the example, subtasks are marked as completed with a slider. The MM corresponds to DP3 and DP6-8. It fills the entire field of view and displays tasks assigned to the user, additional information, and filters. The CM addresses DP2 as it visually highlights objects related to currently active tasks and workflows to guide the user. The visibility of the UI is toggled on the wrist.

6 Evaluation of HoloWFM

Our overall evaluation strategy follows Venable et al. (2016). Stemming from the DRs, the preeminent risk for HoloWFM is user-oriented, i.e., it must be ensured that the user's interactions are efficient, effective, and satisfactory. Furthermore, we place great emphasis on ensuring the benefit of the artifact for practice. Hence, we follow the *human risk & effectiveness* strategy of Venable et al. (2016) and consequently use formative evaluations early in our research process. As described in the awareness phase, we theoretically underpinned our research with a three-step SLR and empirically underpinned our DRs with two MFGs. Since we yet lack a complete operationalization of the DT, i.e., a fully executable prototype, we cannot yet empirically verify if the DPs effectively address the DRs. Thus, we continued our evaluation strategy with a formative evaluation of the tentative DT as part of two moderated reconvened focus groups (MRFG). MRFGs reunite the participants of previous sessions to discuss topics, concepts, theories, or issues in greater depth or to evaluate them under consideration of new information, or both (Morgan et al. 2008). Consequently, we reunited the groups from the problem awareness phase to check whether our tentative DT and prototype correspond to the groups' expectations.

The procedure of the MRFGs consisted of four steps: 1) reintroduction to the topic, 2) discussion of our DT and the HoloWFM prototype, 3) protocolling, and 4) the evaluation of protocols through manual issue clustering. Analogously to the MFGs (cf. Section 3), we based our systematization on Gioia et al. (2012) and distilled clustered verbalized statements, and derived three major themes, displayed in Table 3.

As theme 3 represents a significant expansion of the previously established DPs and requires system and software architecture-related design knowledge, we decided to address this in a second DSR cycle (cf. Section 8).

1st order concepts: clustered verbalized statements	2nd order themes
• Perceived usefulness and ease-of-use of the Technology Acceptance Model (Davis 1989) are established measures of the quality of an artifact. • Usability (ISO 9241-11:2018) not only includes subjective but objective measurements, i.e., efficiency and effectiveness. • Overall usability is the more holistic choice and should be kept.	1) Technology Acceptance Model or ISO 9241-11:2018
• In application scenarios, which restrict the use of hands, e.g., industrial maintenance, HARSes generally offer higher usability than handheld devices, especially because of novel single-hand and hands-free modes of interaction, e.g., eye tracking. • Group 1: HARSes have been evaluated positively in the literature, regarding task efficiency (cf. Section 1). • Group 2: HoloWFM's benefit must be discussed in a realistic context of already using a HARS for workflow task support. Then, using additional devices for workflow management and control is inefficient. • Context-aware selection of information and interaction options for tasks and workflows can be a major strength of HoloWFM .	2) Benefit of HoloWFM for real-world practice
• AR applications in the literature usually are usually hard-coded for a specific application and workflow. • How can AR support be integrated then for multiple workflows? • For HoloWFM, the AR support should be part of the workflow definition. • HoloWFM should enable a seamless integration of AR content from different workflows and workflow management functions into a unified AR user experience.	3) Integration of augmented reality support for various workflows

Note. AR = augmented reality, HARS = headset-based AR system

Table 3. Clustered statements of moderated reconvened focus groups.

In addition to the empirical evaluation via the MRFGs, we formally verified the quality of the DT with the framework by Gregor and Jones (2007), which defines six obligatory and two optional components a DT should include. We find our tentative DT in complete compliance with this framework (Table 4).

Component	Description
Purpose and scope	The goals of a WFMS front end for HARSes are providing a satisfactory user experience for interaction with WFMSes (DR1), improving efficiency for WFMS interaction (DR2), providing the full range of WCA functions for HARSes (DR3), and ensuring interoperability with other WFMSes and HARS (DR4).
Constructs	WFMS, Workflow, WCA, AR, HARS, front end, UI, IS architecture
Principles of form and function	DP1: application context, DP2: context-awareness, DP3: hands-free interaction, DP4: design for HARSes, DP5: session establishment, DP6: workflow queries, DP7: workflow control, DP8: task interaction, DP9: multifunctionality
Artifact mutability	HoloWFM can be used with different HARSes and WFMSes. The UI design and functionality can be adapted for different user tastes and can be enhanced based on specific practical and theoretical requirements.
Testable propositions	A WFMS front-end for augmented reality headsets offers higher user satisfaction, effectiveness, and efficiency than handheld-based approaches.
Justificatory knowledge	A three-step literature analysis and two moderated focus groups justify the derivation of DRs and DPs. Two reconvened moderated focus groups justified that a WFMS front-end for augmented reality headsets generally delivers higher user satisfaction, effectiveness, and efficiency than handheld-based approaches, especially since HARSes offer novel possibilities for UI design and one-hand and hands-free interaction modes.
Expository instantiation	Development of a first prototype, encompassing four UI components: a heads-up display, a quick-access menu, a main menu, and a context-aware mode.

Note. AR = augmented reality, HARS = headset-based AR system, IS = information system, WFMS = workflow management system, ‘ WCA = workflow client application, DT = design theory, DP = design principle, DR = design requirement, UI = user interface.

Table 4. Components of a tentative design theory for HoloWFM

7 Related Work

In SLR 3, we were unable to identify any articles explicitly mentioning WFMSes and no approaches that aim to conceptualize or develop a WCA. We were able to identify one approach (Berkemeier et al. 2019) that explicitly mentions BPMN and an “XML parsing service”, which we interpret as a workflow engine in terms of the WFMS RA (Workflow Management Coalition 1995). Other approaches describe workflows and tasks with unspecified XML (e.g., Makris et al. 2013; Mourtzis et al. 2019). While no approach aims to conceptualize, design, or develop a WCA, some partial and basic WCA functions have been implemented by AR systems focusing on AR-based workflow (task) support. E.g., the AR system prototype by Berkemeier et al. (2019) enables the user to advance to the next or return to the previous task and the prototype by Mourtzis et al. (2019) allows the user to pause and switch tasks. However, the WCA functionalities in the analyzed articles are neither a major focus of the conceptualized or designed AR systems nor do they address workflow control and management holistically, i.e., in terms of the WFMS RA (Workflow Management Coalition 1995). Instead, the analyzed articles conceptualized and developed highly scenario-specific approaches to enable AR support for specific workflows and workflow tasks. Further, we noticed that nearly all AR systems described in the literature in general and all AR systems offering partial WCA functionality address only linear workflows, i.e., no branches or loops. In summary, our approach and DT distinguish themselves from the identified approaches by their purpose and scope (cf. Table 4): HoloWFM is designed explicitly for WFMSes, aims at full WCA functionality, supports complex workflows, and is scenario-agnostic.

8 Conclusion and Next Steps of Research

The goal of our ongoing research is to conceptualize and design a WFMS front end for HARSes, supporting the full range of user interactions. To address the initially raised research question, we consequently presented the results of a first design cycle. We introduced a tentative DT, consisting of four DRs and nine DPs, and implemented a first version of the software artifact HoloWFM. Finally, we evaluated HoloWFM and the tentative DT in two MRFGs with predominantly positive feedback. Practitioners and scientists can use and adapt our DT to develop new AR WFMS front ends for specific application scenarios. Furthermore, the DRs, DPs, and DT contribute to the prescriptive knowledge base of the IS community, according to Gregor and Hevner (2013).

For an adequate interpretation of our results, the following limitations should be considered. First, an inherent weakness to the conceptualization of DTs is the subjectivity of underlying design decisions, e.g., selection and naming of DRs and DPs. Other designers could make different decisions, thus reaching a different DT. However, not all design decisions must or can be grounded in theory and a degree of creativity is unavoidable and essential in the DSR process (Hevner and Chatterjee 2010; Baskerville et al. 2016). Nonetheless, we underpinned our DT methodologically via the consideration of the methods of Möller et al. (2020) for supportive design approaches and of Fu et al. (2016) for the prescriptive articulation of DP. Second, our DT conceptualization and evaluation results depend on our sample, i.e., the choice of other participants for the focus groups could lead to different results. However, consideration must be given to the fact that this was only a first formative evaluation in the first DSR cycle of HoloWFM. Our tentative DT will be refined in further design cycles and our evaluation strategy will consequently be continued with many further evaluations, especially involving end-users. Still, we believe that by selecting subject-specific experts and users for the focus groups in the first design cycle, and considering the comments by Guest et al. (2017) on the required number of groups, we have gained first well-founded insights, based on which we can trigger advancements of HoloWFM.

