HENRI JALO

Factors Affecting the Organizational Adoption of Extended Reality Technologies

Tampere University Dissertations 842

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Henri Jalo
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ABSTRACT

Digitalization and the shift toward remote virtual work are pushing organizations to explore the adoption of emerging technologies, including augmented reality (AR) and virtual reality (VR), which are often examined under the umbrella term extended reality (XR). XR technologies have gained increasing interest from organizations due to their disruptive potential in enabling more immersive and engaging remote collaboration, as well as novel interactions with digital content. By adopting XR technologies, organizations can re-engineer their operations and achieve a competitive advantage. As the maturity and sophistication of XR technologies have been increasing due to significant investments in XR technologies by major technology companies and research institutes, the incentives for companies to adopt XR solutions have also risen as more powerful and versatile XR solutions have become available.

However, only the most pioneering companies are currently using XR solutions extensively. XR technologies can be seen as a new interfaces and platforms that enable an organization's employees to collaborate with each other and engage with the organization's digital resources in a more immersive fashion. The novelty and unique nature of XR, along with the possibilities to utilize it in a multitude of use cases, make its adoption a complex proposition for organizations. However, as an emerging technology, the most critical factors that can either drive or hinder XR adoption in organizations have received little attention in the literature.

This dissertation will respond to this gap in research by identifying the most important adoption factors for XR technologies and by unveiling the relationships and dynamics between these adoption antecedents and an organization's intention to adopt XR technologies. In addition, this dissertation also provides prescriptive recommendations that organizations can utilize to adopt and further develop XR solutions more effectively. The main research question of this dissertation is as follows: *What are the main factors affecting the organizational adoption of extended reality technologies?*

To answer to this main research question, a mixed methods research approach is utilized. Overall, this article-based dissertation consists of five peer-reviewed publications. In the initial explorative phase, a qualitative approach consisting of semi-structured interviews is employed to provide a comprehensive accounting of relevant technological, organizational, and environmental XR adoption factors for organizations. In the following confirmatory stage, an organizational-level XR adoption model is proposed and tested with quantitative survey data using the structural equation modeling approach, with the model being further contextualized in a follow-up qualitative study. Practical insights gained during this process, as well as findings from the extant literature, are used to derive prescriptive recommendations for organizations to assist them in their XR adoption efforts. Lastly, three overarching meta-inferences are developed based on a comparison of the convergent and divergent findings of the qualitative and quantitative results of the individual publications.

Overall, although technological factors emerged as important factors for XR adoption in the explorative phase, the importance of different organizational and environmental factors, such as organizational support capabilities and mimetic pressures, rose to the forefront of the results in the confirmatory stage. The results thus suggest that technological factors, such as XR's compatibility with organizational information systems and existing hardware install base, should be viewed as necessary initial conditions for adoption but insufficient to drive adoption independently. In contrast, more proximate adoption antecedents, such as expected employee resistance and perceived value, emerged as sufficient conditions for adoption. Moreover, organizations were found to prioritize internal capabilities and skills over external support in XR adoption.

This dissertation contributes to the information systems (IS) and technology adoption literatures with a holistic mixed methods examination and identification of the main factors affecting the adoption of XR in organizations. The dissertation's findings will be useful for researchers as a basis for further theory development, particularly in the context of XR and other emerging and transformative technologies. Practitioners can make use of the findings in focusing their efforts on the most important identified adoption factors to ensure a smoother adoption of XR technologies in their organization.

TIIVISTELMÄ

Digitalisaatio ja siirtyminen kohti virtuaalista etätyöskentelyä ovat saaneet organisaatiot tutkimaan uusien teknologioiden, kuten ”laajennetun todellisuuden" (extended reality, XR) kattokäsitteen alle kuuluvien lisätyn todellisuuden (augmented reality, AR) ja virtuaalitodellisuuden (virtual reality, VR), käyttöönottoa. Kiinnostus XR-teknologioita kohtaan on kasvanut organisaatioissa niiden disruptiivisen potentiaalin vuoksi, sillä ne mahdollistavat immersiivisempiä etäyhteistyömahdollisuuksia sekä uudenlaisia tapoja vuorovaikuttaa digitaalisen sisällön kanssa. XR-teknologioiden käyttöönotolla organisaatiot voivat uudistaa toimintojaan ja saavuttaa kilpailuetua. Suurten teknologiayritysten ja tutkimuslaitosten merkittävien investointien ansiosta XR-teknologioiden kypsyys ja kehitystaso ovat kasvaneet, mikä on myös lisännyt yritysten kannustimia ottaa käyttöön XR-ratkaisuja, kun yhä tehokkaampia ja monikäyttöisempiä XR-ratkaisuja on tullut saataville.

XR-ratkaisuja käyttävät kuitenkin tällä hetkellä laajasti vain edelläkävijäyritykset. XR-teknologiat voidaan nähdä uusina rajapintoina ja alustoina, jotka mahdollistavat organisaation työntekijöille immersiivisempiä tapoja yhteistyöskentelylle ja organisaation digitaalisten resurssien hyödyntämiselle. XR:n uutuus ja ainutlaatuisuus sekä mahdollisuudet hyödyntää sitä monissa erilaisissa käyttötapauksissa tekevät sen käyttöönotosta monimutkaista organisaatioille. Koska XR-teknologiat ovat pitkälti vielä kehitysvaiheessa, kirjallisuudessa ei ole vielä juurikaan käsitelty niitä kriittisimpiä tekijöitä, jotka voivat joko edistää tai vaikeuttaa XR:n käyttöönottoa organisaatioissa.

Tämä väitöskirja vastaa tähän tutkimusaukkoon tunnistamalla tärkeimmät XR-teknologioiden käyttöönottoon vaikuttavat tekijät ja paljastamalla näiden käyttöönoton tekijöiden ja organisaation käyttöönottoaikeen väliset suhteet ja dynamiikan. Tässä väitöskirjassa luodaan myös suosituksia, joita organisaatiot voivat hyödyntää XR-ratkaisujen käyttöönoton ja kehittämisen tehostamiseksi. Tämän väitöskirjan päätutkimuskysymys on: *Mitkä tekijät ovat tärkeimpiä laajennetun todellisuuden teknologioiden käyttöönotossa organisaatioissa?*

Tähän päätutkimuskysymykseen vastaamiseen hyödynnetään monimenetelmäistä tutkimuslähestymistapaa. Tämä artikkelipohjainen väitöskirja koostuu viidestä vertaisarvioidusta julkaisusta. Ensimmäisessä eksploratiivisessa tutkimusvaiheessa

pyritään luomaan kattava katsaus tärkeimpiin teknologisiin sekä organisaation sisäisiin ja ulkoisiin tekijöihin, jotka vaikuttavat XR:n organisatoriseen käyttöönottoon. Tässä tutkimusvaiheessa hyödynnetään laadullista lähestymistapaa ja puolistrukturoituja haastatteluita. Tämän jälkeen tutkimuksen konfirmatorisessa vaiheessa kehitetään organisaatiotason XR:n käyttöönottoa selittävä malli, jota testataan määrällisellä kyselyaineistolla hyödyntämällä rakenneyhtälömallintamista. Tämän jälkeen malli kontekstualisoidaan laadullisen tutkimuksen avulla. Tutkimusprosessin aikana saatuja käytännön näkemyksiä sekä kirjallisuuden tuloksia hyödynnetään organisaatioille annettavien käyttöönottoa helpottavien suositusten laatimisessa. Viimeiseksi luodaan kolme metatason päätelmää vertailemalla yksittäisten julkaisujen laadullisten ja määrällisten löydösten yhteneväisyyksiä ja eroavaisuuksia.

Vaikka tutkimuksen eksploratiivisen vaiheen perusteella teknologiset tekijät nousivat tärkeiksi XR:n käyttöönotossa, erilaisten organisaation sisäisten ja ulkoisten tekijöiden, kuten organisaation antaman tuen sekä mimeettisten paineiden, tärkeys korostui tutkimuksen konfirmatorisessa vaiheessa. Tulokset viittaavatkin siihen, että teknologiset tekijät, kuten XR:n yhteensopivuus organisaation tietojärjestelmien ja olemassa olevan laitekannan kanssa, ovat välttämättömiä alkuvaiheen edellytyksiä käyttöönotolle, mutta riittämättömiä ajamaan käyttöönottoa itsessään. Toisaalta proksimaattisemmat käyttöönoton tekijät, kuten työntekijöiden vastustus ja teknologiassa nähty arvo, nousivat esiin riittävinä edellytyksinä käyttöönotolle. Organisaatioiden nähtiin lisäksi priorisoivan sisäisiä kyvykkyyksiä ja taitoja ulkoisen tuen sijaan XR:n käyttöönotossa.

Tämä väitöskirja kontribuoi tietojärjestelmätieteen ja teknologioiden käyttöönoton kirjallisuuksiin tunnistamalla tärkeimmät XR:n organisatoriseen käyttöönottoon vaikuttavat tekijät holistisen monimenetelmäisen tarkastelun avulla. Tämän väitöskirjan löydökset ovat hyödyllisiä tutkijoille teorioiden jatkokehittämisen perustana erityisesti XR:n ja muiden transformatiivisten teknologioiden kontekstissa. Ammattilaiset voivat hyödyntää löydöksiä keskittymällä tärkeimpiin tunnistettuihin käyttöönoton tekijöihin sujuvamman XR-teknologioiden käyttöönoton varmistamiseksi organisaatioissaan.

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ABBREVIATIONS

AEC	Architecture, engineering, and construction
API	Application programming interface
AR	Augmented reality
AV	Augmented virtuality
BIM	Building information modeling
CFA	Confirmatory factor analysis
CR	Critical realism
DOI	Diffusion of innovations
EFA	Exploratory factor analysis
fsQCA	Fuzzy-set qualitative comparative analysis
FM	Facility management
HHD	Hand-held display
HMD	Head-mounted display
IS	Information systems
IT	Information technology
MR	Mixed reality
SEM	Structural equation modeling
SME	Small and medium-sized enterprise
SVR	Social virtual reality
TAM	Technology acceptance model
TOE	Technology–organization–environment
TPB	Theory of planned behavior
TRA	Theory of reasoned action
TTF	Task-technology fit
UTAUT	Unified theory of acceptance and use of technology
VR	Virtual reality
WSR	Wilcoxon signed rank
XR	Extended reality

ORIGINAL PUBLICATIONS

Publication I	Jalo, H., Pirkkalainen, H., Torro, O., Kärkkäinen, H., Puhto, J., & Kankaanpää, T. (2018). How can collaborative augmented reality support operative work in the facility management industry? In Proceedings of the 10th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management – KMIS, ISBN 978-989-758-330-8; ISSN 2184-3228, SciTePress, 41–51.
Publication II	Jalo, H., Pirkkalainen, H., Torro, O., Lounakoski, M., & Puhto, J. (2020). Enabling factors of social virtual reality diffusion in organizations. In Proceedings of the 28th European Conference on Information Systems (ECIS), An Online AIS Conference, June 15-17, 2020.
Publication III	Jalo, H., Pirkkalainen, H. Torro, O., Pessot, E., Zangiacomi, A., & Tepljakov, A. (2022). Extended reality technologies in small and medium-sized European industrial companies: Level of awareness, diffusion and enablers of adoption. Virtual Reality, 26(4), 1745–1761.
Publication IV	Jalo, H., & Pirkkalainen, H. (Submitted for publication). Effect of user resistance on the organizational adoption of extended reality technologies: a mixed methods study.
Publication V	Torro, O., Jalo, H., & Pirkkalainen, H. (2021). Six reasons why virtual reality is a game-changing computing and communication platform for organizations. Communications of the ACM, 64(10), 48–55.

AUTHOR'S CONTRIBUTION TO CO-AUTHORED PUBLICATIONS

In Publication I, I generated the idea for the paper together with my supervisor (the second author). I wrote the theoretical background for the publication and devised the interview protocol in collaboration with the second and third authors. I was primarily responsible for the data collection (i.e., I arranged the interviews and acted as the lead interviewer). However, the other authors were also varyingly present during the interviews. I carried out the qualitative analysis on the collected interview data and wrote a first draft version of the manuscript, which was then reviewed by the other authors. The whole manuscript was then revised based on their feedback. As the corresponding author, I submitted the manuscript to the Knowledge Management and Information Systems (KMIS) conference in 2018. The peer review feedback was examined jointly with the co-authors. I revised the manuscript based on this discussion. I also presented the accepted publication at the KMIS conference in 2018.

In Publication II, I generated the idea for the paper together with my supervisor (the second author). I wrote the theoretical background for the manuscript and devised the interview protocol in collaboration with the other co-authors. I arranged part of the interviews and acted as the lead interviewer with the fourth author acting as the lead interviewer in the rest of the interviews. The other co-authors took part in the interviews varyingly. I carried out the qualitative analysis on the collected interview data and wrote a first draft version of the manuscript, which was then reviewed by the other co-authors. The whole manuscript was then revised based on their feedback. I submitted the manuscript to the European Conference on Information Systems (ECIS) and acted as the corresponding author. The peer review feedback was examined jointly with the co-authors. I revised the manuscript based on this discussion. I presented the accepted publication at the ECIS online conference in 2020.

In Publication III, I generated the idea for the paper together with my supervisor (the second author). I developed the quantitative online survey and the qualitative interview protocol that were used in the data collection based on a review of the literature. Both the online survey and the interview protocol were revised based on feedback from the co-authors and the broader research group of the research project. I arranged the interviews in Finland and acted as the lead interviewer. The third co-author took part in the interviews. I was also primarily responsible for the survey data collection in Finland and for coordinating the data collection with the broader European research group. I carried out the quantitative and qualitative analyses and wrote a first draft version of the manuscript, which was then reviewed by the other co-authors. The whole manuscript was then revised based on their feedback. I submitted the manuscript to the Virtual Reality journal in 2021 and acted as the corresponding author. The peer review feedback was examined together with the co-authors. I revised the manuscript based on this discussion and submitted the revised manuscript in 2022, which was accepted and published by the journal.

In Publication IV (submitted for publication), I generated the idea for the paper together with my supervisor (the second author). I developed the quantitative online survey and the qualitative interview protocol that were used in the data collection based on a review of the literature. Both the survey and the interview protocol were revised based on feedback from the second author and the broader research group of the research project. I arranged the interviews in Finland and acted as the lead interviewer. I was also primarily responsible for the survey data collection in Finland and for coordinating the data collection with the broader European research group. I carried out the quantitative and qualitative analyses and wrote a first draft version of the manuscript, which was then reviewed by the second author. The whole manuscript was then revised based on this feedback. I acted as the corresponding author when the manuscript was submitted to a journal at the beginning of 2022. The peer review feedback was examined together with the second author. I revised the manuscript based on this discussion and submitted the revised manuscript at the end of 2022. After a minor revision decision, the peer review feedback was again examined together with the second author. I revised the manuscript based on this discussion and the peer review feedback. I submitted the revised version of the manuscript to the journal in April 2023.

In Publication V, the initial idea for the paper was developed together with the other co-lead author (the first author). My supervisor (the third author) also provided valuable contributions to the overall development of the paper. This conceptual paper was developed based on a review of the literature and practical insights from previous projects and research endeavours. I was primarily responsible for developing the first half of the publication and supported the development of the latter half for which the other co-lead author was primarily responsible. The introduction, conclusion, and recommendations sections were jointly developed with the other co-lead-author. The third author provided valuable comments and feedback on the development of these sections. The first author submitted the manuscript to the Communications of the ACM journal in 2020 and acted as the corresponding author. The whole publication was then jointly revised based on peer review feedback and a revised version of the manuscript was submitted later in 2020, which was accepted and finally published in 2021. This publication is also included in Osku Torro's doctoral thesis.

1 INTRODUCTION

1.1 Background and motivation

Organizations are ever seeking new ways to enhance their operations and support their employees in collaborating more effectively with the aid of new technologies. In recent years, the shift toward remote work via virtualization of organizational activities and the need to make more effective use of digital assets have been specifically emphasized (Porter & Heppelmann, 2017; Torro et al., 2022). In this regard, augmented reality (AR) and virtual reality (VR) are two technologies that have drawn increasing interest from practitioners and researchers due to their disruptive potential (French et al., 2020). AR technologies are used to add digital content into the user's view of the real environment, while VR immerses the user into a completely virtual environment (Azuma et al., 2001; Bryson, 1995; Jerald, 2015). As such, these technologies enable organizational users to examine digital content more immersively and intuitively, and to collaborate remotely in virtual settings (French et al., 2020; Porter & Heppelmann, 2017; Torro et al., 2021). Collectively, these technologies are often referred to as "extended reality" (XR) technologies (Chuah, 2019; Dwivedi et al., 2021).

In addition to the recent technological advancements in AR and VR (Billinghurst, 2021; Dincelli & Yayla, 2022), XR technologies have also received significant industry backing in contrast to earlier iterations (Kugler, 2017; Porter & Heppelmann, 2017; Walsh & Pawlowski, 2002). Major technology companies, such as Apple, Meta, Google, and Nvidia, have made significant investments in developing both XR hardware and software (Dwivedi et al., 2022). As a result, the incentives for companies to adopt these technologies have also increased as more powerful and versatile industry-focused XR solutions have become available (Dincelli & Yayla, 2022; Torro et al., 2021). The overall XR market is expected to grow significantly in the next few years (Marr, 2019; Research and Markets, 2022). Estimates vary wildly with some analysts predicting the overall XR market to reach $114.5 billion by 2027 (Research and Markets, 2022), while more conservative estimates predict a turn toward more sustainable business cases from the hype surrounding these technologies (IDC, 2018). Although much of this growth is expected to occur in the individual consumer context, the organizational use of XR also shows huge promise (Chi et al., 2013; Dincelli & Yayla, 2022; Porter & Heppelmann, 2017).

In the organizational context, XR technologies can be seen as both immersive 3D interfaces to digital organizational content and as multi-user collaboration platforms (Davila Delgado et al., 2020; Torro et al., 2021). As a result, they have significant application potential throughout the organizational value-chain (Porter & Heppelmann, 2017). Organizational application examples, ranging from design collaboration in VR (Devanesan, 2020; Wolfartsberger, 2019) to remote AR support (Porter & Heppelmann, 2017) and immersive VR training (Dincelli & Yayla, 2022), have already demonstrated the potential of XR to enhance organizational performance. Despite this, XR adoption rates are still lagging behind initial forecasts and only the most pioneering companies are using XR technologies in an extensive manner (Chuah, 2019; Porter & Heppelmann, 2017).