In the next DSR cycle, we will expand our initial problem definition to enhance the benefit of HoloWFM in practice. Based on the combined statements of the MFGs and MRFGs, as well as the existing body of literature (cf. Section 1) well-suited application scenarios for HoloWFM include industrial settings, e.g. assembly, service, maintenance, and warehouse picking. We consequently plan to conduct formative evaluations with practitioners from these domains to inter alia refine our initial UI design. Taking up theme 3 of the MRFGs, we will suggest an adapted DT, and based thereon, a software and system RA and workflow model extension, which we'll instantiate in a solution architecture and advanced prototype. The successful instantiation of the latter thus validates the former. Further, we will summatively evaluate the RA's perceived usefulness and perceived ease-of-use with experts and all three components of the advanced prototype's usability, i.e., user satisfaction, efficiency, and effectiveness with end-users (Venable et al. 2017; Davis 1989; ISO 9241-11:2018). For the aspect of user satisfaction, we'll also consider hedonistic aspects. If evaluation results are not satisfactory, we will continue our research efforts in additional DSR cycles.

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Appendix I: Author's statement on the work shares in the article "A Reference Architecture for a Workflow Management System Front End Designed for Augmented Reality Headsets"

The article *"A Reference Architecture for a Workflow Management System Front End Designed for Augmented Reality Headsets"* was co-authored. The following table gives an overview of the authors' contributions to the article.

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Konzeptualisierung des Themas	JD
Erstellung der Erweiterten Design Theorie	JD
Entwicklung und Dokumentation der Referenzarchitektur	JD
Programmierung des Prototypen	JD
Formale und Qualitative Evaluation	JD, SK
Diskussion und Schlussbetrachtung	JD
Erstellung des Manuskripts	JD
Überprüfung und Überarbeitung vor Einreichung	JD, SK, MB
Überarbeitung nach Begutachtung	JD

Appendix J: Full text of the article “A Reference Architecture for a Workflow Management System Front End Designed for Augmented Reality Headsets”

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A REFERENCE ARCHITECTURE FOR A WORKFLOW MANAGEMENT SYSTEM FRONT END DESIGNED FOR AUGMENTED REALITY HEADSETS

Research Paper

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Abstract

A well-known approach to managing and controlling workflows in organizations is the workflow management system (WFMS). Recently, approaches utilizing augmented reality headsets as WFMS front ends have been discussed, enabling higher efficiency, effectiveness, and usability for certain application scenarios. However, existing design-oriented approaches lack tangible guidance for implementation. A well-known approach to address such knowledge gaps is a reference architecture, which inter alia reduces development times and risks and facilitates collaboration between developers. Based on an existing tentative design theory for an augmented reality-based WFMS front end, we contribute a reference architecture containing an extended design theory, user interface design, and UML models for use cases, components, classes, and sequence flows. The reference architecture was successfully operationalized in a prototype and positively evaluated via a survey of respective users.

Keywords: Augmented Reality, Workflow Management System, Design Theory, Reference Architecture.

1 Introduction

A well-known tool for collaboration, coordination, and communication within organizations is the workflow management system (WFMS) (Reijers *et al.*, 2016). Modern implementations of WFMS have evolved much from older understandings as "organizationally aware groupware" (Ellis, 1999). Still, the well-known definition by the Workflow Management Coalition (1995) of a WFMS as a system that defines, interprets, instantiates, and manages the execution of workflows with software, integrates external applications, and interacts with human workflow participants, still applies (Damarowsky and Kühnel, 2022). Recently, approaches have been discussed to interact with WFMSs by using augmented reality (AR) technology, which combines and aligns real and virtual objects with the real environment for users to interact with in real-time (Azuma *et al.*, 2001). A wide array of applications is discussed, e.g., spatial AR for healthcare (Böhmer *et al.*, 2022), assembly (Wang *et al.*, 2016b), or medical operations (Katić *et al.*, 2013). Although a large empirical base has not yet been established, existing evidence suggests tangible benefits of AR-based workflow execution support, e.g., with AR task instructions. Increased task efficiency, i.e., reduction of error rates, execution times, cognitive loads, or required training, was observed in the domains of collaborative planning, assembly, service, maintenance, warehouse picking, process training, and process modeling (Hanson *et al.*, 2017; Lampen *et al;* Seiger *et al.*, 2021; Jetter *et al.*, 2018; Sääski *et al;* Hofmann *et al.*, 2019; Wang *et al.*, 2016a).

While these AR-enabled task efficiency gains benefit organizations and employees alike, the management and control of workflows via WFMSs is another vector for improvement, i.e., using AR to enhance WFMS front ends. Recent research, however, shows that contemporary approaches only enable very limited and isolated workflow management and control functions (Damarowsky and Kühnel, 2022) e.g., advancing backward and forward through a workflow's tasks or switching to a task of a different workflow (Berkemeier *et al.*, 2019; Mourtzis *et al.*, 2019; Makris *et al.*, 2013). In contrast, the well-known reference architecture (RA) for WFMSs by the Workflow Management Coalition describes a much greater variety of workflow control and management functions, e.g., instantiating, pausing, canceling, and generating filtered lists of workflow instances (Workflow Management Coalition, 1995).

To address this research gap, we followed a design science research (DSR) approach (Vaishnavi and Kuechler, 2015) to develop *HoloWFM*, a WFMS front end designed for AR headsets that supports the entire range of WFMS user interactions, as defined for a workflow client application in the WFMS RA by the Workflow Management Coalition (1995). We developed and evaluated a tentative UI design and design theory (DT), consisting of 4 design requirements (DR) and 9 design principles (DP) (Damarowsky and Kühnel, 2022). However, a summative evaluation with two focus groups revealed a new user requirement for HoloWFM, the seamless integration of AR task support with the HoloWFM application, which we could not properly address without first understanding the software architecture necessary to operationalize a HoloWFM. To systematically bridge this abstraction gap between abstract DT and specific software prototypes and thus properly address the newly raised user requirement, we initiated a second DSR cycle (Vaishnavi and Kuechler, 2015; Meth *et al.*, 2015). This cycle aims to develop an RA for HoloWFM, including, inter alia, an extension of the DT with less-abstract design features and multiple UML class diagrams. By chaining the operationalizable UML diagrams upwards to the increasingly abstract DFs, DPs, and finally DRs, we systematically bridge the abstraction gap and thus can properly address the raised user requirements in the abstract DPs. Also, well-known advantages of RAs, e.g., reduced development time, risks, and improved collaboration via a better common understanding of problem domains, systems, and software (Cloutier *et al.*, 2009; Martinez-Fernandez *et al.*, 2015; Nakagawa *et al.*, 2011), become available for HoloWFM developers, which profit less from the DT than IS and AR researchers. Consequently, we define our research question (RQ) as:

RQ: *What are the models, model elements, and textual descriptions of a system reference architecture for a workflow management system front end designed for augmented reality headsets, providing the full range of workflow user interactions?*

To answer the question, we implement a second design cycle, whose methodological foundations are described in Section 2. In Section 3, we briefly discuss the theoretical background of RAs. The main contributions of this paper are presented in Section 4: a reference architecture description, including an extended DT and multiple UML diagrams. In Section 5, we present the evaluation of the results, including a prototype instantiation. We elicit the implications of our results for theory and practice in Section 6. Finally, Section 7 concludes this article and reflects on our research.

Our study shows that's it possible to implement a WFMS front end with comprehensive functionalities in an AR headset. We thus extend the IS community's prescriptive knowledge base by providing abstract and tangible design knowledge for this novel type of WFMS front end. Methodically, we demonstrate how to bridge the abstraction gap between DTs and software architectures and utilize the system architecture description standard ISO/IEC/IEEE 42010:2011 to document the design knowledge. The operationalizable HoloWFM RA supports especially AR practitioners during development.

2 Research Method

We continue the DSR approach in Damarowsky and Kühnel (2022), which is based on Vaishnavi and Kuechler (2015) and involves five steps: awareness of problem, suggestion, development, evaluation, and conclusion. Compared to alternative DSR approaches (cf. Venable *et al.*, 2017b), the framework by

Vaishnavi and Kuechler (2015) explicitly focuses on the development of theoretically sound DRs and DPs to guide IS development, as these DRs and DPs are the unconditional prerequisites for an RA (Oussalah, 2014). The research approach features two design cycles, each addressing the five steps of Vaishnavi and Kuechler (2015) (Figure 1).

The first cycle was dedicated to the gathering of DRs and conceptualization of a tentative DT. A complete DT is constituted of two types of elements: DRs and DPs, which together embody a general design solution for a class of problems (Baskerville and Pries-Heje, 2010). The DRs describe the general objectives of the DT and function as meta-requirements for the software artifact (Baskerville and Pries-Heje, 2010; Walls *et al.*, 1992). The DPs can be descriptive or – as for HoloWFM – prescriptive, stating how an artifact should be instantiated to fulfill the DRs (Fu *et al.*, 2016). To support the prototype development we followed the *supportive approach* by Möller *et al.* (2020) and defined the DPs prior to development instead of deriving them from the development (*reflective approach*).

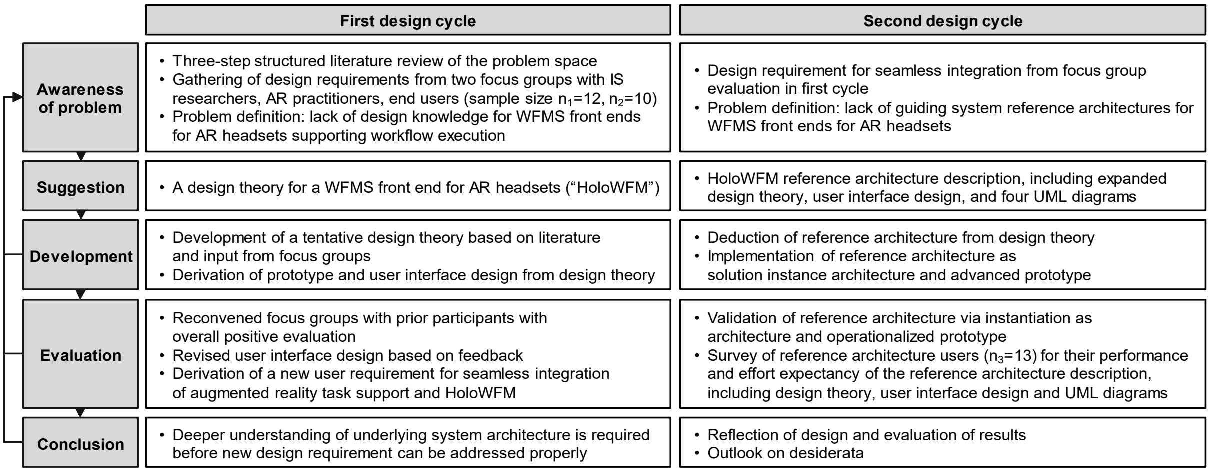


Figure 1. Design Science Research Cycles for HoloWFM.

As we concluded in the evaluation of the first cycle, to rigorously address the newly raised user requirement for seamless integration of AR task support and the HoloWFM application, a deeper understanding of the system architecture is required applies (Damarowsky and Kühnel, 2022). Consequently, the second design cycle addresses this challenge by presenting an RA for a WFMS front end designed for AR headsets that provides the full range of workflow user interactions. Thus, the RA addresses the question of how to successfully implement a HoloWFM, which was raised at the end of the first design cycle. We interpret the user requirement for seamless integration of AR task support and the HoloWFM application, raised in the evaluation of the first design cycle, as a DP rather than a DR, as this will enhance user satisfaction (DR1) and efficiency (DR2) of a HoloWFM. As part of the suggestion phase in Section 4, we consequently update the original DT with an additional DP.

To provide reference design knowledge on how to instantiate the DPs into a software artifact, we also derive design features (DFs) to address the established DPs. Even though it is not a required part of a DT (cf. Baskerville and Pries-Heje, 2010), DFs can be utilized to document how DPs could be implemented in a specific instance (see, e.g., Meth *et al.*, 2015, Böhmer *et al.*, 2022). The DFs then serve as a foundation to systematically develop UML diagrams and textual descriptions for the RA, in line with the supportive approach by Möller *et al.* (2020), followed in the first design cycle.

3 Theoretical Background: Reference Architectures

An RA is an architecture that distills the essence of existing architectures for a certain problem domain and provides a template and guidance to develop solution architectures for specific problem instances in the same domain. As the *problem instance environment* differs, e.g., for different companies, the RA gets adopted into a unique *solution instance architecture*, also based on the specific *stakeholder* *requirements*, e.g., end-user requirements. The solution instance architecture then finally gets implemented into a *solution instance system* (Figure 2) (Cloutier *et al.*, 2009; Martinez-Fernandez *et al.*, 2015; Nakagawa *et al.*, 2011; Oussalah, 2014). An RA can contain multiple elements, e.g., models, figures, or text. When utilized for collaboration, an RA can improve the common understanding of problem domains and systems by providing a common lexicon and terminology. Important concepts are clarified. Functions and qualities above the system level, the relevant context, and consequent design decisions are documented to foster a common understanding and ease the application of the RA for specific problem scenarios. With improved communication, interoperability between systems and organizational units can improve as well. The RA itself facilitates a common architectural vision by functioning as a focal point for information exchange, which in turn focuses and aligns the efforts of multiple people and teams. As RAs capture past experiences, lessons learned, and best practices, their utilization generally reduces development risks and time, helps spread best practices, and can serve as instruments of knowledge management in organizations (Cloutier *et al.*, 2009; Martinez-Fernandez *et al.*, 2015; Nakagawa *et al.*, 2011; Oussalah, 2014).

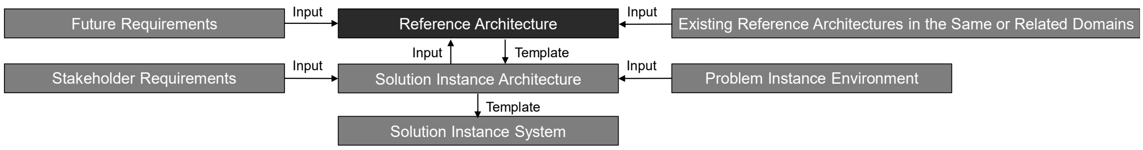


Figure 2. Reference architecture inputs. Based on OASD/NII (2010), Cloutier et al. (2009).

A standard for describing architectures is provided by ISO/IEC/IEEE 42010:2011(E) *Systems and software engineering — Architecture description* (ISO, 2011). Hence, a RA description (RAD) should include: 1) a RAD identifier ("HoloWFM reference architecture"), 2) overview information, 3) the RADs stakeholders and their concerns, 4) a definition for each RA viewpoint, i.e., the target audience's perspective, in the RAD, 5) exactly one RA view for each defined RA viewpoint, possibly containing multiple models, 6) RAD correspondence rules, RAD correspondences, and known inconsistencies among the RAD's content, and 7) rationales for architecture decisions made. These components are presented in Section 4 in the above order. Notably, ISO/IEC/IEEE 42010:2011(E) does not specify which models or modeling languages must be utilized to constitute an RA view. Therefore, DTs, reference UI designs, and UML diagrams are appropriate contents for an RA view.

As we found in an extensive structured review of the literature in Damarowsky and Kühnel (2022), no RA for a HoloWFM is available. Additionally, very few architectures are provided by recent studies for AR-based IS supporting workflow execution, management, or control. Of these, most are highly abstract or do not utilize documentation and modeling standards (e.g., Barenkamp and Niemoller, 2020; Berkemeier *et al.*, 2019; Wang *et al.*, 2016a).