As XR technologies are still emerging and maturing (Chuah, 2019), the extant XR adoption literature is largely exploratory (e.g., Berg & Vance, 2017) and limited in explaining what factors are critical for their organizational adoption. In addition, given that XR differs significantly from traditional information technologies (Mütterlein & Hess, 2017), companies are uncertain what factors they should take into account in their adoption. Moreover, as XR adoption has only truly become relevant for organizations recently due to technological breakthroughs and added multi-user capabilities (Kugler, 2017; Marr, 2019; Porter & Heppelmann, 2017), the transferability of earlier findings that largely focused on single-user systems (Kim et al., 2013) is questionable. The wide organizational application potential of modern XR solutions also requires the involvement of a wide assortment of stakeholders in their adoption. Thus, in addition to technological factors, various organizational, human, and external factors need to be considered to make their adoption and use easy for employees and to enable organizations to utilize XR with external stakeholders in addition to internal operations (Chandra & Kumar, 2018; DePietro et al., 1990). Therefore, XR adoption can be considered to be a complex undertaking for organizations.

Due to the significant potential and still limited use of XR technologies, it is thus crucial to investigate what factors can promote and hinder their adoption in the organizational context. This dissertation aims to address this gap in the research. This context offers opportunities to contribute both to the information systems (IS) and technology adoption literatures regarding the organizational adoption of emerging technologies, such as XR, and into practice by unveiling the most important factors that organizations need to consider when they embark on adopting XR technologies. The main research question of this dissertation is: W*hat are the main factors affecting the organizational adoption of extended reality technologies?*

The empirical research for this dissertation is primarily conducted in the architecture, engineering, and construction (AEC) industry context. XR technologies are highly applicable for the AEC industry, as many of its work tasks are focused on examining visual digital information and achieving a shared understanding between many different stakeholders during a construction project's lifecycle (Dubois & Gadde, 2002; Gann & Salter, 2000). The AEC industry has also shown increasing interest toward applying XR technologies (Du et al., 2018; Goulding et al., 2014). Some of the later studies expand the research context into the manufacturing industry, which has similar characteristics to the AEC industry regarding multi-stakeholder collaboration and visual data relating to products. The issues regarding XR adoption are addressed from an organizational point of view. Theories examining innovation adoption at the organizational level, such as Rogers' (2003) diffusion of innovations (DOI) theory and the technology–organization–environment (TOE) framework (DePietro et al., 1990), are employed in the analysis.

A mixed methods research strategy, employing qualitative and quantitative research approaches, is used in the dissertation (Venkatesh et al., 2013). The overall thesis consists of five peer-reviewed publications. The first two explorative qualitative multiple-case studies (Publications I and II) aim to provide an initial understanding into the critical adoption factors affecting organizational AR and VR adoption using semi-structured interviews (Ghauri & Grønhaug, 2005; Yin, 2009). Publication III utilizes a mixed methods approach, contrasting the AR and VR adoption situation quantitatively and identifying common XR adoption factors qualitatively through an analysis of semi-structured interviews. Following this, Publication IV develops an organizational-level resistance-value adoption model, which is validated with survey data using the structural equation modeling (SEM) approach. The conceptual model is then further contextualized through a follow-up qualitative study involving semi-structured interviews. In Publication V, the value of VR as a novel organizational platform is examined and recommendations for adoption are distilled from the literature and practical insights gained during the dissertation process. Lastly, the qualitative findings and quantitative results of the publications are compared to develop three integrative meta-inferences about organizational XR adoption dynamics (Venkatesh et al., 2013).

1.2 Research questions

The purpose of this dissertation is to examine how companies perceive XR technologies, what potential value they see in them, what different factors play a critical part in their adoption, and to ascertain the dynamics between the identified critical adoption factors. This dissertation aims to provide a better theoretical understanding about organizational XR adoption dynamics via a holistic mixed methods examination (Venkatesh et al., 2013). For practitioners, this dissertation aims to provide insights and suggestions about how the adoption of XR technologies should be carried out in organizations. The following overarching main research question was employed to guide the research:

What are the main factors affecting the organizational adoption of extended reality technologies?

In order to address this broad main research question, three research questions were posed, which were addressed in the exploratory (RQ1), confirmatory (RQ2), and prescriptive (RQ3) phases of the research.

As AR and VR were still extremely novel technologies to most companies at the start of this dissertation process, the extant AR and VR adoption literature (e.g., Berg & Vance, 2017; Chandra & Kumar, 2018; Fernandes et al., 2006; Mütterlein & Hess, 2017) was also quite fragmented, largely exploratory, and often placed within a limited context (e.g., a single industry or country). As a comprehensive accounting of relevant organizational XR adoption factors was missing from the literature, the extant literature provided little guidance for carrying out confirmatory research. An exploratory research approach was thus adopted at the beginning stage of the dissertation to provide an initial understanding of the factors involved in the organizational adoption of AR and VR technologies. This exploratory phase aimed to answer the first research question (RQ1):

RQ1: What are the critical adoption enabling factors for AR and VR for organizations?

This research question was addressed in Publications I, II, and III. Publication I first examined what factors affect the organizational adoption of AR, followed by Publication II, which focused on identifying critical enabling adoption factors for the diffusion of VR in an organization. The rationale for this approach was to identify initially convergent themes applicable to both technologies as a basis for their later joint examination. Publication III then first quantitatively examined the adoption situation and organizational perceptions relating to AR and VR, and then qualitatively identified common technological, organizational, and environmental factors affecting organizational XR adoption.

The aim of the initial exploratory phase of the research was to create a more solid basis for designing the later confirmatory part of the dissertation where AR and VR adoption could be jointly assessed in more detail by confirming the importance of the identified adoption factors, or antecedents, both qualitatively and quantitatively. Due to the limited number of confirmatory studies on organizational XR adoption (e.g., Chandra & Kumar, 2018; Masood & Egger, 2019), establishing the significance of the identified XR adoption factors was seen to be important. Moreover, the relative importance of the identified adoption antecedents was unknown. Thus, the aim of the confirmatory part of the research was to ascertain the significance and more exact relationships between the identified adoption antecedents and organizations' XR adoption intention. The later confirmatory phase aimed to answer the second research question (RQ2):

RQ2: What is the relationship between the identified XR adoption enabling factors and XR adoption intention for organizations?

This research question is primarily addressed in Publication IV. Publications I and II were used in identifying the most important themes affecting organizational XR adoption. Based on these themes, relevant constructs were then identified from the extant literature and adapted for the research context. A conceptual model was then proposed in Publication IV detailing the specific relationships and dynamics between these constructs. Survey data were used to test and validate the model with SEM techniques, which revealed the statistically significant relationships between the model antecedents and organizational XR adoption intention.

Lastly, the dissertation aimed to distill the findings from the exploratory and confirmatory research stages into practical guidelines that organizations could benefit from. This final part of the research process sought to answer the third research question (RQ3):

RQ3: What industry-independent recommendations can be given for adoption of XR solutions?

In Publication V, key findings and results from the XR literature and practical insights gained on organizational XR adoption during the earlier part of the research process (Publications I, II, III, and IV) were distilled into prescriptive recommendations. Thus, the exploratory and confirmatory phases both provided inputs for the prescriptive recommendations phase of the research.

In summary, this dissertation consists of five peer-reviewed academic publications (see Table 1, Publication IV is under review). Although each publication had its own research questions and objectives, they examined the same overarching research theme of XR adoption and use in industry from the organization's perspective. To provide answers to the main research question posed at the beginning of this section, the findings and results of Publications I–IV were finally compared to identify convergent and divergent themes. This process led to the development of three overarching meta-inferences crystallizing the key findings of the research (Venkatesh et al., 2013). Table 1 summarizes how the publications contributed to answering the research questions of the dissertation.

Table 1. Contribution of each publication to the research questions (X = publication contributes to research question)

Research question	Publication I	Publication II	Publication III	Publication IV	Publication V
Main research question: What are the main factors affecting the organizational adoption of extended reality technologies?	X	X	X	X	X
Research question 1 (RQ1): What are the critical adoption enabling factors for AR and VR for organizations?	X	X	X		
Research question 2 (RQ2): What is the relationship between the identified XR adoption enabling factors and XR adoption intention for organizations?				X	
Research question 3 (RQ3): What industry-independent recommendations can be given for adoption of XR solutions?					X

1.3 Research context, process, and strategy

Overall, the dissertation employed a sequential mixed methods research approach (Gable, 1994; Venkatesh et al., 2013), consisting of an initial explorative phase (Publications I, II and III), a confirmatory quantitative phase (Publication IV), and a prescriptive phase (Publication V). Due to the novelty of XR and its limited adoption levels in organizations (Chuah, 2019), little research existed about its organizational adoption at the beginning of the dissertation. Thus, two explorative qualitative multi-case studies and one mixed methods study consisting of a quantitative and qualitative part were carried out at the beginning of the dissertation. These types of studies are appropriate when little is known about the topic (Benbasat et al., 1987; Eisenhardt & Graebner, 2007). These studies first explored the adoption of AR and VR separately and finally jointly with the aim of identifying key adoption enabling factors affecting the adoption of XR in organizational settings. In the second part of the mixed methods research process, the initial explorative findings were used to develop the design of the quantitative confirmatory study (Publication IV).

The first study on AR was carried out in a company-financed Diili research project in 2018. The aim of the Diili project was to identify the value of immersive collaborative technologies, such as AR and VR, in the construction and facility management (FM) industries, and to explore the factors these companies should consider if they were to adopt such technologies. This research was conducted in Finland.

The second VR-focused study was conducted during the SXR co-creation Business Finland research project (2018-2019). The SXR project further explored the value of AR and VR technologies for AEC, FM, and real estate industries with a specific focus on identifying the barriers and drivers affecting their adoption. This research was also conducted in Finland.

Following this, two mixed-methods studies were carried out during the VAM Realities Erasmus+ research project (2020-2022). This research was conducted in Austria, Belgium, Cyprus, Estonia, Finland, Germany, Italy, the Netherlands, and Spain. The VAM Realities project explored the adoption of XR technologies in the manufacturing and AEC industries with a specific focus on small and medium-sized enterprises (SMEs). The first of these studies (Publication III) examined the state of AR and VR adoption and perceptions in European industrial companies and quantitatively compared whether there were any differences between the technologies. Common adoption enabling factors applying to both technologies were then identified based on a qualitative analysis. The second mixed-methods study begun with a deductive quantitative survey study, in which a theoretical model was proposed and tested with survey data obtained from European industrial companies. A follow-up qualitative study further identified critical conditions and manifestations for the validated theoretical model.

Lastly, a more practitioner-focused conceptual publication was written in 2020, where the insights and findings gained during the dissertation process were distilled and recommendations were given to organizations on how to best develop and adopt

VR solutions. The mixed methods research process culminated in the development of three overarching meta-inferences from the qualitative and quantitative strands of the research (Venkatesh et al., 2013).

1.4 Structure of the dissertation

The first part of this dissertation (section 1) contains the introduction. In this section, the background, motivation, context, key concepts, positioning within information systems (IS) literature, and the research questions and strategy of the dissertation are detailed.

In section 2, the theoretical background relating to the examined technologies (AR, VR, and XR) and relevant individual- and organizational-level adoption theories are described.

In section 3, the overall mixed-methods research methodology of the dissertation, as well as the research settings and methods used in the individual publications included in the dissertation, are described. In addition, the overall qualitative and quantitative data collection and analysis methods are presented.

In section 4, the summarized findings of the research publications and their contributions to the overall dissertation are presented. This is followed by a discussion of the findings and results in section 5, where three integrative meta-inferences based on a comparison of the qualitative and quantitative studies are presented.

Finally, the theoretical and practical contributions of the dissertation are detailed in section 6. An evaluation of the research and its limitations, along with some possible future research directions, are included at the end of the dissertation.

2 THEORETICAL BACKGROUND

In this section, the theoretical background of the dissertation related to the examined technologies and adoption theories is outlined.

2.1 Augmented, virtual, and extended reality technologies

The section explores the technologies that were the focus of the empirical examination (AR, VR, and XR). AR and VR are first presented separately, followed by the introduction of XR as an umbrella term for AR and VR. Lastly, key findings related to their organizational adoption are presented.

2.1.1 Augmented reality

Augmented reality (AR) can be defined as a technology that *combines virtual objects into a user's view of the real world in real time while also being interactive* (Azuma et al., 2001). In AR, the user retains their view of the real world while digital content is being added to it. Although all five human senses (sight, sound, touch, smell, and taste) can theoretically be augmented with AR, most of the current systems primarily rely on sight, followed by sound and touch (Azuma et al., 2001; Wang et al., 2013). Examples of these include interacting with augmented virtual content with haptic gloves or hearing navigation directions in AR glasses based on your location and orientation, whereas visual AR augmentations are largely focused on adding 3D digital content, for example building information (BIM) models, into the user's view of the real world (Billinghurst et al., 2015; Wang et al., 2013).

AR experiences can be created with a variety of devices. These include smartphones and tablets, head-mounted displays (HMD), and projection displays (Azuma et al., 2001; Billinghurst et al., 2015). HMDs can be further categorized into video see-through devices, where a camera is used to capture the environment and digital content is embedded into the camera feed and shown to the user, and optical see-through devices, where holograms are portrayed in the user's view of the actual environment (Billinghurst, 2021; Wang et al., 2013). These devices are mainly controlled by hand gestures and voice commands (Billinghurst, 2021). However, hand-held displays (HHD), such as smartphones, are still by far the most popular way to utilize AR, and they offer the widest diffusion potential due to their existing hardware install base and developer support (Billinghurst, 2021; Jalo et al., 2022). Still, HMDs are believed to offer the most potential and the most immersive AR experiences in the long-term (Billinghurst, 2021). They can also provide significant value in specific organizational use cases where the user is required to operate the AR device hands-free (Masood & Egger, 2019).

2.1.2 Virtual reality

In contrast to AR that displays digital information in the user's view of the real environment, virtual reality (VR) *replaces the user's view of the actual world with an immersive 3D virtual environment where objects have a spatial presence* (Bryson, 1995; Jerald, 2015). This is achieved with the help of VR HMDs (Dincelli & Yayla, 2022). These can be further categorized into mobile VR HMDs, standalone VR HMDs, and tethered VR HMDs (Anthes et al., 2016; Elbamby et al., 2018; Kugler, 2021). With mobile VR HMDs, a smartphone is slotted into the VR HMD frame and used as its display. However, most of these types of VR HMDs have been discontinued due to their low performance (Protalinski, 2019), making them largely irrelevant for organizations. Tethered, or wired, VR HMDs are connected to an external PC or a laptop, which provides the headset with its computing power (Perry, 2015). In contrast, standalone VR HMDs can be used independently as all of the required hardware is integrated into the headset (Elbamby et al., 2018; Kugler, 2021). In essence, tethered VR HMDs sacrifice in affordability and ease-of-use compared to standalone VR HMDs but are able to provide more visually advanced and higher fidelity experiences. The choice of the headset thus largely depends on what type of a use case the organizations is interested in (Lounakoski et al., 2022).

Immersion, presence, and interactivity are key concepts in VR (Mütterlein & Hess, 2017; Walsh & Pawlowski, 2002). Here, immersion is defined as *the extent to which the virtual environment is able to isolate the user from the real world and stimulate the user's senses* (Witmer & Singer, 1998). Presence can be defined as *the user's subjective feeling of being present in another place even when they are physically located somewhere else* (Witmer & Singer, 1998). Interactivity refers to *the extent to which the user is able to affect and modify the content of the virtual environment* (Steuer, 1995).

Relatedly, as VR technology developed further, categorizations of VR into non-immersive VR (e.g., virtual worlds viewed via a 2D desktop screen) and immersive VR accessed with VR HMDs also started to emerge (Brooks, 1999; Paes et al., 2017; Slater & Sanchez-Vives, 2016). Recent developments in immersive HMD-based VR have been substantial (Torro et al., 2021) and recent research has found their higher immersion to lead to higher levels of spatial learning, performance, and subjective presence (Parong et al., 2020). Non-immersive and immersive VR can thus essentially be viewed as two distinct technologies due to their differing interaction methods and levels of immersion and presence. Moreover, after non-immersive VR solutions failed to be adopted by organizations (Yoon & George, 2013), the primary organizational interest shifted toward immersive VR (Torro et al., 2021). Thus, this dissertation also focused on examining immersive rather than non-immersive VR solutions as they were the emergent technology of interest to organizations at the start of the research process.

2.1.3 Extended reality as an umbrella term for AR and VR

Due to their similar technological characteristics and use cases (Lounakoski et al., 2022), AR and VR are often examined in conjunction in the scientific and practitioner literature (e.g., Li et al., 2018; Steffen et al., 2019). This has led to the development of different frameworks and categorizations for distinguishing and positioning AR and VR technologies. The Reality-Virtuality Continuum created by Milgram et al. (1994) is widely cited as the first of such categorizations. According to this categorization, these technologies are located on a continuum from the actual real environment to fully virtual environments (i.e., VR; see Figure 1). This categorization adds augmented virtuality (AV) as an intermediate technology form between AR and VR. In AV, elements from the real world are brought into an otherwise virtual environment. However, this term is not widely used in industry as the term mixed reality (MR) has largely taken its place (Rauschnabel et al., 2022). In contrast, in Milgram et al.'s (1994) categorization, MR is used as an umbrella term for all technologies that combine virtual and real elements.

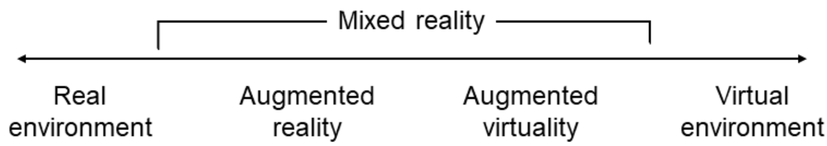

Figure 1. Reality-Virtuality Continuum (Milgram et al., 1994)

In recent years, the term eXtended reality (XR) has taken over as a dominant umbrella term for AR, MR, and VR, especially with practitioners (Marr, 2019; Rauschnabel et al., 2022), but increasingly with researchers as well (e.g., Bujić et al., 2021; Chuah, 2019; Dwivedi et al., 2021). According to this more recent classification, MR is viewed as a more advanced version of AR, where digital content is merged more interactively with the environment, whereas with AR, the information is simply overlaid on the environment (Marr, 2019; Mystikadis, 2022; Rauschnabel et al., 2022). Other classifications describe simple AR as assisted reality, while advanced AR, where users cannot distinguish between real and virtual elements, is referred to as MR (Dwivedi et al., 2021). However, it is difficult to draw clear lines between AR and MR, and as a result, the terms are often used interchangeably.