4 Reference Architecture Description

4.1 Identification and Overview information

The purpose of the "HoloWFM reference architecture" is to support HoloWFM developers, i.e., IT and AR architects and developers, in designing and building a HoloWFM. A HoloWFM aims to enable end-users to manage and control workflows, e.g., to generate filtered lists for specific workflows and workflow tasks, to control the status of workflows, or to interact with the user tasks by filling out forms and checkboxes or reading information. These management and control functions are provided for end users during the usage of AR headsets, and therefore the UI of HoloWFM is entirely presented with AR elements. To enhance the user experience, efficiency, and effectiveness of HoloWFM, it is designed to be context-aware, i.e., it reacts to contextual environmental information, e.g., a user's location or when a certain object is in the headset camera's field-of-view. To process this context, information *context reasoning workflows* are defined by administrators.

4.2 Stakeholders and Stakeholder Concerns

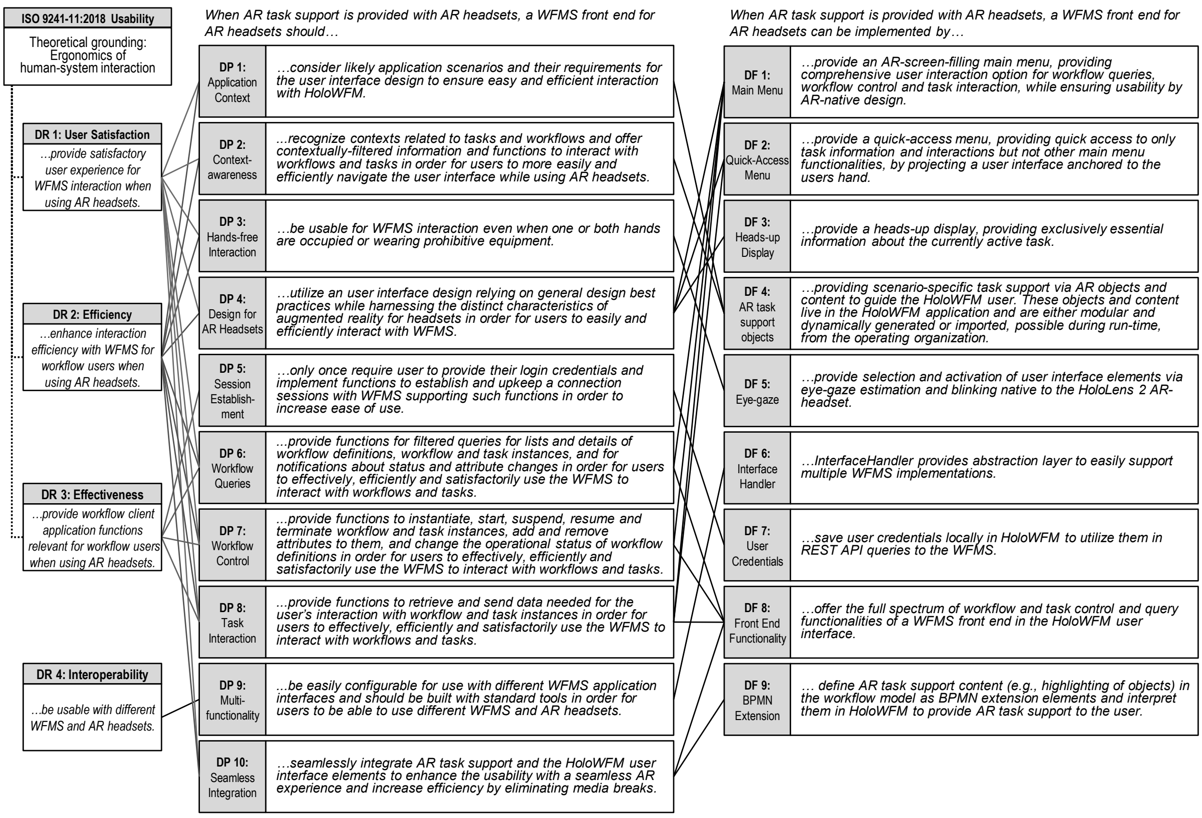
Two stakeholders are of preeminent importance to the HoloWFM RA. First and directly, HoloWFM developers, i.e., IT Architects, software, and AR developers, are concerned with the RA, as it should support them in developing and deploying a HoloWFM instantiation in real organizations. Therefore, we evaluate the expected effort for and performance of HoloWFM with a corresponding target audience in Section 7. The second important stakeholders are HoloWFM end users. Their concerns refer to the efficiency, effectiveness, and usability of HoloWFM, as our qualitative studies in the first design cycle found and are systematically addressed by the DT, DP, and DF, respectively.

4.3 Reference Architecture Viewpoint "HoloWFM Developer" Definition

Consequently, the herein-considered RA viewpoint is that of the *HoloWFM developer*. This viewpoint is concerned with guidance provided by the RA during the actual design and development of a HoloWFM instantiation for an organization. Abstract design knowledge is helpful as it can apply to many different organizations. DTs are, therefore, appropriate in this viewpoint. Tangible architectural knowledge, however, is also important to shorten and ease development cycles (cf. Section 3). Hence, UML diagrams in lower levels of abstractions are appropriate for the *HoloWFM developer's* viewpoint.

4.4 Reference Architecture View "HoloWFM Developer"

4.4.1 Extended Design Theory for HoloWFM



Note. AR = augmented reality, API = application interface, BPMN = business process model and notation, REST = representational state transfer, WFMS = workflow management system.

Figure 3. Extended design theory.

To formalize the update to our tentative DT from the first design cycle and to bridge the gap in abstraction between DPs and an RA, we add one DP and nine novel DFs to the original DT. For an in-depth explanation of the original DT, see Damarowsky and Kühnel (2022), pp. 4-6. The complete DT, with the names and short descriptions of the DRs, DPs, and DFs is depicted in Figure 3.

First, **DP 10** *Seamless Integration* addresses both user satisfaction and efficiency by ensuring that the task support via AR content and the AR UI of HoloWFM are integrated such that no media breaks occur, i.e., the same application provides the HoloWFM UI and task support. In contrast, an alternative approach could start or send a message to a second application in the AR headset, which – after the user switches applications – provides the appropriate task support. Second, to lower the level of abstraction, provide an example instantiation, and systemically derive the RA from, we define a set of DFs. To operationalize DP 4 for an AR headset-native design and provide workflow management and control functionalities (DP 6-8), we propose a *main menu* (**DF 1**), *quick-access menu* (**DF 2**), and *heads-up display* (**DF 3**). The consideration of the relevant application context (DP 1) is inherently realized in *AR task support objects* (**DF 4**), which are also context-aware (DP 2). As the Microsoft HoloLens offers native *Eye-gazing* (**DF 5**) features, we define this solution to operationalize DP 3 for one-handed and hands-free modes of interaction. To maximize interoperability with different WFMS and AR headsets, we utilize an *Interface Handler* (**DF 6**) as an abstraction layer for WFMS functions. To enable session establishment (DP 5), the *User Credentials* (**DF 7**) can be saved in HoloWFM. Since not all UI elements in DF 1-3 enable all functionalities, we define **DF 8** to ensure full *WFMS Front End Functionality*. In addition to DF 8, we utilize a *BPMN Extension* (**DF 9**) to realize the seamless integration of AR UI and AR task support. In particular, workflow elements link to AR task support content via BPMN extension elements. The AR task support objects themselves live in the HoloWFM application.

4.4.2 Reference UML Use Case Diagram

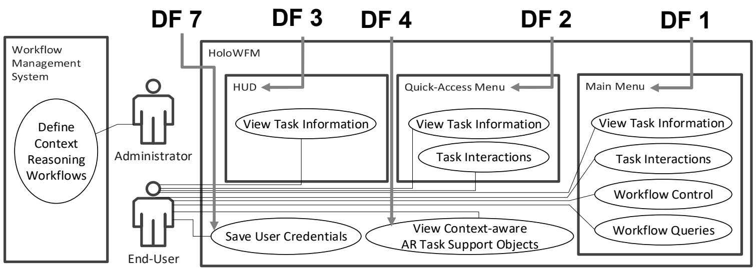


Figure 4. Reference UML use case diagram, with corresponding design features indicated.

The use case diagram depicted in Figure 4 visualizes how two roles, *administrators* and *end users*, can interact with HoloWFM. Their possible actions refer to the DFs and subsequently also to the DPs. DFs 5 and 6 don't apply to the use case diagram. *Administrators* also define context reasoning workflows, i.e., workflows that calculate how to process identified contextual environmental information. Interactions of the *end user* with the organization's workflows aren't depicted.