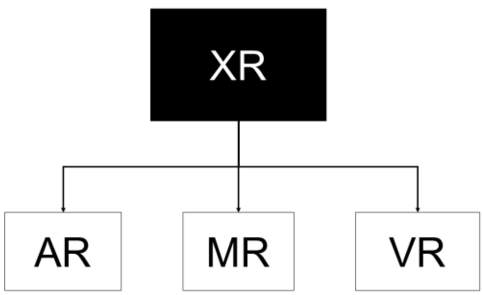

Figure 2. Extended reality (XR) as an umbrella term for AR, MR, and VR (adapted from Dwivedi et al., 2021)

More recent categorizations have also proposed separate continuums for AR and VR. In these categorizations, AR ranges from assisted reality to mixed reality, while VR ranges from atomistic to holistic virtual reality (Rauschnabel et al., 2022). In addition, the term metaverse has recently gained in popularity (Mystakidis, 2022). The metaverse is defined as *a persistent multiuser environment where virtual content and the* *physical reality merge* (Mystakidis, 2022). In the context of the metaverse, XR technologies are viewed as interfaces through which users can access the metaverse. However, all of these terminologies are still very much in flux, and these terms are not used in a consistent manner in industry or in the scientific literature (Rauschnabel et al., 2022). In this dissertation, the XR term was adopted as an umbrella categorization for AR and VR due to its widespread use in both the scientific and practitioner contexts.

2.1.4 Current state of organizational AR and VR adoption

Although AR and VR have only started gaining more widespread awareness and popularity in the last few years (Chuah, 2019; Jalo et al., 2022), they are not entirely new inventions, as they were first introduced several decades ago. Although it is difficult to determine which technological system should be described as the first exemplar of AR or VR technology, the Ultimate Display developed by Ivan Sutherland (1968) is commonly referred to as the first AR or VR system in the scientific literature (Billinghurst, 2021; Billinghurst et al., 2015; Lavalle, 2016).

The first AR and VR systems were limited by their weight, lack of computing power, and software limitations. After decades of research and development in research institutes and the private sector, there were some initial attempts to popularize AR and VR, such as with the Nintendo VirtualBoy in 1995 (Lavalle, 2016), but their widespread diffusion failed to materialize as they were still technologically too immature to be relevant for organizational or personal use (Dincelli & Yayla, 2022; Walsh & Pawlowski, 2002).

As a result, VR already fell off from one of the most hyped technologies in Gartner's technology hype cycle in 1995, only to start its rise again in 2017 as companies started re-evaluating the technology in light of its recent technological developments (Gartner, 2017). Finally, significant advancements in several key enabling technologies, including chipsets, artificial intelligence, computer vision, and 5G networks (Bastug et al., 2017, Egger & Masood, 2020; Elbamby et al., 2018), have made it possible to develop visually immersive, portable, affordable, and easy-to-use AR and VR devices (Kugler, 2021). These advancements have made their adoption increasingly relevant in many enterprise and personal use contexts (Kugler, 2021; Lounakoski et al., 2022; Marr, 2019).

One of the most significant watershed moments for VR occurred when the Oculus Rift headset began development in 2012 as a crowdfunded project on

Kickstarter (Lavalle, 2016; Liberatore & Wagner, 2021). Oculus was then acquired by Facebook (now rebranded as Meta) in 2014. After a few years, VR started reaching mainstream awareness and its use has expanded significantly since then (Lavalle, 2016; Torro et al., 2021). For AR, smartphone-based AR experiences, such as Pokémon GO and Snapchat filters, are widely considered as one of the significant developments that popularized the technology for the public at large (Porter & Heppelmann, 2017). AR headsets, which were primarily focused on enterprise use (such as the Microsoft HoloLens), were also introduced at the same time (Liberatore & Wagner, 2021).

Following these developments, organizations started piloting and experimenting with these technologies in different industries, for instance, in construction (Ververidis et al., 2022), manufacturing (Schein & Rauschnabel, 2022), and medicine (Glegg et al., 2013). Key industrial XR use cases emerged throughout the organizational value chain. These include, for instance, design, collaboration, training, marketing, and remote assistance (Lounakoski et al., 2022). The COVID-19 pandemic spurred further interest in AR and VR as organizations were forced to take almost all of their activities remote (Dincelli & Yayla, 2022; Torro et al., 2021).

In this drastically different operating environment, AR and VR were seen to offer significant potential in enhancing remote work practices and enabling entirely new ways of doing business (Jalo et al., 2022). For instance, Kia Motors transferred much of their design review processes to XR environments, resulting in several days of saved travel time and significantly faster design iterations (Devanesan, 2020). Other examples include remote expert instructions by using AR HMDs (Castellanos, 2021) and onboarding new employees in VR environments (Fink, 2021). Many pioneering companies have reported productivity improvements of 25% or more from XR implementations (Porter & Heppelmann, 2017).

However, despite these promising application opportunities and proven achieved benefits, XR adoption rates are still lagging behind many earlier forecasts (Chuah, 2019; Grand View Research, 2021). For instance, IDC predicted in 2018 that the overall XR market would reach $215 billion by 2021 (Chuah, 2019), but these predictions were later revised to only reach $50.9 billion in 2026 (John, 2022). As a result, only the most pioneering and innovative companies are currently using of XR technologies (Jalo et al., 2022; Porter & Heppelmann, 2017).

Moreover, only limited research has been carried out to identify what factors affect organizational XR adoption (e.g., Berg & Vance, Chandra & Kumar, 2018; Masood & Egger, 2019, 2020). To provide a more in-depth understanding of the relevant factors affecting organizational XR adoption and to support organizations in their adoption efforts, further research is required to shed light onto these issues. Here, organizational adoption theories can help in narrowing down the potential hindrances and essential drivers of adoption. The next section provides an overview of pertinent individual, resistance, and organizational adoption theories, as well as extant research on organizational XR adoption.

2.2 Technology adoption theories

This section presents the technology and innovation adoption theories and literature that influenced the development of the theoretical approaches in the included publications. Individual-level adoption and user resistance theories are presented first, followed by organizational-level adoption theories. Additionally, key XR-related findings based on the DOI theory and TOE framework are also presented.

2.2.1 Individual-level adoption and user resistance theories

Technology adoption theories can be broadly categorized into individual- and organization-focused theories, although sometimes the examination also focuses on group-level adoption (Gangwar et al., 2014; Venkatesh, 2006). Individual-level theories have received the most attention and are a relatively mature research stream (Venkatesh, 2006; Venkatesh et al., 2003). Many individual-level adoption theories have been proposed and validated in the IS literature throughout the years. Some of the most widely used of these theories include the theory of reasoned action (TRA; Fishbein & Ajzen, 1975), its extension, the theory of planned behavior (TPB; Ajzen, 1991), the technology acceptance model (TAM; Davis, 1989) and its extensions TAM2 (Venkatesh & Davis, 2000) and TAM3 (Venkatesh & Bala, 2008), the unified theory of acceptance and use of technology (UTAUT, Venkatesh et al., 2003), and the task-technology fit theory (TTF; Goodhue & Thompson, 1995). Some theories also focus on the longitudinal adoption process. An example of this would be the expectation-confirmation model proposed by Bhattacherjee (2001).

However, scholars have also noted that user resistance can be a critical factor in failed technology adoptions (Jiang et al., 2000; Markus, 1983). Although its importance has been noted several decades ago (e.g., Markus, 1983), the user resistance perspective has only gained increased attention at the individual level of inquiry in recent years (e.g., Ali et al., 2016; Kim & Kankanhalli, 2009; Laumer &

Eckhardt, 2012). The user resistance model developed by Kim and Kankanhalli (2009) is perhaps the most widely cited theory explaining user resistance towards new innovations and ways of working in the organizational context. It is theoretically based on the idea that people prefer maintaining the status quo and that they generally weigh the potential switching costs related to adopting a new technology more strongly than the potential benefits that could be gained from switching to a new way of working with the new technology in their cost-benefit analysis.

Other user resistance theories have also been proposed. Selander and Henfridsson (2012) proposed that user cynicism towards adoption-related managerial goals may have a key role in user resistance behavior. Polites and Karahanna (2012) revealed how individuals' habit of using previous systems can lead to inertia and result in a lower intention to use new systems. In an earlier work, Markus (1983) categorized the reasons for user resistance into system-, people-, and interaction-oriented causes. According to this categorization, flaws in the system (e.g., confusing user interface), internal human factors (e.g., lack of skills), and how the use of the new system influences and changes power relations in the organization (i.e., organizational politics) can cause user resistance. In this work, the organizational politics-focused interaction explanation was shown to have the most explanatory power. Users' personality characteristics have also been shown to influence resistance behavior (Laumer et al., 2016).

Nevertheless, while the user resistance aspect has received some attention in qualitative empirical examinations at the organizational level of adoption (e.g., Lapointe & Rivard, 2005), it has not yet been utilized to extend or adapt quantitative theoretical organizational-level adoption models. Although the adoption of technologies is often not voluntary for employees, expected resistance will likely influence organizational adoption intention and value perceptions as a technology that is resisted by employees is likely to be used less, which can decrease the overall value that the technology can bring to an organization. Moreover, addressing and mitigating user resistance requires time and resources from managers (Ilie & Turel, 2020; Markus, 1983). Therefore, expected user resistance is likely to play a part in organizational adoption dynamics.

2.2.2 Organizational-level adoption theories

Organizational-level adoption theories are much scarcer and less well-established compared to individual-focused adoption theories (Oliveira & Martins, 2011). Due to the more complex adoption context, these theories are usually also more holistic and examine adoption from several different angles. Moreover, the goals and interests of different organizational constituents can vary significantly (Markus, 1983), which adds further complexity to the analysis. For instance, top management is likely to be focused on the profitability, overall viability, and the future strategic direction of the company. However, they are also individual actors in the company, and thus, interested in their position and status, which certain technologies can enhance or threaten. On the other hand, employees of the company are likely to focus on their own position in the company. Therefore, they may either support or resist new technologies depending on whether they are particularly difficult to learn or if they threaten or enhance their position, status, or employment within the company (Markus, 1983; Rivard & Lapointe, 2012). These competing interests naturally bring tensions into the adoption process as different organizational constituents try to assess each other's goals.

In addition, external stakeholders can affect the adoption of a technology (Yoon & George, 2013). For example, a large company can pressure smaller companies in its stakeholder network to adopt a technology or a new way of working if they want to continue working with the larger company. Power dynamics and network effects can thus affect adoption. A competing company can also influence a company (or rather, its top decision-makers) to adopt a technology to avoid being left behind their competitors (Chwelos et al., 2001; Yoon & George, 2013). Other external stakeholders, such as state institutions, innovation hubs, and regulators, can also influence the ease or difficulty of adopting new technologies, and in some cases, they may even mandate their adoption (DiMaggio & Powell, 1983).

Some of the more prominent approaches in investigating organizational adoption include the diffusion of innovations (DOI) theory (Rogers, 2003), the technology-organization-environment (TOE) framework, and the institutional theory (DiMaggio & Powell, 1983). The DOI theory specifically focuses on how the technological characteristics of the innovation affect its diffusion in a system, while the TOE framework is often used as a theorizing framework where relevant adoption antecedents are identified for each of the framework's categories (DePietro et al., 1990; Rogers, 2003). The institutional theory examines how the various social structures and behaviors present in an organization's environment drive organizations to behave and act similarly (DiMaggio & Powell, 1983). More specifically, the theory states that coercive pressures (e.g., when an influential organization coerces or persuades other organizations to adopt a technology), mimetic pressures (e.g., an organization adopts a technology because other successful companies have done so), and normative pressures (e.g., when something is adopted because it is seen to be the professional standard) can influence an organization to change its behavior and adopt new technologies (DiMaggio & Powell, 1983).

Individual-level theories, such as TAM, are also often applied and adapted to the organizational-level context, even though they were initially developed to examine how individuals adopt new technologies (Gangwar et al., 2014). Theories pertaining to specific contexts and technologies have also been developed. For instance, Gao et al. (2012) proposed and validated a model for the adoption of expensive and discontinuous technologies. The theory posits that the perceived value and risks of the technology influence organizational adoption intention, with external market pressure and internal adoption readiness influencing the value and risk perceptions associated with the technology. Another example of such a theory is the theory proposed by Iacovou et al. (1995), where perceived benefits, organizational readiness, and external pressure influence electronic data interchange adoption in small organizations. Overall, both theories emphasize the role of organizational and environmental factors in determining organizational adoption behaviors.

Although these theories vary in their complexity and in which order the antecedents are proposed to influence adoption, commonalities can also be identified. Most theories include some elements relating to the technology (e.g., benefits, value, or complexity), the organization's capabilities to adopt and integrate the new technology into their operations (e.g., organizational support structures), and how the external environment affects adoption (e.g., pressure from competitors). Thus, elements from many of the previously described theories (e.g., the institutional theory and user resistance theories) were also used, combined, and adapted in the dissertation's publications. However, as the DOI theory and TOE framework were specifically and more prominently applied and extended in several of the included publications, they will be described in more depth in the following sections. In addition, key findings from the XR literature where these theories were used are also detailed.

2.2.2.1 The diffusion of innovations theory

Rogers' (2003) DOI theory has been used to examine adoption at both individual and organizational levels, as well as to study the overall or systemic diffusion of innovations (Taherdoost, 2018). The DOI theory was initially developed in 1962 and it focuses on analyzing the diffusion of innovations based on their technological characteristics, including relative advantage, complexity, compatibility, trialability, and observability (Rogers, 2003).

DOI theory meta-analyses have identified relative advantage, complexity, and compatibility to be the most consistently significant predictors of a technology's diffusion in an organization (Tornatzky & Klein, 1982; Vagnani & Volpe, 2017). Here, relative advantage refers to whether a technology is perceived to be better than the technologies that have preceded it, compatibility to how well the technology matches with the adopter's values, experiences, and needs, and complexity to how difficult the technology is to understand and to learn how to use (Rogers, 2003). Accordingly, higher degrees of relative advantage and compatibility are positively related to higher levels of diffusion, while higher levels of complexity are negatively related to diffusion (Rogers, 2003).

DOI also includes adopters' characteristics in its analysis framework. This analysis is carried out based on different adopter categories. According to DOI, individuals and organizations can be placed into innovator (2.5% of the total), early adopter (13.5%), early majority (34%), late majority (34%), or laggard (16%) categories. When it comes to technologies like XR that are still emerging and maturing, it is likely that only innovators and early adopters would currently be using these technologies in a significant manner (Jalo et al., 2022). As such, it makes sense to focus on analyzing the three most critical antecedents of diffusion: relative advantage, compatibility, and complexity. Innovative companies may not be as concerned about how easy it is to observe the benefits of XR from other companies (given its limited diffusion) or how trialable the technology is, as they are typically more risk-tolerant and eager to acquire new technologies to begin experimenting with them immediately without thorough testing prior to purchase (Rogers, 2003).

Extant XR adoption literature has identified some key manifestations for these antecedents. More efficient knowledge transfer can for instance be a relative advantage of VR over other existing solutions, such as videoconferencing (e.g., Du et al., 2018). The degree to which VR technologies can easily be integrated with organizational business processes can be considered to play a key part when evaluating the compatibility of VR with an organization (Du et al., 2018). Lastly, the unique nature of VR (high immersion, presence, and interactivity) adds to the complexity of learning to use VR technologies (Mütterlein & Hess, 2017). However, the contextual moderators that either amplify or mitigate the effects that these antecedents have on the adoption and diffusion of VR remain largely missing from the literature.

2.2.2.2 The TOE framework

The TOE framework examines organizational adoption based on three categories: (1) the characteristics of the technology (the technological context), (2) internal organizational factors affecting adoption (the organizational context), and (3) the external factors promoting or deterring the adoption of a technology (the environmental context; DePietro et al., 1990). In addition to the technological and organizational contexts that were included in Rogers' DOI theory, the TOE framework thus also includes the environmental context (Gangwar et al., 2014).

However, as its name implies, it is merely a framework without clearly defined individual constructs. Rather, the technological, organizational, and environmental constructs of interest are hypothesized based on the examined technology and what type of environment the examined organizations operate in (Gangwar et al., 2014). Typical constructs in the technological context include relative advantage and compatibility (e.g., Martins et al., 2016). In the organizational context, top management support and organizational readiness are relevant (e.g., Chandra & Kumar, 2018; Martins et al., 2016). In the environmental context, competitor pressure has been identified as one of the most significant factors (e.g., Yoon & George, 2013; Zhu & Kraemer, 2005).

The TOE framework is highly adaptable (Baker, 2012), which is one of the reasons why it has been applied so widely in studying the adoption of Industry 4.0 technologies (e.g., Chandra & Kumar, 2018; Masood & Egger, 2019, 2020; Martins et al., 2016). The TOE framework is also one of the most widely applied theories used in explaining XR's organizational adoption. For instance, using an online survey, Chandra and Kumar (2018) found that AR's relative advantage, a firm's technological competence, top management support, and consumer readiness were positively related to AR adoption intention. Masood and Egger's (2019) survey study found system configuration, hardware readiness, compatibility, and organizational fit to be positively related with AR implementation success. Moreover, their follow-up qualitative survey study (Masood & Egger, 2020) found lack of IS-AR compatibility, limited AR hardware capabilities, content creation difficulties, and lack of user acceptance to be key challenges in implementing AR in industry.

Due to its generic nature and high-level focus, the TOE framework itself has experienced relatively little development (Zhu & Kraemer, 2005). This is partly explained by the fact that the TOE framework is highly compatible with other theories as constructs from, for example, the DOI and institutional theories are often included as technological or environmental antecedents in hypothesized TOE framework-based models (Baker, 2012; Martins et al., 2016). Nevertheless, possible areas for development can be identified. For instance, in most extant studies, the hypothesized TOE framework models propose a direct relationship between all the TOE antecedents and adoption intention (e.g., Chandra & Kumar, 2018; Yoon & George, 2013; Martins et al., 2016). This approach assumes that the TOE-based factors directly influence adoption intention, without considering the possibility of some more proximate factors mediating their effect. Thus, more complex relationship paths could be included in future TOE-based theoretical models.

2.3 Summary

Organizations find it imperative to find new ways to enhance and renew their operations and processes to stay competitive. XR technologies have become an area of increasing interest for organizations due to their disruptive potential (French et al., 2020). The main potential of XR is seen to be in enabling more effective, immersive, and engaging remote work practices, and in providing workers access to relevant organizational digital information in an intuitive manner in the actual use context (Porter & Heppelmann, 2017; Torro et al., 2021). However, XR adoption rates have still remained relatively low despite these potential significant benefits (Chuah, 2019). In order to enhance the theoretical understanding of organizational XR adoption and provide support for practitioners in XR adoption and implementation, further research is needed to uncover the critical factors that contribute to organizational adoption of XR technologies and to understand the dynamics between these factors.

Extant organizational adoption literature presents several theories and frameworks that can serve as analytical lenses in studying and exploring organizational XR adoption in more depth, as well as for identifying important adoption antecedents. Moreover, due to the unique specifics of XR technologies and the paucity of confirmatory research on organizational XR adoption, avenues for theory development and testing are also open. Accordingly, the aforementioned theories and frameworks could be extended, adapted, or integrated via empirical research as has been done previously in other IS and technology contexts (e.g., Martins et al., 2016; Yoon & George, 2013).

Extant research has suggested that the DOI theory should be applied to reveal what specific technological factors are highlighted in the XR adoption context (Fernandes et al., 2006). However, since XR adoption in the enterprise context is still in its early stages, it is also important to understand the different internal organizational and external environmental factors that can drive XR adoption. As literature reviews on organizational technology adoption have noted (Baker, 2012; Jeyaraj et al., 2006), various technological, organizational, and environmental adoption antecedents can be emphasized depending on the technology and adoption context.

Thus, the TOE framework should also be used to provide a more comprehensive understanding about the relevant adoption enabling factors affecting organizational XR adoption. In addition, newer perspectives such as user resistance (Kim & Kankanhalli, 2009) should also be integrated into organizational-level adoption models, as user resistance has been found to be one of the most critical factors contributing to failed adoption attempts (Jiang et al., 2000). Still, the relative importance and magnitude of user resistance on adoption intention at the organizational level remains missing from the literature. These deficiencies in the literature indicate a clear need to enhance our understanding of critical XR adoption antecedents and their relationship dynamics.

3 METHODOLOGY

This section presents the chosen research strategy (mixed methods approach), the research design (sequential and semi-iterative), and the different research methods that were used in the qualitative and quantitative stages of the research.

3.1 Mixed methods research strategy

Broadly speaking, there are three approaches to conducting research: (1) qualitative research (e.g., interviews and focus groups), (2) quantitative research (e.g., analyzing numerical survey data), and (3) multiple methods or mixed methods research that combines different elements and methodologies from the two previous categories (Venkatesh et al., 2016). Overall, the dissertation followed a mixed methods approach, which has been argued to be extremely useful in situations where little extant research exists on the phenomena, as it enables both exploratory and confirmatory research to be combined in the same research endeavor (Venkatesh et al., 2013). This can help the researcher gain deeper insights about the examined phenomena (Pappas & Woodside, 2021). Moreover, employing multiple methods in the same research is seen to be helpful when existing theories do not provide sufficient insights to explain the examined phenomena (Venkatesh et al., 2013). In this regard, relatively little literature had been published at the beginning of the dissertation process on the topic to guide the research.

Mingers and Brocklesby (1997) further categorized multiple methods research into methodological combination and multimethodology research. In methodological combination, methodologies from different paradigms (i.e., quantitative and qualitative) are employed, whereas multimethodology research can use different methodologies from the same or different research paradigms (e.g., qualitative interviews and ethnography). According to this classification, this dissertation falls more specifically into the methodological combination category as it employed a quantitative survey and multiple case study interviews in its data collection and analysis. This type of research is often described as *mixed methods* *research* as it combines methodological approaches from different paradigms (Venkatesh et al., 2013; Zachariadis et al., 2013).

In general, qualitative case studies collect data from a more limited number of respondents and explore the research topic in its natural setting in order to provide rich insights to enable the researcher to understand the problem in depth (Benbasat et al., 1987; Gable, 1994; Venkatesh et al., 2013). However, this approach limits the generalizability of the findings and makes repeating the research more difficult compared to survey research, which is generally seen as better equipped to address these challenges (Gable, 1994; Jick, 1979). Nevertheless, especially cross-sectional survey designs can often only provide a snapshot of the current situation and can provide results that are difficult to interpret (Gable, 1994).

Thus, employing multiple methods to probe the research topic from multiple angles can be useful to generate a more nuanced understanding of the research problem. For instance, qualitative analysis can be used to empirically identify relevant survey items before survey data collection and to provide further insights on the survey results after the survey data have been analyzed (Jick, 1979). Post-survey qualitative analysis can be used, for instance, to provide contextual explanations for statistical relationships and help clarify inconsistent or unexpected survey findings (Jick, 1979). Moreover, when employing survey research, the researcher must have a clear understanding about what questions to ask in the survey due to its inherent inflexibility after the data collection has commenced (Gable, 1994).

To mitigate these problems, the decision was made to first explore the topic in detail with a qualitative approach to generate a better understanding and a more solid knowledge base for designing the survey (Venkatesh et al., 2013). The explorative publications were used to identify themes that are likely to be relevant in organizational XR adoption intention. Specific constructs associated with these themes were then identified from the extant literature and adapted to the research context in the confirmatory phase of the research. The identified themes from the qualitative portion of the research were thus integrated into the survey and tested with quantitative analysis methods (Gable, 1994).

Recent IS methodology literature has also urged researchers to combine and integrate findings from different paradigmatic research methods to help them achieve more nuanced and theoretically novel insights to their research questions (Venkatesh et al., 2013; Zachariadis et al., 2013). In this regard, the *critical realist (CR) paradigm* has been argued to be especially applicable to the IS field, which is usually concerned with practice-based research problems (Venkatesh et al., 2013; Zachariadis et al., 2013). CR can be positioned between positivism and interpretivism, and it accepts the use of different methodological approaches within the same research endeavor (Zachariadis et al., 2013). This dissertation thus adopted the CR paradigm to guide the overall research endeavor.

According to CR, the world (i.e., reality) exists independent of human perception and knowledge (Mingers et al., 2013). However, humans can generate knowledge about this reality by establishing facts about it with different methods and techniques, which can then be used to develop theories and models about its causal mechanisms (Mingers et al., 2013; Zachariadis et al., 2013). Although CR views this socially produced knowledge to be fallible, it also acknowledges that some of these explanations are likely to be more valid and accurate than others (Mingers et al., 2013; Zachariadis et al., 2013). Moreover, CR is focused on revealing the generative mechanisms between events, that is, in understanding the processes and conditions under which events follow each other, rather than merely pointing out that some events are related to each other (Zachariadis et al., 2013). As this dissertation was focused on holistically understanding the different antecedent factors of organizational XR adoption and under which conditions these factors are relevant, CR was deemed to be an appropriate paradigm for the dissertation.

3.2 Sequential semi-iterative research design

Mixed methods research designs are often characterized by a linear approach, where initial qualitative exploratory studies are employed to develop a deeper understanding of the phenomena, which is then followed by a confirmatory phase that often utilizes quantitative surveys (Gable, 1994; Venkatesh et al., 2013). However, the qualitative and quantitative parts of this dissertation's mixed methods research process were also semi-iterative, that is, the earlier qualitative findings informed the preparation of the data collection and the analysis of the subsequent quantitative publications, and the quantitative results were then in turn re-examined by following qualitative analysis rounds to generate new understandings and provide further context to the results (Gable, 1994). Mixed methods were thus used in the overall dissertation in a developmental sense (i.e., methods used in the initial phase of the study provide inferences and hypotheses that are tested at later phases of the research) and to corroborate and confirm the credibility of the findings from the initial strands of research (Venkatesh et al., 2013).

One of the additional rationales for using mixed methods was to provide complementarity, as qualitative methods were also used in analyzing the quantitative results to provide additional insights into the phenomena (Venkatesh et al., 2013). Different methods were used to achieve a more complete picture about the situation, for instance, by collecting quantitative data about real rates of AR and VR use to test whether there are differences between these technologies in addition to providing an understanding about what common antecedents are critical in their adoption (Venkatesh et al., 2013). Quantitative methods were also used to compensate for the inherent and typical weaknesses of qualitative research (i.e., small sample sizes and low generalizability; Venkatesh et al., 2013).

Overall, the choice of research method at different stages of the research was contingent on the focus and aims of the study at the time, as well as on whether a particular method was better suited for examining the topic compared to other methods (Gable, 1994). The use of mixed methods can also enhance the robustness of the findings by incorporating different data sources, which can then be cross-examined in order to determine where the results and findings derived from these data converge and diverge (Kaplan & Duchon, 1988). As such, this research considers the qualitative and quantitative approaches as complementary rather than conflicting with each other (Gable, 1994).

A succinct description of the overall dissertation research process can be seen in Figure 3. Publications I and II were carried out as qualitative multiple case studies, whereas Publications III and IV used a mixed methods approach, combining quantitative confirmatory survey research and additional qualitative exploratory research based on semi-structured interviews. Finally, the more practice-focused Publication V sought to develop prescriptive guidelines based on the latest scientific literature (including Publications I–IV) and practical insights gained during the dissertation process.

In mixed methods research, the researcher can also derive integrative *meta-inferences* by comparing, contrasting, and integrating the findings from the qualitative and quantitative strands of research (Venkatesh et al., 2013). The development of such meta-inferences is seen as an essential part of mixed methods research (Tashakkori & Teddlie, 2008). Convergent results achieved through different methods are generally seen to increase confidence in the findings, while diverging results provide opportunities for researchers to hypothesize or uncover new explanations by reconciling the differing outcomes (Jick, 1979). Divergent findings are thus not an intractable problem; instead, they can be advantageous if they prompt the researcher to reassess the conceptual frameworks and assumptions of the different research strands. This reevaluation has the potential to yield novel insights into the research problem (Venkatesh et al., 2013). This type of an approach can also assist researchers in identifying previously unnoticed and interesting research avenues (Venkatesh et al., 2013). To answer to the main research question of this dissertation, the mixed methods research process culminated in the development of three overarching meta-inferences. These meta-inferences and their development process are described in more detail in section 5.4.

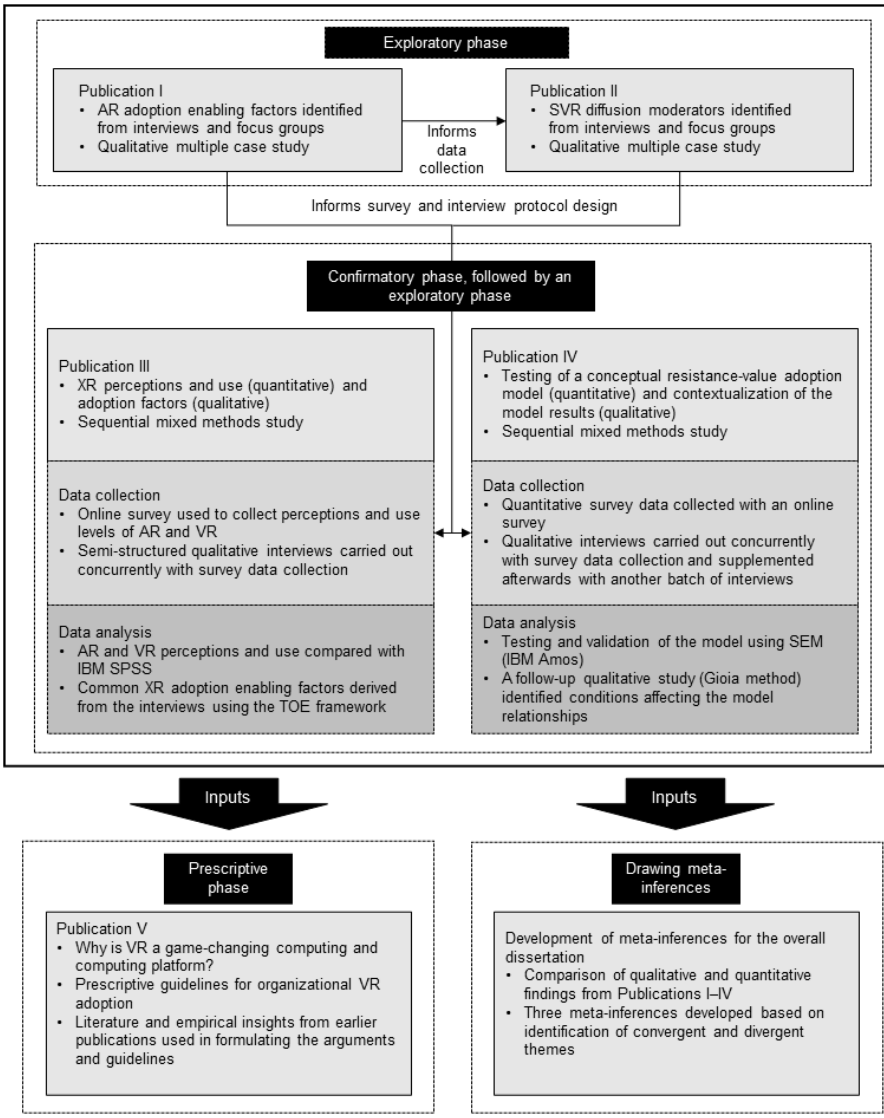

Figure 3. The mixed methods research process of the dissertation

3.3 Research timeline

Overall, the research sought a balance between finding new points of view (explorative qualitative research) and testing theory (confirmatory quantitative research) to get a more comprehensive view on the topic to generate deeper insights. The theory testing carried out in the latter part of the process aimed to validate the importance of the identified themes based on initial findings and to improve the generalizability of the results. The research thus followed a largely sequential logic, with the exploratory Publications I and II being completed first. These initial publications then informed the data collection and survey designs of Publications III and IV. This approach proved to be appropriate as many newly identified problems that arose during this initial part of the research, such as the role of user resistance (see e.g., Kim & Kankanhalli, 2009), were not highlighted in the extant XR adoption literature available at the beginning of the dissertation process. The more prescriptive Publication V was written after Publications I and II. The initial, although still unpublished, data analysis results of Publications III and IV were also used as inputs and guidance in the development of Publication V. The overall timeline of the dissertation process can be seen in Table 2.

Table 2. Dissertation timeline

<table>
<tr><th rowspan="2"></th><th colspan="2">2018</th><th colspan="2">2019</th><th colspan="2">2020</th><th colspan="2">2021</th><th colspan="2">2022</th><th>2023</th></tr>
<tr><th>Spring</th><th>Autumn</th><th>Spring</th><th>Autumn</th><th>Spring</th><th>Autumn</th><th>Spring</th><th>Autumn</th><th>Spring</th><th>Autumn</th><th>Spring</th></tr>
<tr><td>Data collection</td><td colspan="3"></td><td></td><td colspan="2"></td><td></td><td colspan="3"></td><td></td></tr>
<tr><td>Data analysis</td><td colspan="11"></td></tr>
<tr><td rowspan="5">Publications</td><td colspan="2">Pub. I</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Pub. II</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>Dissertation manuscript</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">Synopsis</td></tr>
</table>

3.4 Data collection methods

The initial foundation of the dissertation was built on qualitative interviews and focus groups, often involving multiple interviewees (Ghauri & Grønhaug, 2005). The interviews were carried out as semi-structured interviews. This approach allowed the researchers to flexibly ask follow-up questions and pursue interesting themes that emerged during the interviews in more depth, instead of strictly following a rigidly structured interview protocol. At the same time, it provided a general direction and structure to the interviews (Gillham, 2005). The research designs and approaches, data collection logic, and the amount of collected data for each publication are summarized in Table 3.

Table 3. Summary of the publications' research designs, data sampling, and data collection approaches

	Research design and approach	Data sampling logic	Amount of data collected
Publication I	Multiple case study (abductive and qualitative)	Five Finnish FM companies, purposive sampling	two semi-structured interviews seven focus group interviews
Publication II	Multiple case study (abductive and qualitative)	20 Finnish AEC companies, purposive sampling	12 semi-structured interviews 14 focus group interviews
Publication III	Mixed methods study (deductive quantitative part, followed by an abductive qualitative part)	Qualitative: 45 European AEC and manufacturing companies, purposive sampling Quantitative: 208 respondents from European companies, convenience sampling (cross-sectional survey)	45 semi-structured interviews 208 survey responses (initial part of the survey)
Publication IV	Mixed methods study (deductive quantitative part, followed by an abductive qualitative part)	Qualitative: 47 European AEC and manufacturing companies, purposive sampling Quantitative: 206 respondents from European companies, convenience sampling (cross-sectional survey)	58 semi-structured interviews 206 survey responses (complete survey)
Publication V	Practice-focused review (abductive)	Purposive non-systematic literature review	-

The exploratory research employed a multiple case study instead of a single case study approach. The aim of the research was to expand upon previous theories, such as the DOI theory and the TOE framework, by generating abstract concepts from cross-case analysis (Benbasat et al., 1987). The interviews and focus groups were recorded with the consent of the interviewees and transcribed for analysis purposes. Part of the interviews were also carried out by other researchers (from Tampere University, Finland) in a Business Finland co-creation project called Social Extended Reality (SXR) and by research partners from various European countries in an Erasmus+ funded research project called VAM Realities.

The case companies and interviewees were selected from organizations that were either contemplating the adoption of AR and VR solutions in their business or had already begun using these technologies. This enabled the collection of data from highly knowledgeable informants who had already encountered or assessed potential issues that were pertinent to the research topic. The sampling logic for the qualitative interviews was thus purposive (Patton, 2002).

The interview data collection was carried out in four waves. The initial interviews (n = 9) for Publication I were carried out between October 2017 and February 2018 in a company-funded research project called Diili. These interviews were then supplemented for Publication II by an additional interview round (n = 17) carried out between November 2018 and February 2019 during the SXR research project. The interviews for Publication III (n = 45) were conducted between April 2020 and October 2020 during the VAM Realities project. Additionally, these interviews were supplemented with 13 in-depth interviews involving four interviewees between October 2021 and September 2022. The 45 initial interviews and 13 supplementary interviews were used in Publication IV (n = 58).

The quantitative data for Publications III and IV were collected via an online survey from respondents from Europe. A conceptual model about organizational XR adoption was developed based on the extant XR literature and findings of Publications I and II. This model was then used to determine the type of questions to be included in the survey. The survey was pilot tested with two SMEs (one from Finland and one from Italy) to identify any unclear and confusing wordings, as well as any overlapping or redundant survey items. Moreover, two academic experts with extensive experience in survey research evaluated the survey's structure and face validity. The survey was then amended according to this feedback.

The research partner network from the VAM Realities project was utilized in spreading the survey to a diverse group of experts, managers, and top decision-makers in European AEC and manufacturing companies in the research consortium's network. All of the quantitative data for Publication III (n = 208) and IV (n = 206) were collected between April 2020 and October 2020 by using the SurveyGizmo online platform (now known as Alchemer).