4.4.3 Reference User Interface Design

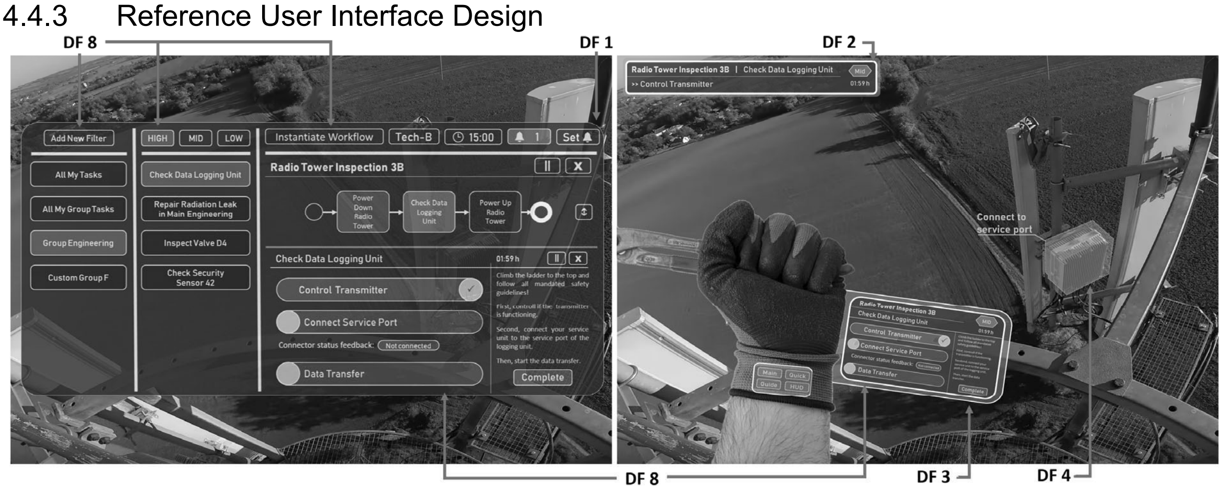


Figure 5. Reference design for main menu (5a), heads-up display, and quick-access menu (5b).

Figure 5 depicts the reference UI design (Damarowsky and Kühnel, 2022) and the corresponding DFs. The DFs 5-7 and 9 don't apply to the UI design. In Figure 5a, the main menu offers two levels to filter tasks on the left and a full, more detailed view of the currently selected user task on the right. In this menu, the user can also switch tasks or workflows and access advanced management and control functions. In Figure 5b, the heads-up display is depicted in the upper left corner, visualizing some minimalistic information about the currently active task. Attached to the wrist and hand is the quick-access menu, which provides users with task interactions and access to the main menu. The context-aware recognition and highlighting of an object identified as relevant for the action "connect to service port" (visible in the quick-access menu) is shown on the right.

4.4.4 Reference UML Component Diagram

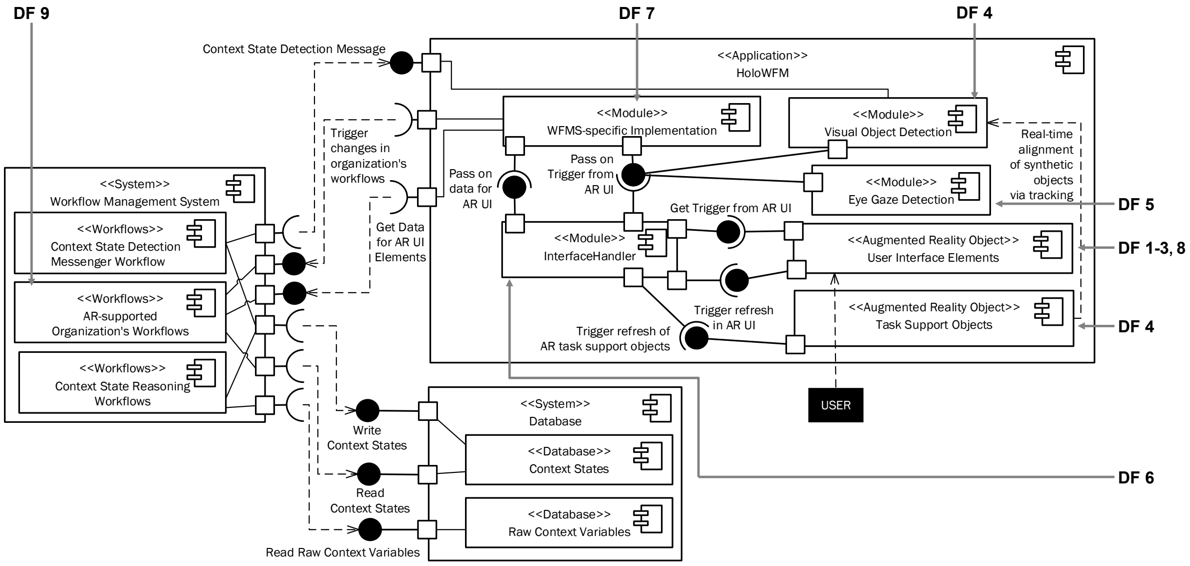


Figure 6. Reference UML component diagram, with corresponding design features indicated.

The component diagram and corresponding DFs are depicted in Figure 6. It contains three systems: 1) a WFMS, 2) a database system, and 3) the HoloWFM application. The database system contains two databases for a) *raw context variables* directly from the sensors. e.g., a temperature data point of 42° Celsius ("42"), and b) *context states*, which are calculated from the raw context variables, e.g., "hot" or "cold" (cf. DP 2). The organization's data, e.g., for workflows, is not depicted. The WFMS contains three sets of workflows. Reading from the database's *raw context variables* are the *context state reasoning workflows*, which calculate context states from the raw data and write these to the *context states* database accordingly. Reading from the context states are the *AR-supported organization's workflows*, i.e., the organization's workflows that are supported with AR and are managed and controlled via HoloWFM. These workflows utilize BPMN extension elements to link corresponding AR *Task Support Objects*, e.g., object highlights. The third type of workflow is the *context state detection messenger workflow*, which is triggered by the *visual object detection* module of the HoloWFM application. E.g., when a certain object is within the field-of-view of the headset camera, the context state "objectVisible" is set to 1 in the context state database. The visual detection module might be natively implemented in the utilized IDE, e.g., *Unity*. The organization's workflows also interact with the *WFMS-specific implementation* module of HoloWFM, which can trigger changes in workflow definitions and instances, and read data from these for display in the AR-based UI of HoloWFM. The *WMFS-specific implementation* contains all the methods, data formats, and communication protocols necessary to communicate with specific WFMSs, e.g., *Camunda (see Figure 8)*. Abstracting from these implementations is the *interfaceHandler* module. Leaning on the Model-View-Controller software architectural pattern, the *interfaceHandler* sends triggers from and receives data for the AR UI from the

WFMS-specific implementations and receives, and vice versa sends them to the *user interface elements*. It also triggers refreshes of AR *task support objects*, which are not part of the UI but, e.g., highlight task-relevant objects directly. These objects are also tracked with the visual object detection module to align AR objects in real-time. The *interfaceHandler* thus integrates the user experience of AR task support objects and HoloWFM UI, addressing DP 10 raised at the end of the first design cycle. Finally, the end user's points of contact with HoloWFM are the AR-based UI elements.