3.5 Data analysis methods

The qualitative analysis of the interviews in this dissertation in Publications I, II, III, and IV largely followed an abductive approach, in which theories and frameworks (such as the DOI theory and the TOE framework) were used as theoretical lenses in structuring the analysis. The qualitative analysis mostly followed the same process in each publication. In the first phase of the analysis, smaller pieces of data were given codes, which were then combined into higher-level labels and concepts (Creswell, 2015). Illustrative quotations were included in each publication to demonstrate to the reader how the related concepts were derived during the analysis. This was done to improve the transparency of the analysis process and to enhance the credibility of the findings (Venkatesh et al., 2016). The qualitative data analysis and coding was mainly carried out by the dissertation author; however, the analysis outputs were also reviewed by the co-authors who participated in the data collection process. This was done to further ensure the accuracy of the findings (Creswell, 2015).

The quantitative data analysis in Publications III and IV used a deductive approach where the study design was chosen before the data collection. For Publication III, the potential differences between AR and VR perceptions and use levels were compared by using the Wilcoxon Signed Rank (WSR) test and the Mann-Whitney U test (Blair & Higgins, 1985; Rasmussen & Dunlap, 1991; Serlin & Harwell, 2004). Same tests were used to compare potential differences between SMEs and large enterprises.

In Publication IV, a conceptual model was theorized, and data were collected for the chosen constructs included in the model with an online survey. The data were then cleaned up and initially analyzed by using IBM SPSS version 27 and Microsoft Excel. After this initial exploratory factor analysis (EFA) phase, where the factor structure of the model and its constructs were confirmed to work as intended, a confirmatory factor analysis (CFA) phase was then carried out by using IBM Amos version 27 to confirm the factor structure and initial model fit for the measurement model (Kline, 2015).

After confirming the reliability and validity of the measurement model by assessing the discriminant and convergent validities of the constructs and items (Fornell & Larcker, 1981; Franke & Sarstedt, 2019; Henseler et al., 2015; Voorhees et al., 2016), SEM testing of the model was carried out in IBM Amos version 27 to evaluate the path relationships and model fit of the proposed conceptual model (Kline, 2015). Plugins provided by Gaskin et al. (2019, 2020) were used in both the CFA and SEM portions of the analysis.

This SEM analysis was followed by a qualitative study that aimed to contextualize the validated theoretical model. The study identified key conditions affecting the model relationships, as well as key manifestations of XR adoption intention in organizations. This study employed a variation of the Gioia method in its qualitative analysis (Gioia et al., 2013). The utilization of templates in the form of data tables and data structures is a fundamental characteristic of the Gioia method (Cornelissen, 2017). The data structure consists of descriptive informant-driven first-order themes and theoretical second-order themes, which are derived based on the grouping of the first-order themes (Gioia et al., 2013). The data tables provide supportive quotations for each identified second-order theme (Gioia et al., 2013). The aim of the data tables and data structures is to provide further transparency into the analysis process and to enhance the trustworthiness of the findings (Cornelissen, 2017; Gioia et al., 2013). A section where the derived second-order themes (i.e., conditions and manifestations) were further explained with the aid of additional quotations was also included in the analysis. The identified conditions and manifestations were then used to extend and contextualize the validated theoretical model.

4 SUMMARIES AND MAJOR CONTRIBUTIONS OF THE INDIVIDUAL PUBLICATIONS

In this section, each individual publication included in the dissertation is summarized and their contributions to the overall dissertation are described. The author's role and contributions to each co-authored publication are detailed at the beginning of the dissertation after the listing of the original publications.

4.1 Publication I: How can collaborative augmented reality support operative work in the facility management industry?

4.1.1 Background and objectives of Publication I

The aim of the first publication was to understand how and in which specific application areas collaborative AR can bring value to organizations in the context of the facility management (FM) industry. As the work tasks in the FM industry heavily emphasize remote collaboration and independent problem solving, FM companies are generally interested in the adoption new digital technologies, such as collaborative AR, to enhance their business operations.

As a comprehensive accounting of the relevant elements associated with collaborative AR was missing from the literature due to the relative novelty of AR as a technology, developing a new framework containing the characteristics of collaborative AR was also an aim of the study. Moreover, the research aimed to unveil the most important factors contributing toward the adoption of AR. The aforementioned collaborative AR characteristics framework was used as a lens in analyzing the challenges in the adoption of AR in the FM industry context in order to identify key enabling factors that can support the adoption of collaborative AR.

The research also aimed to succinctly describe key activities organizations need to take to leverage the identified enabling factors effectively. The empirical findings of the study were based on qualitative semi-structured interviews and focus groups with FM company representatives, which were then iteratively analyzed to identify the most important application areas of collaborative AR and which enabling factors are critical for its adoption in the FM industry.

4.1.2 Contribution of Publication I

The FM industry context brings several challenges for the adoption of digital technologies, and especially for cutting-edge novel technologies such as collaborative AR. Digitalization efforts have been relatively minor in the FM industry due to its challenging technology adoption environment; however, the interviewed companies believed that despite this challenging adoption context, collaborative AR solutions could provide them with a competitive advantage if they had a better understanding about where collaborative AR could be applied in their industry and how they should go about adopting such solutions.

This empirical study identified key applications areas of collaborative AR where companies believed it could create value for them. These key use cases were services, collaborative co-design, marketing and sales, operative work, and education and simulation. The analysis also identified operative work and training (i.e., education and simulation) as the most important use cases in the short-term as these use cases could largely be implemented with off-the-shelf solutions, whereas the other use cases were seen to require more custom-development and broader diffusion of AR hardware into their stakeholder networks for them to become viable to apply in daily work tasks.

Due to these factors, the research also identified that different types of collaborative AR solutions can be adopted in the short- and long-term. Off-the-shelf remote AR support applications were the most likely AR application area in the short-term, as they require very little to no integrations with existing organizational IS. In contrast, accessing location- and context-based digital information inside the facilities with collaborative AR was seen to necessitate the wide diffusion of many critical enabling technologies, such as building information modeling (BIM) and indoor positioning technologies, as well as open application programming interfaces (APIs) for the multitude of IS that were in use in the diverse range of facilities these companies were operating in. Although much value was seen to exist in such solutions, their adoption was identified as a more of a long-term prospect for the FM industry, as they would also require more custom development and increased cooperation between different organizations (e.g., different facility owners would have to open their facility data to be used by AR solutions employed by external organizations).

4.2 Publication II: Enabling factors of social virtual reality diffusion in organizations

4.2.1 Background and objectives of Publication II

The aim of the second publication was to identify what factors moderate the diffusion of social virtual reality (SVR) solutions in organizations in the architecture, engineering, and construction (AEC) context. The diffusion of innovations (DOI) theory was used as a theoretical lens in the study where specific moderators were identified for the three most predictive antecedents of the DOI theory (relative advantage, compatibility, and complexity). Extant meta-analytical examinations of the DOI theory's findings were used to narrow the analysis to these antecedents, as they have been found to be the most consistently significant diffusion antecedents. In addition, testable theoretical propositions were derived from these identified moderator-antecedent relationships. The study's empirical findings were based on 12 semi-structured interviews and 14 focus groups with AEC industry representatives.

The study focused specifically on multi-user VR (i.e., SVR). The work tasks in AEC rely heavily on visual information and multi-stakeholder collaboration, which has led to increasing interest in adopting SVR in the industry. However, in order to achieve significant benefits from the use of SVR in the complex collaboration networks that are characteristic to the AEC industry, companies first need to understand how they can best ensure that SVR is adopted widely both within their own companies and their stakeholder networks in order to enable its use in a broader set of collaboration processes.

4.2.2 Contribution of Publication II

The analysis identified eight enabling factors moderating the effects that DOI antecedents (relative advantage, compatibility, and complexity) have on SVR's diffusion in organizations. First, two collaboration intensity variables, namely

"Collaboration around complex visual information" and "Geographically distributed teamwork", were found to moderate the positive effect that SVR's relative advantage (efficient knowledge transfer) has on its diffusion. As the visual and immersive nature of SVR can be used to transfer knowledge between different collaborators more efficiently, if the organization relies heavily on business processes where complex visual information is examined collaboratively and where teamwork is carried out remotely from different locations, SVR's relative advantage will become more prominent.

Second, two SVR-technical infrastructure fit variables, namely "Intra- and interorganizational IS integration" and "Multi-device participation in SVR space", were found to moderate the positive diffusion effect of SVR's compatibility (conceptualized in this study as "ease of business process integration"). In other words, the more information systems are integrated, both inside the organization and with its external stakeholders, the more teams can access and explore relevant digital information in SVR. In addition, if different collaborators can utilize the chosen SVR solution with different end-user devices, it becomes easier to integrate SVR into various business processes when more users can be included in the collaboration.

Third, four mitigating actions were identified that could dampen the negative effect of SVR's perceived complexity (technology utilization difficulty) on SVR diffusion in organizations. These mitigating actions were (1) "Utilizing younger and more innovative users as lead users", (2) "Testing SVR simultaneously with multiple users", (3) "Aligning stand-alone VR HMDs for suitable work tasks", and (4) "Increasing organizational competence with 3D models".

Due to the novelty of SVR, it is crucial for organizations to identify and utilize lead users (or champions) to aid its diffusion in the organization. These champions were believed to primarily come from younger and more innovative employees who were seen as being more eager to experiment with novel technologies. The multi-user nature of SVR was also found to necessitate collaborative testing in the early stages to facilitate the identification of key benefits and challenges that may arise during adoption. Moreover, whenever possible, organizations should try to ensure that stand-alone VR headsets can be used with the chosen SVR solution as much as possible due to their relative ease of use to mitigate the initial difficulties in using VR devices. Lastly, both the employees and the organization as a whole should acquire additional skills in effective handling of 3D models, as a significant portion of the digital content examined in SVR often revolves around this type of content. As such, increased competence in, for instance, importing and exporting 3D models between different software and SVR can enable the employees to carry out the business processes more independently without the need of internal or external support functions.

Finally, these moderator-antecedent relationships were also formulated as explicit hypotheses that can be operationalized and tested in future studies. Overall, the study revealed that organizations need to pay attention to a multitude of factors if they want to ensure that the use of SVR reaches a critical mass of users, which can drive adoption of SVR among other employees within the organization as well as external stakeholders. Organizations and their stakeholders will also need to dedicate a significant amount of resources and secure commitment from management to facilitate the diffusion of SVR.

4.3 Publication III: Extended reality technologies in small and medium-sized European industrial companies: Level of awareness, diffusion and enablers of adoption

4.3.1 Background and objectives of Publication III

The third publication aimed to examine the overall adoption situation with AR and VR in European industrial companies, as well as to gauge their awareness and perceived limitations regarding these technologies. The data on these technologies was also compared to ascertain whether there are any differences in companies' perceptions and use levels with AR and VR. This comparison was carried out to ascertain whether it is justified to examine AR and VR together under the recently popularized umbrella term extended reality (XR). Moreover, small and medium-sized enterprises (SMEs) and large companies' situations with AR and VR were compared. A European-wide survey was carried out to collect the survey data, resulting in 208 responses.

After this quantitative analysis, the study sought to identify common XR adoption factors affecting both AR and VR. Forty-five semi-structured interviews were conducted in nine European countries to gather the managers' perspectives on these issues. The interviews and their analysis were structured using the technology–organization–environment (TOE) framework. A literature review was also carried out where the extant state of organizational AR and VR adoption research was summarized and used in developing the interview protocol. The research also sought to identify which adoption factors were especially highlighted in the SME context.

4.3.2 Contribution of Publication III

The quantitative analysis found there to be no differences in companies' perceptions (awareness and perceived limitations) or use levels of AR and VR. These findings provide further justification to examine AR and VR together under the umbrella term XR. However, when comparing SMEs and large companies, the use levels of both AR and VR differed such that large companies were found to be using these technologies more extensively than SMEs ($p = 0.011$, $p < 0.05$ for AR; $p < 0.06$, $p < 0.1$ for VR). Nevertheless, no statistically significant differences were found between SMEs and large companies on awareness or perceived limitations related to AR and VR. These results indicate that SMEs are lagging behind large companies in XR adoption, highlighting the need for a better understanding of the most critical XR adoption factors to support their adoption efforts.

Qualitative analysis of the semi-structured interviews resulted in 13 distinct XR adoption enabling factors. Five technological enabling factors were identified. These related to (1) the technological install base of XR within the company and among its stakeholders, along with the resultant network effects, which could make it easier for companies to justify investments in XR, (2) the ability to identify XR hardware with an optimal balance between performance and ease-of-use for the company's employees and business processes, (3) the ability to secure testing opportunities both for XR hardware and software to help the company identify appropriate solutions, (4) the level of compatibility between organizational IS and software and the chosen XR solution, and finally (5) the rapidness of workflows between the chosen XR solution and organizational IS, which could make integrating XR into everyday business processes more efficient and effective.

For SMEs, the analysis indicated that the importance of testing opportunities was emphasized, as SMEs often do not possess the resources to buy different types of devices for experimentation purposes. Moreover, these testing opportunities could be used to glean expertise from external expert networks. In addition, the importance of IS and XR compatibility was highlighted, as SMEs were less likely to embark on customizing an XR solution due to the higher financial risks that are associated with such software development projects.

Five organizational XR adoption enabling factors were identified as well. First, the company's top management's knowledge and first-hand experience with XR were found to be crucial in securing the needed adoption resources. Second, the availability of resources for XR research and development (R&D) was found to be critical, as XR solutions would likely need to be tailored to fit the organization's business processes. Third, the company's ability to recruit people with XR expertise was found to be important, as the cutting-edge nature of XR can make its implementation difficult for the organization and force it to rely on external support. Fourth, the company's capabilities in developing mitigation strategies to address potential user resistance from their employees towards XR adoption were seen to help ensure a smoother and more successful adoption process. Fifth, the company's capabilities in facilitating the initial adoption and use situations were seen to create a positive impression of XR among future users, which can help integrate XR more seamlessly into daily business processes.

For SMEs, the availability of resources for XR R&D was found to be extremely important, as SMEs often lack slack resources to experiment and re-engineer their business processes to leverage the potential of new technologies. The ability of SMEs to hire XR experts was also seen to be a key limitation, as SMEs could likely not afford to hire personnel specifically dedicated to XR endeavours.

Lastly, three environmental XR adoption enabling factors were identified. These included (1) the level of XR capabilities and readiness of the company's external stakeholders, which could help the company extend the use of XR to external business processes, (2) companies observing benefits gained by their competitors from successful XR use, which could encourage the company's top management to support its adoption within the company, and (3) the maturity of the XR vendor and training ecosystem, which could offer a wider range of solutions and external support for the company as needed.

All of these environmental enabling factors were found to be more critical for SMEs than large companies. First, SMEs often operate within complex networks where stakeholders' abilities to use XR need to develop based on their own interest, as SMEs rarely possess the leverage to mandate the adoption of a specific technology among their stakeholders. Second, SMEs are more reluctant to experiment with new technologies compared to large companies due to their more limited resources and capacity to handle the risks associated with investing in novel technologies. SMEs thus often wait for larger companies to first demonstrate the practical effectiveness of new technologies before actively considering their adoption. Third, SMEs were found to be more likely to require external support in XR adoption due to their more focused competencies.

Overall, the study demonstrated that companies have similar awareness of AR and VR and perceive a comparable level of limitations in their adoption. The actual use levels of AR and VR were also not found to differ statistically. This analysis provided further justification to examine AR and VR conjointly under the umbrella term XR. Since large companies were found to be using AR and VR more than SMEs, the study also identified critical XR adoption enabling factors that SMEs should prioritize in their adoption efforts.

4.4 Publication IV: Effect of user resistance on the organizational adoption of extended reality technologies: a mixed methods study

4.4.1 Background and objectives of Publication IV

Although XR technologies have garnered a lot of interest in companies, their adoption rates are still relatively low and lagging behind initial predictions. Extant literature indicates that user resistance can significantly contribute to failed technology adoptions. Furthermore, initial research on organizational XR adoption also suggests that user resistance is one of the most significant barriers to XR adoption. Therefore, it is important to examine what specific role user resistance plays in organizational XR adoption dynamics.

Moreover, as much of the extant XR adoption literature has been exploratory and qualitative in nature, confirmatory research on the relative importance of various proposed adoption antecedents is still largely missing from the literature. To address this research gap and assist organizations in adopting XR more effectively, the fourth publication developed a theoretical model based on XR literature and tested it using quantitative survey data (n = 206) collected from managers and decision makers of European manufacturing and AEC companies.

As XR technologies are considered cutting-edge and largely unfamiliar to most employees, the research model incorporated the manager's expected level of employee resistance to XR as a key dependent variable, along with the perceived value of XR for the organization. These two primary and proximate antecedents were theorized to influence the organization's XR adoption intention, which served as the ultimate dependent variable in the model. Additionally, six distal antecedents for these two proximate antecedents were identified and categorized based on the TOE framework.

The proximate-distal categorization was adopted as the paper theorized that certain factors influence the ultimate dependent variable (organizational XR adoption intention) directly, while the distal antecedents have an indirect impact on the ultimate dependent variable through their influence on the proximate antecedents. The logic of the final resistance-value adoption model was developed based on two earlier theoretical models, namely the value-risk adoption model developed by Gao et al. (2012) and the user resistance model developed by Kim and Kankanhalli (2009). The value-risk adoption model (Gao et al., 2012) served as the foundation of the model, with expected employee resistance being proposed as a specific risk in organizational XR adoption.

In addition, to better contextualize the results of the survey study, a follow-up qualitative study based on 58 semi-structured interviews was conducted to clarify what conditions either amplify or mitigate the relationships between the three dependent variables (expected employee resistance to XR, the perceived organizational value of XR, and organizational XR adoption intention). A variation of the Gioia method was used to carry out the analysis.

4.4.2 Contribution of Publication IV

The results of the survey study revealed that the perceived organizational value of XR was more strongly associated with organizational XR adoption intention than expected employee resistance to XR (0.539*** and -0.234*, respectively). However, expected employee resistance to XR was also significantly negatively related with perceived organizational value of XR (-0.189*). These results indicate that organizational decision-makers attach significant importance to how their employees might respond to a new technology, although the value of a technology remains their primary consideration when evaluating its adoption in their organization.

Out of the six antecedents for perceived organizational value of XR and expected employee resistance to XR, the organization's ability to provide support for the adoption and use of the technology (-0.376***) and their employee's skills in using the technology (-0.297***), as well as the ability to test out the technology before its adoption (-0.200**) were negatively related with expected level of employee resistance to XR adoption. These antecedents also had small positive indirect effects on organizational XR adoption intention via expected employee resistance to XR (0.088** for organizational support, 0.069* for employee technology use skills, and 0.047* for trialability). However, the compatibility of XR with organizational IS or the organization's ability to procure external support were not found to be related with expected employee resistance to XR in a statistically significant way.

Regarding the perceived organizational value of XR, only the actions of the company's competitors (i.e., mimetic pressure) were found to have a positive relationship with the perceived value of XR. In addition, mimetic pressure also had an indirect effect on XR adoption intention via perceived value (0.206***). Trialability, compatibility, and organizational support were not found to be statistically related with the perceived value of XR. These results indicate that companies closely monitor what kind of technologies their competitors are adopting, and that these external signals strongly influence an organization's perception of the value of technologies. Ultimately, this can lead to the adoption of the technology within the organization.

The follow-up qualitative study identified 12 conditions affecting the relationships between the three key dependent variables of the SEM model and two key manifestations of XR adoption intention for organizations. Organizations' adoption intentions were seen to manifest in two key overall use cases: (1) using remote XR collaboration to remove the need to travel and (2) using XR's intuitive spatial visualization capabilities to enhance stakeholders' understanding of digital content and 3D models.

Two conditions that strengthen and two that weaken the relationship between the perceived organizational value of XR and organizational XR adoption intention were identified: A visionary champion in top management (+), long-term adoption roadmap (+), insufficient benefits-costs difference for key use cases to provide a risk buffer (-), and high costs in XR hardware, software licenses, and customized XR content creation (-).

Further, four conditions amplifying the negative relationship between expected employee resistance to XR and organizational XR adoption intention were identified: entrenched skepticism toward XR due to negative previous experiences with XR that did not match the hype surrounding the technology (+), users' negative physical reactions from XR use (+), high cognitive demands of XR devices and robustness limitations (+), and novice users' reluctance to use XR devices in public social settings.

Lastly, two conditions amplifying and two conditions mitigating the negative relationship between expected employee resistance to XR and the perceived organizational value of XR were identified: XR's potential in invalidating extant employee expertise that is tied to old work methods (+), high learning demands placed on users due to highly heterogeneous assortment of XR devices in use (+), differing adoption readiness of the employees based on the industry's innovativeness context (-), and a practical champion at the grass-roots level (-).

4.5 Publication V: Six reasons why virtual reality is a game-changing computing and communication platform for organizations

4.5.1 Background and objectives of Publication V

The aim of the fifth publication was to argue for the uniqueness and transformativeness of VR as a computing and communication platform in the organizational context. Although VR has long held significant potential for organizational use due to its unique characteristics, organizational decision-makers are still largely lacking a through and structured understanding of its transformative potential and what practical steps they would have to take to leverage its potential in their own context.

The knowledge and experience accumulated during the dissertation process, as well as a review of the latest scientific and professional literature, were used in formulating the argumentation of the paper. After establishing six key reasons regarding VR's uniqueness as a computing and communication platform, the publication then aimed to distill the key implications of VR for organizations by listing the six key aspects of VR and their potential organizational benefits. Critical actions that organizations need to undertake to achieve these benefits were also proposed. These potential organizational benefits and key actions were formulated to provide organizations with practical guidelines that they can utilize to ensure a smoother and more successful VR adoption process.

4.5.2 Contribution of Publication V

The study argued for VR's unique transformative potential as a computing and computing platform with three separate arguments for both aspects. Regarding VR's potential as a computing platform, the study posited that VR differentiates itself from other IS by its ability to (1) enrich data and information by providing an enhanced spatial understanding of the digital content, (2) create immersive and intuitive workflows and training scenarios to replace expensive, dangerous, or even impossible real-world alternatives, and (3) how these capabilities can further increase synergies with other organizational IS and emerging technologies as VR is, for instance, integrated into construction processes for information handling and simulations.

Regarding VR's potential as a communication platform, the study posited that VR's ability to (4) simulate any communication process in a spatial 3D setting, (5) transform group dynamics by customizing and manipulating user avatars, and (6) bring in AI agents as organizational actors via interactable avatars distinguishes VR from other remote communication tools.

As VR has finally matured to a stage where the technology's sophistication and ease-of-use make its adoption a plausible option for organizations, these organizations are now also in need of adoption and development guidelines. Accordingly, Publication V provided a concise summary table that organizations can use to identify the most relevant organizational benefits and the accompanying actions needed to achieve these benefits.

In order to enrich organizational data and information, organizations need to build up their capabilities on VR-related knowledge management practices and create awareness within the organization about its possible benefits. Identifying current and novel digital assets that could be examined in VR, either in their current format or after adaptation, is critical. Similarly, organizations need to identify key business workflows that could benefit from a virtual spatial setting and natural interactions with digital content. These workflows and training scenarios (for either soft or hard skills) should then be prioritized based on how costly, dangerous, or impossible their current real-life scenarios are. Moreover, as organizational VR competences increase, these workflows should then be gamified to increase engagement and performance. These new VR workflows need to also be integrated into current organizational IS with bi-directional information flows. New emerging technologies can then be introduced into VR-enabled workflows as new synergies are identified.

Regarding VR's social and communication aspects, organizations need to first facilitate interpersonal communication in VR by providing the users with customizable avatars that provide individuating information about the users. Moreover, attention needs to be paid to what demands formal and informal meetings in VR create for communication tools (e.g., which playful features and content could be used to facilitate informal bonding). Organizations should also make sure that users have access to both realistic and enhanced or transformed avatars, depending on the specific business process and desired organizational outcome. Finally, AI agents can be implemented in the VR environment to support the users' and external stakeholders' (e.g., customers) activities in VR. Ideally, these AI agents should possess the ability to support users in both routine tasks and more complex problem-solving scenarios.

Overall, organizations can use these guidelines to construct a roadmap to support them in their VR adoption and development efforts. However, it is important to note that all aspects of VR are not critical for every organization, and that every feature and business process does not have be implemented in VR from the outset. Moreover, organizations should understand that VR can not only be used to replicate existing workflows virtually, but that organizations can also transform their processes with VR by adopting completely novel ways of working. As organizations gain experience with VR as a computing and communication platform, its features and capabilities can be expanded based on the demands of the organization and its users.

5 DISCUSSION

This section describes how the qualitative findings and quantitative results of the publications address the research questions of the dissertation. Integrative meta-inferences are also developed based on a comparison of the findings and results to provide overarching answers to the main research question of the dissertation.

5.1 What factors are critical in the organizational adoption of XR?

The purpose of the explorative phase and the first research question (*What are the critical adoption enabling factors for AR and VR for organizations?*) was to identify what factors organizations perceive to be critical in the adoption of XR technologies. The confirmatory phase of this mixed methods dissertation then examined whether these factors had a statistically significant relationship with adoption intention. The first research question was addressed in Publications I, II and III, which first explored AR and VR technologies separately (Publications I and II) and finally jointly under the XR umbrella term (Publication III). The findings from the extant literature were used as a basis for designing the data collection (i.e., interview protocols). The key findings and their comparison with extant literature have been divided into the three following subsections. These subsections examine the identified technological, organizational, and environmental factors as per the TOE framework (DePietro et al., 1990).

5.1.1 Technological XR adoption factors

XR's compatibility with organizational IS and software (Jalo et al., 2018, 2020, 2022), the availability of APIs (Jalo et al., 2018), and the speed of the associated workflows (Jalo et al., 2022) were identified to be critical factors affecting XR adoption. The extant literature has also broadly identified these issues as important initial enablers of adoption (e.g., Du et al., 2018; Masood & Egger, 2019) since XR technologies are widely utilized as novel visualization tools and interfaces for organizational digital information and 3D content (Davila Delgado et al., 2020). However, the speed and bidirectionality of the workflows (Jalo et al., 2022) emerged as an especially critical and novel finding, as they can determine the practicality and efficiency of new XR-enabled business processes.

Furthermore, the diffusion of enabling technologies, such as BIM and indoor positioning systems, were noted to be important in the development of AR solutions in the FM industry context (Jalo et al., 2018). The specific technological background infrastructure elements that need to be in place naturally depend on the industry context where XR technologies will be applied. For instance, indoor positioning technologies will be crucial if companies want to display contextual digital information within facilities with AR (Jalo et al., 2018), while digital twins will be crucial in the broader industry and manufacturing context (Sharma et al., 2022).

In addition to these technological infrastructure elements, organizations should also evaluate the current XR-ready end-user device install base within their organization and among their stakeholders to effectively leverage network effects (Jalo et al., 2022). In comparison with older single-user XR systems, which had been the focus of much previous XR research (Kim et al., 2013), network effects are specifically highlighted in the context of novel multi-user XR systems (Bastug et al., 2017). For instance, in AR-based remote maintenance collaboration, the organization should first evaluate whether they can leverage the AR capabilities of their current smartphones instead of acquiring expensive AR headsets. This approach can provide quicker time-to-value and increase overall support for XR implementations in the organization.

Accordingly, it has been noted that HHDs possess higher diffusion potential for AR compared to HMDs, even though HMDs offer more functionalities and hands-free operation (Billinghurst, 2021). Nevertheless, the specific work tasks will also impose demands on the hardware. For instance, the end user may need to be able to operate the XR device hands-free for safety reasons. Thus, organizations should only employ their extant XR-compatible hardware if the fit with the organization's work tasks is high (Goodhue & Thompson, 1995).

The characteristics of the XR hardware and software emerged as another pertinent topic. More specifically, the multi-device compatibility of XR solutions was seen to be critical, as it maximized the number of users who can participate in XR-enabled collaboration processes (Jalo et al., 2020). Therefore, organizations should strive to ensure that the chosen XR solution is as device agnostic as possible. To achieve this, opportunities to test different XR hardware and software with multiple users in order to find the right balance in performance and ease of use were deemed critical, given the emerging nature of XR technologies (Jalo et al., 2020, 2022).

Previous findings have also emphasized the importance of configuring XR solutions to align with the organization's work tasks to achieve a better organizational fit (Berg & Vance, 2017; Masood & Egger, 2019). To leverage the inherent advantages of XR in the examination of visual and spatial information (Torro et al., 2021), organizations need to identify relevant work tasks characterized by geographically distributed collaboration focused on complex visual information (Jalo et al., 2020).

5.1.2 Organizational XR adoption factors

Due to the inherent complexity and unique characteristics of XR compared to traditional IT (Mütterlein & Hess, 2017), organizations need to mitigate the initial complexity of learning to use XR technologies (Jalo et al., 2022, 2022). First, it was identified that organizations need to promote younger and more innovative employees as lead users to provide peer support to other employees (Jalo et al., 2020). Although the prevalence of XR skills in industry is still low, the number of XR experts has been increasing in recent years (Noghabaei et al., 2020). Nevertheless, finding industry-applicable XR expertise may still prove to be challenging for organizations. As much of XR investment and development is still focused on consumer applications (Dincelli & Yayla, 2022), organizations should consider leveraging employees who have experience with XR technologies in the entertainment context to spearhead their use in the organization.

XR use cases can be found throughout a product's lifecycle (Lounakoski et al., 2022), making a holistic application of XR a potentially synergistic yet difficult proposition. To achieve this, top management champions were identified to be crucial in securing the needed R&D resources and multi-stakeholder collaboration (Jalo et al., 2022). The lack of available slack R&D resources for XR implementations has also been noted to be an issue in the literature (Davila Delgado et al., 2020; Noghabaei et al., 2020). Publication IV further elaborated on this by noting that in addition to top management champions, grass-roots level champions were also needed. The role of these practice-focused champions in developing their peers' XR capabilities and skills, as well as in demonstrating end-user interest for XR, was seen to enable a smoother XR adoption process. The importance of XR champions has been widely noted (e.g., Berg & Vance, 2017; Chandra & Kumar, 2018; Masood &

Egger, 2019), which makes it one of the more robust findings in the extant XR literature. However, the identification of distinct types of champions and their dynamics is a novel and important finding.

The ability to recruit employees with XR skills and expertise was seen to be a serious challenge due to the emerging and cutting-edge nature of XR (Jalo et al., 2022). This challenge has also been noted in recent literature (Badamasi et al., 2022; Noghabaei et al., 2020). As XR technologies often make use of 3D content, increasing employees' competence in handling 3D models was also seen to enhance the effectiveness and rapidness of business processes (Jalo et al., 2020). Moreover, to reduce the complexity of learning how to use XR headsets, organizations should aim to re-engineer their XR-enabled work tasks to utilize stand-alone XR headsets, as they were seen to be easier to use (Jalo et al., 2020). These aspects are crucial, as they increase the self-efficacy of workers and their confidence in their ability to carry out work tasks independently (Kim & Kankanhalli, 2009).

Due to the novelty of XR and the changes it will likely bring, effective facilitation of the initial adoption and use situations, as well as finding effective ways to mitigate potential user resistance, were also seen as critical (Jalo et al., 2022). This is crucial to ensure good first impressions for XR technologies and to increase the usage rate of XR among employees. Recent literature has also highlighted user resistance as a pertinent factor that needs to be taken into account (Badamasi et al., 2022; Davila Delgado et al., 2020; Masood & Egger, 2019). More specifically, users' aversion to change (Davila Delgado et al., 2020), the cultural change required by new XR work methods (Badamasi et al., 2022), lack of user acceptance (Masood & Egger, 2020), and users' tendency to revert back to using old tools and methods due to inertia (Berg & Vance, 2017) have been identified as specific manifestations of resistance. However, the quantitative effect of user resistance on organizational XR adoption intention is still missing from the literature.

5.1.3 Environmental XR adoption factors

As with most technologies, the external organizational environment can also promote and hinder the adoption of XR technologies. In this regard, this dissertation identified open cooperation between companies as an important enabler for the implementation of many types of XR solutions (Jalo et al., 2018). For instance, facility owners need to provide access and APIs for FM companies' AR maintenance applications to show relevant information of buildings to maintenance personnel in the actual use context (Jalo et al., 2018).

To facilitate interorganizational XR collaboration, organizations need to ensure that the required IS integrations and XR compatibilities are in place (Jalo et al., 2020). To help achieve this, companies need to monitor their stakeholder networks' XR capabilities and readiness to identify potential use cases and opportunities for collaboration (Jalo et al., 2022). Here, a broad assortment of stakeholders should be taken into account, ranging from suppliers to customers and other end users. Relatedly, research by Chandra and Kumar (2018) also noted consumer readiness to be an important factor affecting AR adoption in the retail context. Therefore, organizations should also monitor their customers' XR-ready hardware levels to identify the optimal timing for customer-facing XR deployments.

The maturity of the XR vendor and training ecosystem was also found to be a potentially important factor, especially for SMEs that often lack dedicated internal IT support departments (Jalo et al., 2022). However, some research challenges this finding. For instance, Masood and Egger (2019) found external support to not be statistically related to XR implementation success. Nevertheless, it is plausible that some companies will have to resort to acquiring external expertise to resolve issues with their XR solutions if the company lacks internal XR expertise or encounters complex and time-critical troubleshooting issues.

Competitors' achieved XR benefits were also found to increase internal support for XR adoption (Jalo et al., 2022). This was particularly true for SMEs, which often wait for larger and more risk-tolerant companies to first demonstrate the effectiveness of a technology in practice before committing their more limited resources to new technology implementations. This finding is broadly in line with previous research on virtual worlds (Yoon & George, 2013) and the institutional theory in general (Liang et al., 2007; Son & Benbasat, 2007). This factor highlights the need for internal change agents to monitor and disseminate their observations about their competitors' XR-related activities to relevant decision-makers.

5.2 What is the relationship between the identified adoption enabling factors?

The aim of the second research question (*What is the relationship between the identified XR adoption enabling factors and XR adoption intention for organizations?*) was to unveil the more specific relationships and dynamics between the adoption enabling factors that were identified in the explorative research phase of this dissertation. This topic was examined in Publications III and IV. In Publication III, companies' perceptions relating to AR and VR, as well as their use levels, were first compared to ascertain whether there were any perceptual differences between the technologies. The analysis showed no differences between AR and VR regarding the companies' awareness, perceived adoption limitations, or use levels. This provided further evidence supporting the approach to examine these technologies together under the XR umbrella term, as has already been done in much extant organizational XR adoption research (e.g., Chuah, 2019; Davila Delgado et al., 2020; Gong et al., 2021).

Following this, a conceptual organizational XR adoption model was developed in Publication IV based on a literature review and findings from Publications I and II. The model posited that two proximate antecedents (perceived organizational value of XR and expected employee resistance to XR) were related to adoption intention, and that six distal antecedents based on the TOE framework were related to these two proximate antecedents. The overall results of this publication can be seen in Figure 4. The results revealed that the perceived organizational value of XR (0.539***) was positively associated with organizational XR adoption intention, while expected employee resistance to XR (-0.234**) had a negative association with this dependent variable. Moreover, expected employee resistance to XR was also negatively associated with the perceived organizational value of XR (-0.189*).

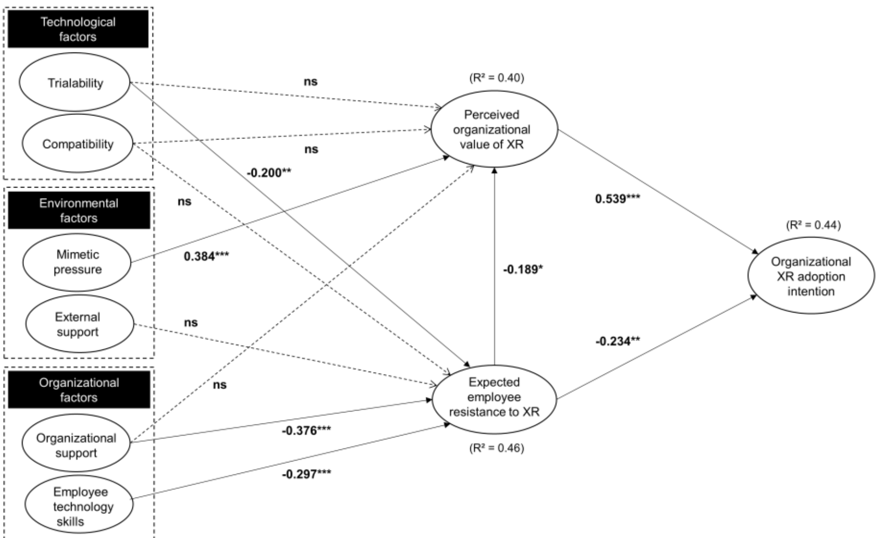

Figure 4. Results of the validated theoretical model from Publication IV (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, ns = not supported)

The results on the effect of perceived value are in line with previous research (Chandra & Kumar, 2018; Gao et al., 2012), confirming the robustness of this relationship. Although the importance of user resistance in failed organizational technology adoptions has been widely noted in literature (e.g., Ali et al., 2016; Jiang et al., 2000), the novel association between expected resistance and perceived value as well as adoption intention had not been previously established quantitatively in the extant literature. This makes it one of the more interesting overall findings of this dissertation.