4.4.5 Reference UML Sequence Diagram

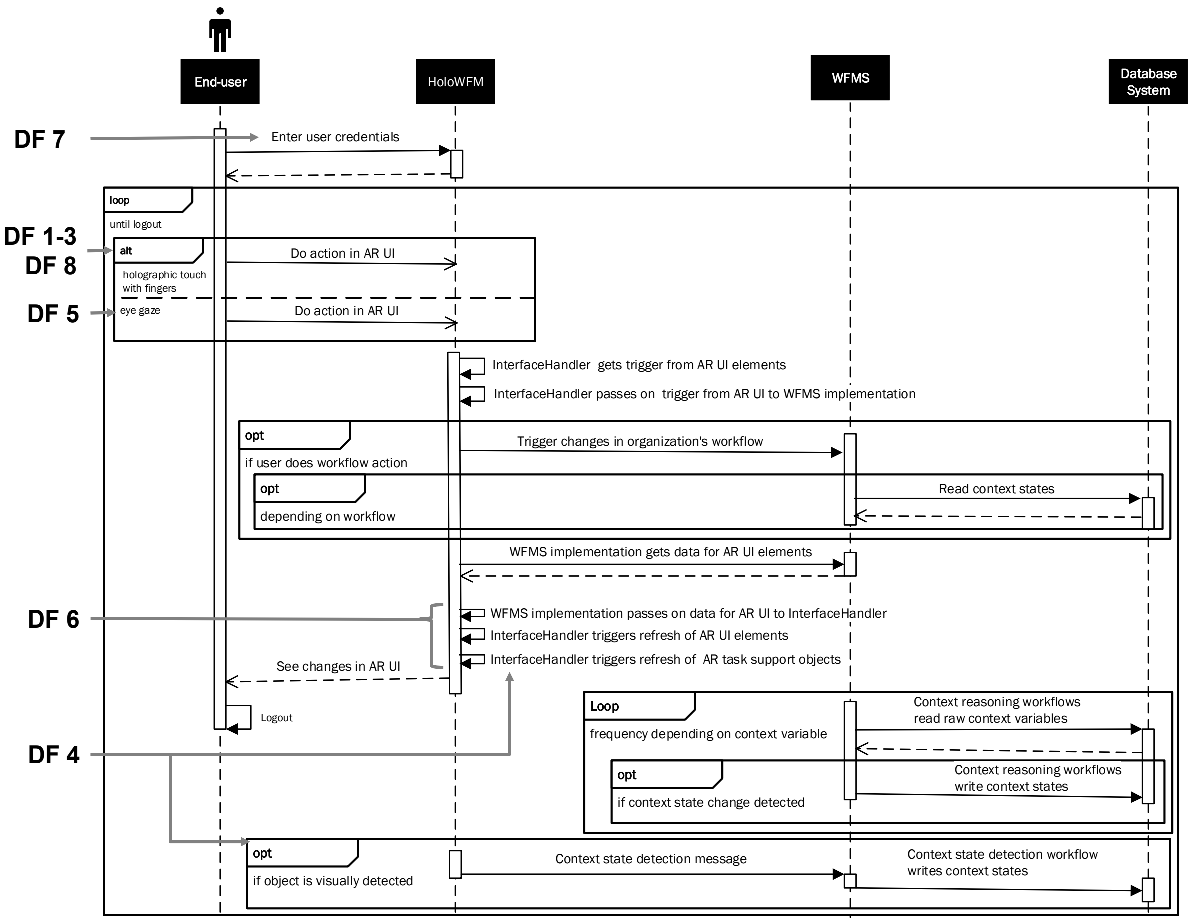


Figure 7. Reference UML sequence diagram, with corresponding design features indicated.

The UML sequence diagram in Figure 7 depicts the flow of information and actions between those components logically and chronologically, which have been depicted as a static UML component diagram in Figure 6. The main action starts with the end user's lifeline, interacting with the AR UI either via holographic touch or eye gaze (first *alt* box). Afterward, HoloWFM processes the input and may forward the user's actions to the WFMS or read from the database system. After processing possible responses, HoloWFM finally updated the AR UI for the end user. Independently from these user interactions, a loop runs to read and check for updates of the context variables and states (small *loop* box). Also, if the sensors of HoloWFM recognize a known object, a context state might be changed for that (last *opt* box).

4.4.6 Reference Simplified UML Class Diagram

Figure 8 shows the UML class diagram for HoloWFM, with the corresponding DFs, but no methods for attributes for the classes to enhance comprehensibility. The *InterfaceHandler* class acts as an abstraction layer between *AR UI elements* and is attached to the *Unity scene*, where the AR-based task support objects are also implemented for activation. Also, the eye-gazing module is implemented natively in Unity. For each UI component (cf. Section 4.4.3), custom data types are defined. The *interfaceHandler* thus controls, interacts with, and handles the UI and the users' inputs, independently of the WFMS used with HoloWFM: The functionalities of the UI are defined abstractly in *IWFMSMethods*, according to DP 6-8 or DF 8, e.g., starting workflows. This is necessary since every specific WFMS implements these UI functionalities differently and the *interface* IWFMSMethods acts as a contract with the WFMSs to be fulfilled. Because of this necessary abstraction layer, several abstract classes for tasks, workflow instances, workflow definitions, and respective filters are also defined, containing methods and attributes every WFMS must fulfil in order to be compatible with HoloWFM. A WFMS then operationalizes these abstract classes in its *WFMS-specific* manner. For our prototype, we implemented the interface IWFMSMethods and the abstract classes for Camunda 7.15, as shown at the bottom.

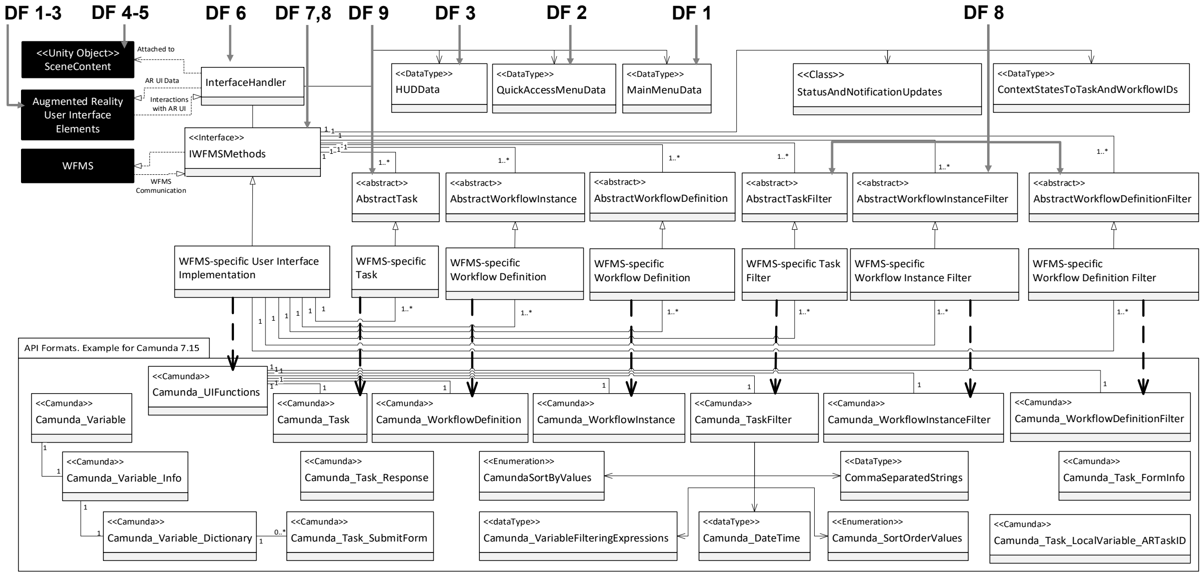


Figure 8. Reference UML class diagram for HoloWFM, with example implementation (bottom).

4.5 Reference Architecture Description Correspondences

The names of elements in the UML diagrams are instructive, i.e., the names and relationships correspond between models. E.g., the *InterfaceHandler* in Figure 6 indicates the same object as in Figure 8.

4.6 Rationales for Architectural Decision

Three key design decisions may be of interest. First, regarding the abstraction layer between UI and WFMS constituted by the *InterfaceHandler* class and *IWFMSMethods* interface. We chose not to include WMFS-specific implementations of methods in the *InterfaceHandler.* Instead, it selects and calls the appropriate *WFMS-specific User Interface Implementation* and passes any parameters to the WMFS-specific implementation of the method. This was done to enhance maintainability and enable better parallel development for multiple WMFS implementations.

Second, we chose to outsource the storage and processing of the *raw context variables* and *context states* from HoloWFM to the *database system* and *WFMS*. This was done to support cases where the amount of context variables collected becomes very large. In these cases, context-state reasoning workflows might also utilize further IT services, e.g., machine learning modules. To enable optimal performance, the context reasoning system was therefore entirely outsourced from the HoloWFM application.