Nevertheless, when comparing the magnitudes of the relationships (0.539*** vs. -0.234**), perceived organizational value proved to be the strongest proximate adoption antecedent. Interestingly, the difference between perceived value and perceived adopter risk (0.63** vs. -0.33**) was very similar in the original Gao et al. (2012) model, which served as the basis for the development of the theoretical model in this publication. This effect disparity suggests that while the value of a technology is paramount in the minds of managers evaluating its adoption in organizations, expected resistance and risk can still mitigate the perceived value of a technology and temper adoption intentions.

Out of the TOE-based distal adoption antecedents, organizational support capabilities (-0376***), employee XR use skills (-0.297***), and trialability (-0.200**) were negatively associated with expected employee resistance. These results confirm earlier findings on the importance of users' existing skills and their development in XR adoption (Masood & Egger, 2019; Badamasi et al., 2022). Moreover, Chandra and Kumar (2018) also found that an organization's technological competence and capabilities to adapt their IT infrastructure, as well as train their employees in using XR, were positively associated with adoption intention. The negative relationship between trialability and expected resistance is a novel result, which adds to the mixed results on its relevance to adoption (Vagnani & Volpe, 2017).

Out of the proposed hypotheses for the perceived organizational value of XR, only mimetic pressure (0.384***) had a statistically significant positive relationship. Mimetic pressure was found to be similarly important in the context of virtual worlds (Yoon & George, 2013), further confirming the overall findings from institutional theory (Liang et al., 2007; Son & Benbasat, 2007). The non-significance of compatibility with either perceived value or expected resistance is perhaps the most confusing finding, as compatibility has consistently been found to be an important adoption antecedent in the XR literature (e.g., Jalo et al., 2020, 2022; Masood & Egger, 2019). External support was also found to be non-significant, confirming earlier findings in the XR context (e.g., Masood & Egger, 2019).

Publication IV also qualitatively identified eight conditions that may amplify or mitigate the negative relationships between expected resistance, perceived value, and adoption intention (Figure 5). In addition, four conditions that either strengthen or weaken the positive relationship between the perceived organizational value of XR and organizational XR adoption intention were identified.

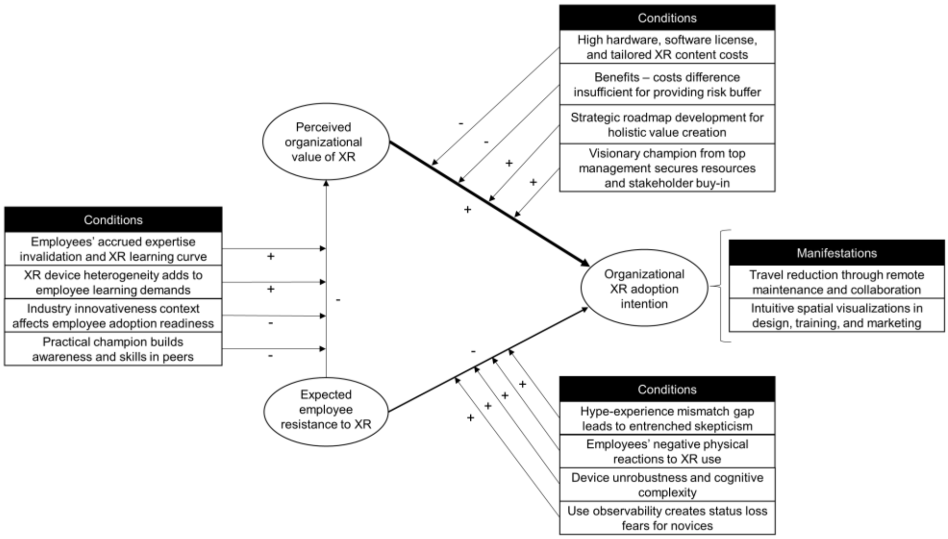

Figure 5. Integrated mixed-methods findings of Publication IV

5.3 Prescriptive recommendations for industry

The third research question (*What industry-independent recommendations can be given for adoption of XR solutions?*) was mainly addressed by Publication V, although the findings of Publications I–IV also contain implicit recommendations for organizations. However, Publication V crystallized these recommendations and made them explicit in the context of VR. The publication first outlined the various reasons why VR can bring value to organizations, highlighting the incentives for organizations to adopt VR solutions. Following this, prescriptive recommendations on how organizations should approach the development of their VR solutions were listed.

The benefits of VR have been examined in the extant literature in various contexts, for instance for AEC design reviews (e.g., Paes et al., 2017) and collaborative decision-making (e.g., Du et al., 2018). However, these results remained scattered in the literature and a comprehensive overview of VR's benefits and value for organizations was missing. Moreover, although factors affecting the adoption of VR have drawn some research interest (e.g., Badamasi et al., 2022; Berg & Vance, 2017), these have often not been specifically linked to different types of VR implementations. As such, there was a lack of guidance for organizations interested in understanding how to develop VR applications with a specific focus (e.g., for visualization or collaboration purposes). Publication V argued for the transformative potential of VR for organizations by identifying three reasons for the value of VR as a computing platform and three reasons for the value of VR as a communication platform. Key organizational benefits for each were then described, followed by key actions organizations should take to realize those benefits.

5.4 Integrative meta-inferences: Comparison of qualitative findings and quantitative results

To provide answers to the main research question (*What are the main factors affecting the organizational adoption of extended reality technologies?*), it is imperative to compare the qualitative findings and quantitative results of the included publications to derive overarching conclusions. The publications constituting the overall dissertation each derived inferences from the data that were collected during specific parts of the dissertation process. Publications I and II largely derived inferences abductively from initial explorative qualitative interviews. In Publication III, the data analysis followed a sequential quantitative-qualitative approach. The quantitative inferences were based on deductive reasoning and testing of the survey data, followed by abductive analysis of another batch of qualitative interviews. Publication IV used a sequential quantitative-qualitative analysis process. First, a conceptual organizational XR adoption model was hypothesized based on extant organizational XR adoption literature and findings of Publications I and II. Then, the model was empirically tested with quantitative survey data and SEM techniques. A follow-up qualitative analysis of qualitative interview data, collected both concurrently with the survey data and later supplemented with another batch of interviews, provided additional insights into the manifestations and conditions affecting the relationships between the dependent variables included in the validated theoretical model. Overall, the process of inference derivation can be described as iterative or cyclical.

Meta-inferences can be defined as *theoretical statements, narratives, or stories that are derived from integrating the findings and results from the qualitative and quantitative strands of the mixed methods research process* (Venkatesh et al., 2013, 2016). This dissertation's meta-inferences were developed by comparing, contrasting, and integrating the findings of Publications I–IV (Venkatesh et al., 2013). Publication V is omitted from this comparison as no new empirical data were collected and analyzed in this publication. The developed meta-inferences can be seen in Table 4.

The meta-inference development utilized the bracketing approach, which involved analyzing and resolving especially diverging and opposing findings from the publications to develop further understandings (Venkatesh et al., 2013). However, some individual publications (specifically Publications III and IV) also developed meta-inferences using the bridging approach where sequential analysis stages were used to develop a consensus between the findings. For instance, in Publication III, the initial literature review described the extant understanding of factors affecting XR adoption. The quantitative part then revealed that SMEs use XR less than large companies, highlighting the need for additional knowledge to assist them in their adoption efforts. This was followed by a qualitative analysis of interviews, which identified important XR adoption enabling factors. These factors were then contextualized based on their novelty and relative importance for SMEs. Moreover, in Publication IV, the extant XR adoption literature was used to theorize a new organizational adoption model. The model was then tested empirically with a survey, followed by a qualitative analysis where the manifestations and conditions affecting the relationships between the three dependent variables of the theoretical model (perceived organizational value of XR, expected employee resistance to XR adoption, and organizational XR adoption intention) were identified and presented.

Table 4. Comparison of the empirical findings and results of the mixed methods research

TOE category and factor	Qualitative findings (I, II, III)	Quantitative results (IV)	Findings converge or diverge?	Interpretation (meta-inference)	Future research avenues
Technology: Compatibility	XR compatibility with IS, fast workflows, and multi-device compatibility of XR critical	Compatibility not a statistically significant antecedent for perceived value or expected resistance	Diverge	Compatibility may be a necessary initial condition, but it is not a driver for adoption by itself	Adapt the compatibility construct to examine different aspects (e.g., required effort in importing digital content)
Technology: Trialability	Testing opportunities important for identifying optimal XR hardware and software	Trialability negatively associated with expected employee resistance	Converge	Trialability may be particularly important for ensuring that the chosen	Examine the importance of trialability for different adopter categories (e.g.,

TOE category and factor	Qualitative findings (I, II, III)	Quantitative results (IV)	Findings converge or diverge?	Interpretation (meta-inference)	Future research avenues
				XR solution aligns with end-user needs, thereby mitigating potential resistance	innovators and laggards)
Technology: Perceived value	Collaboration intensity enhances the relative advantage of XR in companies where the examination of complex visual information and remote teamwork are prevalent	Perceived organizational value of XR very strongly associated with organizational XR adoption intention	Converge	The strengths of XR are emphasized in specific use cases and contexts where spatial visual information and remote collaboration play an integral role in the company's operations	Examine whether work task characteristics act as a moderator for perceived value and adoption intention
Organization: Internal support capabilities	Resource availability for R&D and internal champions critical in XR adoption	Organizational support capabilities negatively associated with expected resistance	Converge	Organizational capabilities are crucial, as they enable the company to independently support their employees and adapt XR for new contexts	Examine the dynamics between different types of champions in more detail
Organization: User skills	Difficulties in finding employees with XR expertise hinder XR adoption	Employees' XR skills negatively associated with expected resistance	Converge	Existing XR use skills make adoption easier and reduce resistance; however, skills may still be scarce due to the emerging nature of XR	Identify types of companies where XR skills are most prevalent (e.g., younger workforce) and the source of these skills

TOE category and factor	Qualitative findings (I, II, III)	Quantitative results (IV)	Findings converge or diverge?	Interpretation (meta-inference)	Future research avenues
Organization: User resistance	The ability to effectively facilitate initial use and mitigate user resistance is critical, as first impressions can be decisive with new technologies	Expected user resistance negatively associated with perceived value and adoption intention	Converge	The role of user resistance likely highlighted in the context of emerging and maturing technologies	Examine the antecedents of user resistance (e.g., lack of skills or fear of status loss) and the effect of resistance from different stakeholders (e.g., customers)
Environment: Mimetic pressure	Competitors' achieved benefits important for generating support for adoption in top management	Mimetic pressure is strongly associated with perceived value and indirectly associated with adoption intention	Converge	Competitors' actions are critical in driving adoption, especially for SMEs, as they often wait for larger pioneering companies to demonstrate the viability of new technologies	Ascertain the importance of mimetic pressure for different adopter categories (e.g., early majority and laggards)
Environment: External support	XR vendor ecosystem maturity is important, especially for SMEs lacking internal expertise	External support not statistically significantly related with expected resistance	Diverge	External support may be necessary as a backup option, but companies do not want to rely on it	Investigate the importance of indirect external support (e.g., embedded in-app tutorials)

The qualitative findings and quantitative results offered partly contradictory evidence on what factors affect organizational XR adoption. For instance, Publication III found that some SMEs believed that external support was likely needed to overcome the initial challenges of XR adoption due to their lack of digitalization skills and more business-focused competences. However, the survey results from Publication IV did not find the availability of external support to be statistically significantly related with lower levels of expected employee resistance, nor was its effect on XR adoption intention mediated via expected employee resistance.

Although AR and VR are cutting-edge technologies that may be quite complex for many organizations, technological factors, specifically compatibility, were also not found to be statistically relevant for their perceived value, expected resistance, or adoption intention, with the exception of trialability, which was found to be negatively associated with expected employee resistance. Instead, environmental and organizational factors were found to have the strongest relationships with perceived value and expected employee resistance.

It is possible that technological factors, such as compatibility, may need to reach a certain threshold for companies to even begin contemplating the adoption of a novel technology. However, these factors may not directly drive adoption. Rather, they should be viewed as initial filtering antecedents, or necessary conditions, for adoption. However, external factors, such as competitors successfully adopting the technology, and organizational factors, such as the organization's ability to support its employees during the adoption process, are ultimately more important as necessary conditions driving organizational technology adoption, given their statistical significance. The following three overarching meta-inferences can be drawn from these converging and diverging findings.

Meta-inference 1: **Technological antecedents do not directly drive adoption but serve as necessary initial conditions when organizations consider the adoption of a new technology.** Technological adoption antecedents should not be considered as proximate adoption antecedents directly driving adoption. Rather, they can better be described as initial filtering antecedents or necessary conditions that must be met before an organization can adopt a technology. However, by their nature, they are unlikely to directly drive adoption because, for example, several different technologies can be compatible with an organization's IS, but the organization will obviously not adopt all of these technologies.

Nevertheless, technological antecedents are also likely to have an influence on other more proximate adoption antecedents. For example, the compatibility of a new technology with the organization's existing software is likely to be negatively related to the perceived cost of the system, which, in turn, is negatively related to adoption intention. Previous organizational IS choices can also contribute to a perception of path dependency, which can, in practice, hinder the adoption of certain new technologies (Zhu et al., 2006).

Even technological factors that have been found to be critical in extant literature (Vagnani & Volpe, 2017), such as the complexity of a technology (which is likely related to the level of existing user skills, as employees are less likely to be skilled in using complex technologies), are also likely to act as filtering variables or necessary conditions rather than sufficient conditions for adoption. This is because there are likely many technologies and innovations that are simpler to use than many of the organization's current or potential new technologies. However, simplicity alone cannot drive adoption if the technology does not possess a relative advantage over other potential solutions or if it does not fit in with the company's tasks and operations (i.e., task-technology fit; see Goodhue & Thompson, 1995).

Meta-inference 2: **Organizations prioritize internal capabilities over external support when considering the adoption of a new technology.** Although the importance of external support networks and providers was identified to be significant in XR adoption during the qualitative explorative phase of the dissertation, they were not found to be statistically significant in the quantitatively tested and validated theoretical model. Rather, the model testing revealed that internal organizational capabilities, such as organizational support capabilities and employees' technology utilization skills, were strongly related with lower levels of expected employee resistance. Therefore, organizations should prioritize these internal capabilities when they embark on adopting XR solutions. Nevertheless, external support options will still likely be important for some companies that cannot develop sufficient internal support capabilities, even though they want to adopt XR solutions. External support may also be needed in troubleshooting cases that require extensive and highly specialized XR development and technical knowledge.

From a practical standpoint, these insights should be used as broad guidelines to help companies focus their efforts on the right areas, rather than as absolute and unconditional truths, as every organization's capabilities and situations are somewhat unique. Thus, even though external support was not found to be statistically related with lower levels of expected resistance, organizations should still be aware of external sources of assistance to be able to access them when needed. Moreover, XR vendors and developers should likely explore ways to provide indirect external support for their client organizations. This can be achieved, for instance, through embedded tutorials or AI agents in the XR software (Torro et al., 2021).

Meta-inference 3: **Expected employee resistance can diminish an organization's intention to adopt a technology that the organization perceives to be valuable.** Due to the significance of expected employee resistance in lowering organizational XR adoption intention, it is crucial for organizations to develop strategies for mitigating the perceived complexity of a new technology for their employees. The findings from Publication II (such as employing lead users and using stand-alone VR headsets whenever possible), the importance of facilitating the initial adoption and use situations, and mitigating employee resistance towards adoption as suggested by Publication III, along with the negative statistical relationship between expected employee resistance and XR adoption intention and perceived organizational value as revealed by Publication IV, clearly point to a convergent theme. This theme emphasizes the significance of assessing potential user resistance towards XR and identifying appropriate mitigation strategies to address such resistance.

This is crucial because user resistance has been identified as one of the most important causes of failed technology adoptions (Jiang et al., 2000; Markus, 1983). However, because the perceived organizational value of XR had a much stronger relationship with adoption intention (0.539*** vs -0.234**), the relative advantage or perceived value of XR should still be considered the primary sufficient condition for organizational XR adoption, provided that a few important necessary (but insufficient) conditions are first in place. For most organizations, mimetic pressures were seen to be especially critical in enhancing value perceptions. Thus, except for the most pioneering and innovative companies, it may first be necessary for some competitors to demonstrate the effectiveness of XR in practice.

6 CONCLUSIONS

In this section, the theoretical contributions and practical implications of the dissertation are described first, followed by an evaluation of the mixed methods approach. Finally, the limitations of the study are described, and some possible future research directions are suggested.

6.1 Theoretical contributions

This mixed methods dissertation focused on unveiling the main factors affecting the organizational adoption of AR and VR, collectively referred to as XR technologies. The research began with a focus on explorative qualitative research, aiming to identify critical XR adoption enabling factors through interviews. These initial exploratory findings are the first contribution of this thesis. These findings were then used as inputs for a quantitative confirmatory phase, in which a hypothesized conceptual model was tested and validated using collected survey data and SEM techniques. The survey analysis results were further contextualized by analyzing an additional set of qualitative interviews. This is the second contribution of the dissertation. Finally, the qualitative findings and quantitative results were compared to identify areas of convergence and divergence, and integrative meta-inferences were developed based on this analysis (Venkatesh et al., 2013). This is the third contribution of this dissertation. Overall, this research offers a holistic perspective on XR adoption in organizations based on an iterative qualitative-quantitative mixed-methods research design (Venkatesh et al., 2013).

The first contribution of this dissertation is the identification of relevant technological, organizational, and environmental antecedents for organizational XR adoption. These exploratory findings are important, as the extant literature at the beginning of this dissertation was still largely scattered and inconclusive (e.g., Berg & Vance, 2017; Chandra & Kumar, 2018; Masood & Egger, 2019). This dissertation contributes to the organizational adoption literature by outlining the organizational value of collaborative AR and its key adoption enabling factors (Publication I), extending the DOI model with key moderators in the context of social VR

(Publication II), and by identifying 13 TOE-based adoption factors that apply for XR technologies collectively (Publication III). These contributions addressed the topic in-depth and outlined the most important factors that can potentially affect XR adoption in industry.