Third, we utilize BPMN extension elements to refer to and pass on parameters to appropriate AR task support objects, which may be stored or dynamically generated in Unity. An alternative approach we explored was to somehow embed AR task support objects directly in the XML underlying the BPMN model. However, this would massively increase the size of the BPMN models and would make them and the AR objects harder to maintain. Instead, in our approach, the AR task support objects need to be somehow imported into the HoloWFM application, in the particular the *Unity scene*. This import could be done during build-time, however, this would require a new build of HoloWFM for each change in AR workflow support. As such, parallel distributed work would be a difficult thing. A better approach, therefore, is to dynamically load or preload AR task support objects into HoloWFM during runtime. Thus, no update of the HoloWFM application itself is needed. The AR task support objects then can be built in a distributed fashion alongside their respective workflows.

5 Evaluation

5.1 Evaluation Strategy

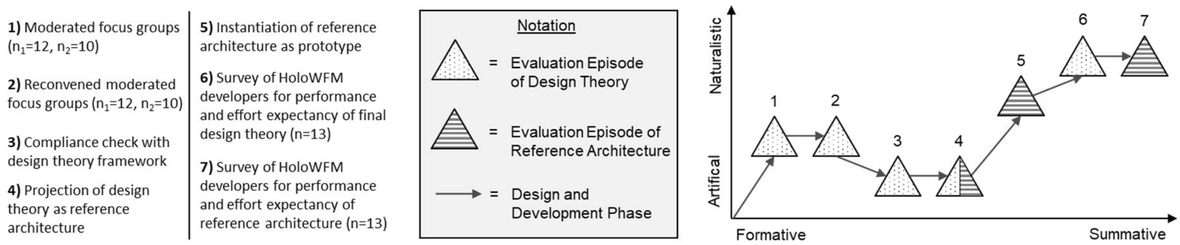


Figure 9. Evaluations mapped to the evaluation framework by Venable et al. (2017a).

Our overall evaluation strategy follows the framework for evaluation in design science research (FEDS) (Venable *et al.*, 2017a) (see Figure *9*). As the goal of the research project was to develop tangible design knowledge for a HoloWFM, the goal of the evaluation was to ensure the utility of the developed DT and RA in real practice, i.e., the developed RA must both be correct and useful for the RAs users: IS and AR architects, practitioners, and researchers. Also, while instantiating a prototype to demonstrate the technical feasibility is relatively cheap, an extensive evaluation with a "polished prototype", e.g. with a high-quality UI, in a real setting with real users would be prohibitively expensive. Therefore, the *Technical Risk & Efficacy* strategy of the FEDS is appropriate for our research project. Three evaluation phases were already performed in the first design cycle, which focuses on the end users. First, two moderated focus groups (MFG) (n_1=12, n_2=10) (Morgan, 1997) established the DRs for HoloWFM. Second, two reconvened MFGs with the same participants (Morgan *et al.*, 2008) confirmed the quality of the tentative DT and UI design. Third, the DT was formally verified by checking its compliance with the framework for DTs by Jones and Gregor (2007). We add to these evaluations with a validation of the DT via projection as an RA, a test of the RA's feasibility via operationalization as a prototype, and evaluations of the RA and DT by HoloWFM developers (n=13).

5.2 Evaluation of Design Theory via Projection as Reference Architecture

We understand the derivation of the RA from the DT in terms of the conceptual framework of *projectability* by Goodman (1955), as recommended by Baskerville and Pries-Heje (2014). According to this, a DT is *actually projected* when it's instantiated. When this *projection* is successful, i.e., no observation in opposition to the DT is made, but not all possible instantiations have been examined, a DT is *projectable*. The more frequently a DT is actually projected, the more entrenched it becomes (Goodman, 1955, pp. 80–81). We, therefore, demonstrated the projectability of the DT by deriving an RA from it as an actual projection. Also, as Fu *et al.* (2016) find, the majority of publications containing DPs lack their validation. By developing the RA, we not only address this common shortcoming but also are in line with other approaches to validation, as by far the most common validation principle is the application of the DPs for the actual design of an artifact (Fu *et al.*, 2016, p. 8).

5.3 Feasibility of Reference Architecture via Operationalization

To evaluate whether the developed design and derived RA are *feasible*, we orient ourselves on the framework by Sonnenberg and Vom Brocke (2012) and perform *evaluation activity 3* via a *demonstration with a prototype* (Sonnenberg and Vom Brocke, 2012, p. 393). We utilized the WFMS *Camunda*, a *MySQL* database, and a *Unity* application running on the *Microsoft HoloLens*. In our prototype, we focused on demonstrating the feasibility of the architecture to ensure utility for *HoloWFM developers*, i.e., if the approaches to structure the components, classes, and sequence logic work. We hence did not implement the full reference UI. In Figure 10 on the right, a tasklist filter for user-specific user tasks via the Camunda API demonstrates the use case "workflow queries" (cf. Figure 4) and displays them as pushable buttons. In the center, a user task is shown with the rendered HTML that Camunda would send to a web browser. The user task is also shown to be moveable. In contrast, the left image shows some AR UI elements, which correspond to workflow variables that are gathered from and sent to the WFMS for an update when the task is completed ("Task beenden"). The text in German is a meaningless placeholder for some task instructions.

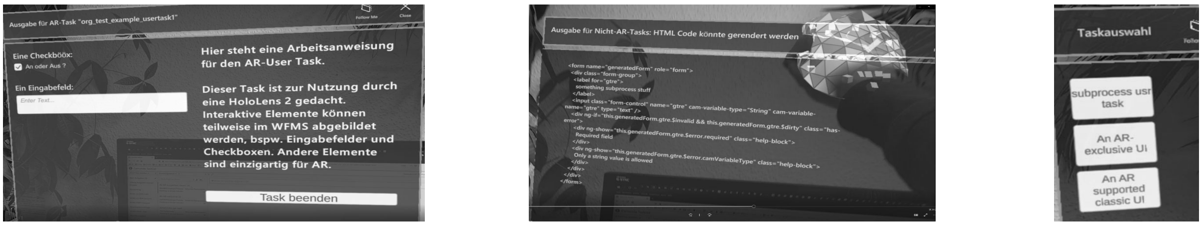


Figure 10. Prototype user task with UI elements (left), in HTML (centre) and tasklist (right).

5.4 Summative Evaluation of Performance and Effort Expectancy of Design Theory and Reference Architecture

To ascertain the usefulness of the RA and DT in more general terms, we evaluated the RA's and DT's *performance expectancy* (PE) and *effort expectancy* (EE) via surveying potential HoloWFM developers, i.e., IS and AR architects, developers, and researchers. As PE and EE as constructs are not directly measurable, we drew on the well-known scale items by Venkatesh *et al.* (2003). These are, for PE: usefulness (PE1), quickness (PE2), productivity (PE3), and increased chance of getting a raise (PE4); for EE: clarity (EE1), easiness to master (EE2), easiness to use (EE3), and easiness to learn (EE4). We specified the PE and EE for our application context, i.e., for the development of a WFMS front end for AR headsets. Additionally, we asked the experts about the conciseness (CON), extendibility (EXT), and explanatory power (EXP) of the artifacts, following Nickerson *et al.*'s (2013) approach to subjective ending conditions from their well-known taxonomy development method.

The questionnaire included: 1) an introductory text about the research project, 2) the DT, 3) a prompt to imagine an application scenario for the DT, 4) the statements on the EE, CON, EXT, and EXP, 5) the RA's UML models and descriptions, 6) a prompt to imagine an application scenario for these, 7) the statements on the PE, EE, CON, EXT, and EXP, and 8) some socio-economic questions. For data collection, we used interval-scaled verbal-numeric 7-point Likert-style scales. In choosing the sample size, we considered the so-called "10±2 rule" (Hwang and Salvendy, 2010), which suggests that 8 to 12 respondents are sufficient for our evaluations. Based on an expected response rate of 50 %, we sent the questionnaire by email to a total of 24 experts, whom we identified within our research institute's network as potential HoloWFM developers based on their profession and industry. We received 13 completed questionnaires (actual response rate: 54.2 %). The sending and receiving of the surveys were not done by the authors, and the responses were anonymized before being sent to the authors. The respondents partially fulfilled multiple professional roles and included 1 project manager, 5 project leads, 6 research associates, 3 senior researchers, 2 multimedia developers, and 1 usability engineer, all active in the workflow and AR domain, possessing 1-15 years (median: 3.5, mean: 4.88) of experience in their roles. Among the experts, eleven work in large, and two in micro-sized companies/organizations.

Figure 11 depicts the boxplots of the responses. For both the DT and RA, we received high levels of agreement for all items, with medians of m=6 and m=7. Thus, the sum scores of the PE and EE for the DT and RA with medians of m=26 and m=25 on a 7-28 scale summarize the overall evaluation well.

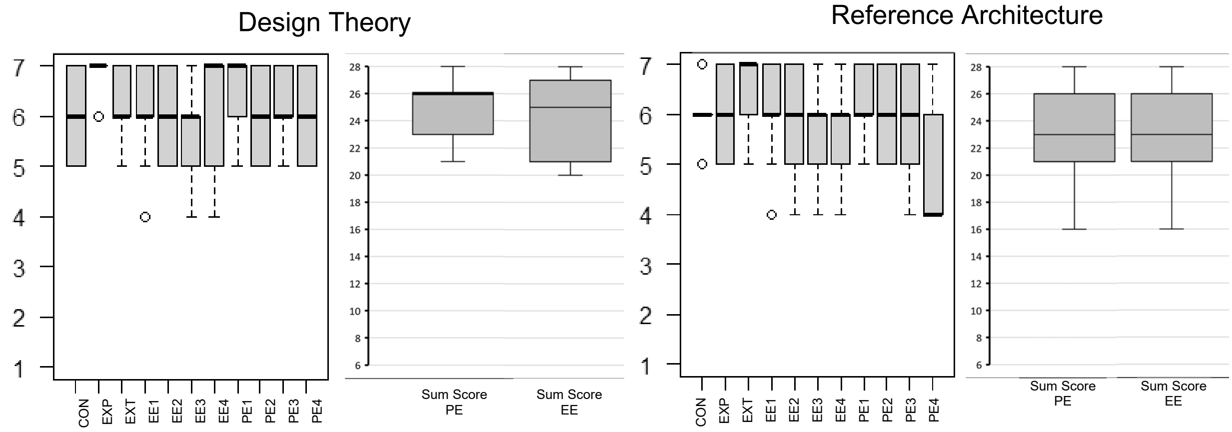


Figure 11. Boxplots for design theory and reference architecture evaluations.

Performance Expectancy		Design Theory	Reference Architecture	**Effort Expectancy**		Design Theory	Reference Architecture
Loadings	Usefulness	.554	.712	Loadings	Clarity	.582	.662
	Quickness	.998	.717		Easy to Master	.664	.585
	Productivity	.871	.998		Easy to Use	.655	.904
	Chance of Raise	.426	.435		Easy to Learn	.940	.998
	AVE	.560	.551		**AVE**	.523	.648
	CCR	.822	.820		**CCR**	.809	.876

Note. AVE = average variance extracted, CCR = composite construct reliability.

Table 1. Construct validation.

To validate the quality of the constructs PE and EE, we examine individual *item reliability* (loadings), *composite construct reliability*, and *average variance extracted* (Hulland, 1999). Item reliability is examined by evaluating the loadings of the measured items on their respective construct. We performed a confirmatory factor analysis in *R* for this purpose (Table 1). It is generally known that items with low loadings (rule of thumb: < 0.4) should be carefully scrutinized as they offer little additional explanatory power but attenuate (and thus bias) parameter estimates (Nunnally, 1978; Hulland, 1999). In our models, all item loadings exceed the 0.4 limits. The average variance extracted is a measure to assess the amount of variance captured by the construct, compared to the variance due to measurement error, and should be above 0.5, which is given for all our constructs and artifacts, indicating that the variance captured by the construct is greater than the measurement error (Fornell and Larcker, 1981). Composite construct reliability measures the overall reliability of items loading on a construct and, therefore, the internal consistency of a construct. It should exceed the threshold of 0.7 (Hulland, 1999; Nunnally, 1978), which is given for all our items and artifacts. Discriminant validity was assessed by comparing the average variance extracted with the squared correlation between the constructs (Fornell and Larcker, 1981). To calculate the correlation, the Kendall tau coefficient was used, which is particularly appropriate for Likert-style scales (Jamieson, 2004). The comparison shows that the average variances extracted of PE and EE (see table 1) are each higher than the squared correlations (cor) between PE and EE for both the DT (cor^2=0.480) and the RA (cor^2=0.354). Based on these validity criteria, our measurement models with four items each for the constructs PE and EE are suitable for evaluation. We also consider the PE and EE constructs as well as the underlying items to be valid since we adopted them from Venkatesh *et al.*'s (2003) well-known Unified Theory of Acceptance and Use of Technology (UTAUT) and these have been proven to be effective in numerous further studies.

6 Implications for Theory and Practice

The HoloWFM research project produced and evaluated a DT and an RA for a novel AR-based WFMS front end. From these contributions, implications for theory and practice can be derived. For research, the contributions to the knowledge base of the IS community are threefold (Gregor and Hevner, 2013). First, new descriptive knowledge is added by identifying the research gap for HoloWFM and extending existing contributions to address this gap (cf. Damarowsky and Kühnel, 2022).

Second, methodically, we demonstrate how to bridge the gap between highly abstract DRs and DPs with tangible and operationalizable RA UML diagrams by utilizing DFs and how to utilize the system architecture description standard ISO/IEC/IEEE 42010:2011 to document this developed design knowledge. To the best of our knowledge, this has not been shown previously.

Third, the UML diagrams of the RA add to the prescriptive knowledge base by providing tangible design knowledge since existing studies lack such less-abstract contributions. In line with the known benefits of RAs (see Section 3), researchers (and practitioners) can more easily implement a HoloWFM or similar IS. As many studies use prototype implementations to test certain functions or scenarios, the RA presented herein could provide tangible benefits to other researchers. Also, the RA can be expanded to incorporate new stakeholder requirements and new technologies, thus serving as a basis for future research endeavors. Indeed, research opportunities naturally arise to define different DPs, DFs, and RAs than ours, since a well-known inherent weakness in the development of DFs and RAs is the subjectivity of underlying design and architectural decisions, e.g., the number and partition of DFs, systems and (sub)components. Certainly, not all design decisions must or can be grounded in theory and a degree of creativity is unavoidable and essential in the DSR process (Hevner and Chatterjee, 2010; Baskerville *et al.*, 2016). Further, we derived the DFs from well-built DPs and the RA in turn from these DFs. Yet, each of these steps presents its own challenges and thus future research opportunities.

For practice, the positive survey indicates that generally, the DT and RA can provide valuable guidance to practitioners when developing a WFMS front end that is designed for AR headsets. The UI design provides a tangible template to build on but also can be used as a mockup in further design studies with end users. The requirements and principles of design from the DT guide the overall development process. Since we provide tangible, operationalizable component- and class-level design knowledge in standard notation UML, these models can directly be utilized in system and software development. The documentation of key architectural decisions also saves time and resources, e.g., utilizing an abstraction layer between UI and WFMS, linking AR task support objects via BPMN extensions, and placing the context reasoning system outside the HoloWFM application, are not entirely obvious decisions. Thus, the well-known benefits of RAs (see Section 3) can be realized in practice. Finally, the RA's complexity is not overbearing as Figure 7 summarizes. Thus, the instantiation of a HoloWFM is not prohibitively difficult for companies, the main challenge being the construction of a stakeholder-specific AR UI. With the instantiations of HoloWFMs (or related artifacts) for known application scenarios of ARSs for workflow execution support (cf. Section 1), organizations can benefit from the superior workflow management and control functionalities and thus better integrate ARSs into an existing WFMS infrastructure. End users meanwhile can effectively operate workflows and WFMSs more efficiently while benefiting from AR task support, therefore potentially increasing overall productivity.

7 Conclusion & Outlook

The goal of the HoloWFM DSR project was to conceptualize and design a WFMS front end for AR headsets, supporting the full range of user interactions. Based on the positive evaluations, this has been accomplished. Yet, by their very nature, RAs have a shelf life and need to be updated regularly – or discarded eventually. The implementation of HoloWFMs (or derived artifacts) in practice will create the opportunity to refine and update the RA – which we strive to do in our future research.

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