The findings provided supportive evidence for previous research, as well as novel insights. For instance, the importance of compatibility emerged as a clear theme, echoing much extant research (Davila Delgado et al., 2020; Masood & Egger, 2019, 2020). Top management support was also identified to be critical, adding to the robustness of earlier findings (Berg & Vance, 2017; Chandra & Kumar, 2018). Finally, user resistance emerged as a critical concern, which has also been supported by more recent literature (Badamasi et al., 2022; Davila Delgado et al., 2020; Masood & Egger, 2020). This dissertation also identified several external factors affecting adoption, such as mimetic pressure and XR vendor ecosystem maturity, which have not been highlighted in previous literature. However, as these findings were derived based on an interpretivist approach, they should be considered as broader patterns rather than direct causal inferences. Consequently, the dynamics between these exploratively identified factors were examined in the subsequent confirmatory phase of the dissertation.

The second contribution of this dissertation to the IS literature is the unveiling of the more specific relationships between the identified adoption antecedents. This contribution is important, as very little confirmatory research has been carried out in this area (e.g., Chandra & Kumar, 2018; Masood & Egger, 2019). The confirmatory stage of the research (Publication IV) generated the insight that the identified adoption-related antecedents are not equally important. In this regard, Publication IV proposed and validated a theoretical model in which proximate adoption antecedents (perceived organizational value and expected employee resistance) are directly related to organizational adoption intention, while TOE-based distal antecedents (organizational support capabilities, user skills, trialability, and mimetic pressure) are related to the proximate antecedents (see Figure 4). Thus, according to this view, the distal antecedents should be considered as necessary (but insufficient) conditions for adoption, and the proximate antecedents should be regarded as sufficient conditions affecting the organizational adoption of XR technologies. The results suggest that the proximate antecedents are the most critical adoption antecedents in organizational XR adoption. However, the role of distal antecedents is still crucial, as their absence can significantly hinder XR adoption in organizations.

The conceptualization of perceived organizational value and expected employee resistance as proximate adoption antecedents is novel to organizational XR adoption literature, as in most quantitative models each antecedent is typically proposed to have a direct relationship with adoption intention or outcome (see e.g., Chandra & Kumar, 2018; Masood & Egger, 2019). However, this novel categorization also makes logical sense. For instance, an organization's capability to support the adoption of a specific technology should not logically directly drive the organization to adopt the technology, as there are practically limitless numbers of solutions that could fall under this category. Rather, the perceived organizational value of a technology drives the adoption of a technology, provided that the organization has the capabilities to support its adoption. In contrast, expected employee resistance can deter an organization from adopting a technology, even if the required capabilities are in place. These insights generated by the confirmatory part of the mixed methods research process can help researchers extend or revise existing IS adoption theories or develop entirely new ones (Venkatesh et al., 2013).

The third contribution of this dissertation is the development of three overarching meta-inferences. These meta-inferences were developed based on a comparison of the qualitative findings and quantitative results of the individual publications. First, categorizing technological adoption antecedents as initial filtering variables or necessary conditions for adoption is an important finding, as technological factors have been proposed to be directly related to adoption intention in XR literature (e.g., Badamasi et al., 2022; Davila Delgado et al., 2020; Masood & Egger, 2019). Second, the finding that organizations prioritize internal capabilities over external support provides clarity on the dynamics of resistance expectations. This insight further consolidates earlier findings relating to the non-significance of external support in XR implementations, as well as the importance of internal technological competence (Chandra & Kumar, 2018; Masood & Egger, 2019). Third, the notion that user resistance influences both value perceptions and organizational adoption intention highlights the importance of considering user resistance as concept in organizational adoption considerations. This contribution is important to the organizational adoption literature, as the importance of this construct had not been validated by prior quantitative empirical research at the organizational level, but rather only at the individual level of inquiry (e.g., Kim & Kankanhalli, 2009).

Finally, Publication V synthesized the value proposition of VR for organizations and provided specific recommendations for organizations on how they should develop their VR solutions and platforms. Although the advantages of VR over other more traditional IT solutions have been examined in the prior literature (e.g., Berg & Vance, 2017; Paes et al., 2017), a comprehensive synthesis was still lacking. Publication V can therefore serve as a reference for both researchers and practitioners. The publication also provided recommendations on how organizations can reach these proposed benefits. The relevance of these recommendations could also be examined in future confirmatory research.

6.2 Practical implications

This dissertation has several implications for organizations that are considering adopting XR solutions, as well as for XR developers and vendors. First, although many recent examples have shown the possible benefits organizations can reap by adopting XR solutions and revising their business processes to make use of XR's potential (e.g., Porter & Heppelmann, 2017), XR adoption rates are still quite limited (Chuah, 2019; Jalo et al., 2022). This dissertation provides a useful overview of the value and benefits of XR for organizations, which managers and change agents can use to advocate for its adoption within their organizations.

Second, managers can benefit from gaining a more holistic understanding of the factors they need to consider when their organization decides to adopt XR solutions. This dissertation identified a broad collection of adoption enabling factors and antecedents, which can serve as a template and initial guidelines for managers involved in XR implementation projects. However, the importance and applicability of these factors is likely highly dependent on the organizational context. For instance, if the organization is considering adopting remote AR support solutions, the decision regarding whether to utilize the company's existing hardware install base or acquire new AR headsets will be highly relevant to the value proposition of the AR solution (Jalo et al., 2022). Thus, managers need to evaluate the relevance of the antecedents for their organization and prioritize their attention and effort on factors that are most relevant to the specific solution of interest.

Third, the categorization of adoption antecedents into necessary and sufficient conditions brings further clarity for managers on the factors that need to be ensured to be at a required base level and the more proximate or sufficient factors that actually drive XR adoption in organizations. However, managers should first focus on an initial assessment of the proximate adoption antecedents (perceived organizational value of XR and expected employee resistance to XR) to determine the applicability and fit of XR for the organization. This will help avoid blindly copying other organization's XR implementation approaches (Wolf et al., 2012). As Publication IV showed perceived value to have the strongest relationship with adoption intention, managers need to convince internal organizational stakeholders of its value to gain the required support and resources for adoption.

Fourth, after establishing organizational fit, managers should focus on creating mitigation strategies to address potential employee resistance. According to the results of Publication IV, managers should facilitate initial trials of XR solutions with future end users to gather feedback and customize the solution to meet their needs. Moreover, organizations should develop appropriate support capabilities to assist employees during XR adoption and subsequent use. Efforts should also be made to develop employees' XR skills to enhance their self-efficacy in using XR solutions, as research has shown that this can help reduce resistance (Kim & Kankanhalli, 2009).

Fifth, the findings of this dissertation also indicate that managers need to develop a clear roadmap for comprehensive XR adoption and create plans on how to tackle the adoption barriers identified in this research. The need for a roadmap largely stems from the fact that XR technologies primarily serve as collaboration platforms and novel immersive interfaces for organizational digital information (Davila Delgado et al., 2020). Consequently, value-adding use cases can be identified throughout the organization's value chain. Taking a holistic approach to adoption can thus bring greater value to the organization. For instance, the same digital twins of the company's products can be utilized in various XR use cases such as design, collaboration, maintenance, and sales (Lounakoski et al., 2022).

Sixth, Publication IV also suggests that an organization requires champions for XR at both the top management level and the grass-roots level in each department where XR solutions are to be implemented. The findings suggest that these different champions should collaborate in such a way that the champion in top management first secures the needed inter-stakeholder collaboration required for more comprehensive XR implementations, while the practice-focused XR champions help specify how XR should be used to re-engineer the business processes and provide peer support to other employees on how to use XR solutions.

Lastly, XR developers and vendors can also benefit from understanding how their clients (i.e., organizations and end users) perceive XR technologies and their adoption. For instance, Publication IV indicated that external support was not found to be negatively related to expected employee resistance. Thus, XR developers and vendors should redirect their efforts toward providing indirect external support to end users and organizations. This can be achieved through clear guidelines and engaging in-app tutorials, which can enhance the organization's and its employees' capabilities to solve problems independently. Such tutorials can also aid in the development of the organization's employees' XR use skills, which were found to have a negative relationship with expected user resistance.

6.3 Evaluating the validity and reliability of the research

Some researchers have noted that combining different paradigmatic research approaches (i.e., qualitative and quantitative) can bring additional challenges and issues to assessing the validity of the research, as qualitative and quantitative research have their own principles and approaches for evaluating validity and reliability (Creswell & Clark, 2007; Venkatesh et al., 2013). Accordingly, specific evaluation criteria for mixed methods research have been proposed (e.g., Hirose & Creswell, 2023; Teddlie & Tashakkori, 2003, 2009; Venkatesh et al., 2013).

However, since the overall dissertation comprises five peer-reviewed publications, each of these publications also examined its validity based on the recommendations of its respective paradigm. Consequently, the validity of each publication will not be explored in minute detail in this section, although a general description of their approaches will be provided. Instead, this section will evaluate the validity of the overall mixed methods approach that was chosen for the dissertation (Venkatesh et al., 2013).

Mixed methods validation guidelines and terminology developed by Teddlie & Tashakkori (2003, 2009) and the integrative framework developed by Venkatesh et al. (2013) were used in this evaluation. These guidelines encompass the following aspects: (1) assessing the appropriateness of employing mixed methods for conducting the research, (2) evaluating the overall research strategy and design, (3) examining how the findings and results were derived through the use of multiple data collection methods, (4) validating the quality of the integrative meta-inferences (through an assessment of inference quality, integrative efficacy, correspondence, and inference transferability), and (5) providing a concise overview of the validity evaluation approaches utilized in the individual studies that form the overall mixed methods study.

6.3.1 Appropriateness of the mixed methods approach for the dissertation

The first question posed by the mixed methods validation guidelines (Teddlie & Tashakkori, 2003, 2009; Venkatesh et al., 2013) is whether the choice of mixed methods is driven by the research questions, objectives, and context. First, it is important to note that the extant XR adoption and use literature was still very limited and fragmented at the beginning of the dissertation and provided only limited guidance for carrying out confirmatory research. The limited number of available organizational-level adoption models (e.g., Gao et al., 2012) or their generic nature (e.g., the TOE framework by DePietro et al., 1990) also indicated an evident need for the development of new theoretical models that would be more applicable to the organizational XR adoption context. These conditions indicate that a mixed methods approach combining exploratory and confirmatory research was sensible in this research context (Venkatesh et al., 2013).

The novelty of the technologies and the limited adoption of XR also provided a context that justified the use of mixed methods. In other words, it was crucial to first establish an initial understanding of how organizations perceive these emerging technologies. Furthermore, it was essential to identify the most relevant adoption antecedents and subsequently test a conceptual model to assess their relative importance. As evidence of this, the concept of user resistance (see e.g., Kim & Kankanhalli, 2009) was seldom incorporated into organizational XR adoption models (e.g., Masood & Egger, 2019), yet it emerged as an important concept during the initial exploratory phase of the research and its importance was validated in the confirmatory stage.

The literature was also largely inconclusive, with many different antecedents being proposed. Therefore, employing a mixed methods approach was considered appropriate to provide a holistic view of the subject. The research questions also justify the use of mixed methods, as they encompass different levels of inquiry that are best addressed with different methods. For instance, identifying the most important adoption enabling factors can be achieved through exploratory qualitative methods, and their relationships and dynamics can subsequently be tested through confirmatory survey research. Meanwhile, assessing the current levels of AR and VR use and exploring potential differences between these technologies are better examined using quantitative methods.

6.3.2 Evaluating the overall mixed methods strategy and design

The second step is to evaluate the overall strategy for the mixed methods design. Although overall the dissertation can largely be described to have utilized a sequential design, it is important to note that some of the data collection and analysis were also carried out concurrently (Venkatesh et al., 2013) due to practical considerations. The initial phases were predominantly sequential, as the research effort at that stage primarily focused on establishing an initial understanding and laying the groundwork for theoretical model development. In other words, the aim was to utilize the findings from the earlier studies (Publications I and II) to inform the data collection and analysis of the later publications (Publications III, IV, and V). This approach was thus aligned with the guidelines provided by Venkatesh et al. (2013).

However, Publications III and IV also employed a primarily concurrent design, where quantitative and qualitative data were collected and analyzed simultaneously. However, later qualitative insights on the quantitative results of Publication IV were also derived based on newly collected and analyzed qualitative data. This kind of an iterative approach to analyzing data was deemed to be justified, as it allowed for the development of new insights by re-examining previously collected data in light of new results (Venkatesh et al., 2013). Moreover, by employing several iterations or cycles of qualitative-quantitative examination, the final conclusions are likely to be more robust (Venkatesh et al., 2013).

Nevertheless, a more sequential design would likely have been more optimal, such as finalizing the identification of relevant XR adoption antecedents in Publication III, which would have determined the survey design of Publication IV. However, practical considerations such as project timelines and uncertainties about upcoming opportunities for data collection made this approach infeasible.

6.3.3 Evaluating the data collection and analysis methods

The third step is to evaluate how the data were collected, analyzed, and integrated. Overall, the research followed rigorous methods in data collection and analysis. In Publications I, II, III, and IV, the interviews were audio-recorded, and pertinent sections of the interviews were transcribed for analysis. Illustrative quotations were included to enhance transparency and to enable the readers to understand how the inferences were derived. Additionally, each publication openly explained the analysis process, and Publication III also included the interview protocol.

In Publication IV, the quantitative survey was developed based on an extensive literature review and refined based on feedback from two professors with extensive experience in survey data collection and analysis. The survey was further refined based on pilot tests conducted with two companies to enhance the face validity of the survey items. Survey data were analyzed using IBM SPSS and IBM SPSS Amos, following guidance from the literature and employing rigorous statistical tests (e.g., Fornell & Larcker, 1981; Franke & Sarstedt, 2019; Henseler et al., 2015). These analysis processes were openly and extensively reported in Publications III and IV.

Although mixed methods studies should aim to avoid having some studies be more dominant that others in terms of rigor (Venkatesh et al., 2013), it could be characterized that Publications III and IV were slightly more dominant in this regard compared to the initial exploratory Publications I and II. However, this distinction largely resulted from the accumulated knowledge and experience gained during the dissertation process, rather than from a deliberate choice. Given that the dissertation process spanned approximately five years, it is to be expected that later publications would be more robust in nature.

6.3.4 Meta-inference development and quality evaluation

The fourth step is to evaluate the meta-inference development process and their quality. It is worth noting that much of the extant mixed methods research has neglected the development of integrative meta-inferences, despite it being recognized as one of the strengths and even a critical and essential part of the mixed methods research approach (Venkatesh et al., 2013). This dissertation developed three overarching meta-inferences (see Discussion section 5.4). As the mixed methods analysis process was primarily sequential rather than concurrent in nature, the development of the meta-inferences relied heavily on comparing and contrasting the quantitative results and qualitative findings, rather than infusing, linking, or blending different types of data together (Bryman, 2007).

In this regard, Venkatesh et al. (2013) recommend assessing the quality of how the findings and results were compared and contrasted (referred to as integrative efficacy). Accordingly, this dissertation compared the XR adoption factors that were identified to be important in the earlier exploratory studies with the statistical results of the confirmatory study. The analysis then identified areas of convergence and divergence among the results and findings. Convergent findings were considered to indicate more robust overall results. However, when the results diverged, possible explanations for these divergences were suggested. Future research directions were also proposed for both convergent and divergent results (see Table 4).

Since the main research question of the dissertation aimed to identify the primary factors affecting organizational XR adoption, the identification of more robust antecedents and areas where the findings diverged proved valuable in fulfilling this objective. Both the explorative and confirmatory phases contributed to developing an understanding of the most important factors impacting the organizational adoption of XR, as they were used as inputs in deriving the overarching meta-inferences. For instance, while the qualitative analysis indicated that technological antecedents were important, the confirmatory study suggested that they should be viewed as necessary conditions for adoption rather than sufficient conditions driving adoption. The integrative correspondence of the meta-inferences, in terms of relevance to the overall aim of the mixed methods study (Venkatesh et al., 2013), was thus also satisfied. Each publication also aimed to address the same overarching research question established at the beginning of the dissertation process (i.e., what are the main factors affecting the organizational adoption of extended reality technologies?), albeit from different angles and with different methods. The degree of integrative correspondence of the mixed methods research process can therefore be considered to be high (Venkatesh et al., 2013).

Finally, the boundary conditions of the developed meta-inferences (i.e., inference transferability) are discussed in the Discussion and Limitations sections of the study, highlighting that they primarily apply to private sector organizations and other emerging technologies.

6.3.5 Overview and evaluation of the individual publications' validity and reliability

Lastly, although this section has mainly focused on evaluating the overall mixed methods research process, it is also necessary to provide a brief overview of the validity consideration for each publication. Publications I–IV extensively discussed the validity and reliability of their findings and results within each respective publication (Publication V did not include empirical data). The validity and reliability discussions were further expanded based on feedback received during the peer review process.

The most formal validations can be found in the quantitative sections of Publications III and IV, where various statistical tools and tests were employed to assess the validity and reliability of the data collection and analysis procedures. These assessments were conducted according to well-established guidelines from the literature. These tests and assessments included, for instance, the nonresponse bias test, standardized item loadings, scale and item validities and reliabilities, common method variance, and measurement and path model fits (Armstrong & Overton, 1977; Hair et al. 2014; Milfont & Fischer, 2010; Podsakoff et al., 2003, 2012; Schermelleh-Engel et al., 2003; van der Schoot et al., 2012).

Regarding the qualitative sections of the analysis in Publications I–IV, each publication offered detailed descriptions of the research contexts and the methods employed in data collection and analysis. These details enhance the transparency, credibility, and confirmability of the findings, while also facilitating the evaluation of their transferability to other contexts (Lincoln & Guba, 2000).

6.4 Limitations and future research topics

This dissertation has certain limitations that should be considered when interpreting its findings and results. First, it should be noted that XR technologies can be regarded as cutting-edge and disruptive technologies, rather than incremental technologies (Damanpour, 1991; Dewar & Dutton, 1986; Rauschnabel, 2021). Consequently, the findings of this dissertation are likely to be more applicable to other technologies with similar characteristics. Therefore, the transferability of the findings to other technology contexts characterized by higher degrees of standardization and diffusion (e.g., laptops) may be more limited. Nevertheless, exploring whether the results of this dissertation, such as the validated theoretical model in Publication IV, hold true in the context of other technologies could provide valuable insights.

Moreover, the findings are likely to be more applicable to adopter categories that are interested in adopting emerging technologies, such as innovators and early adopters (Rogers, 2003). Exploring whether different factors become more relevant for late adopters as a technology becomes more established would be an intriguing area for future research. Moreover, investigating whether early adopters end up utilizing XR solutions more extensively than late adopters could yield interesting results. Understanding whether early adopters later expand the use of XR from specific types of initial use cases into more complex ones could also assist in developing organizational adoption roadmaps, which would be beneficial for later adopters.

In addition, future conceptual adoption models could encompass a broader range of antecedents. Depending on whether they focus on organizational or individual adoption, different antecedents may be relevant. In the individual context, further research could explore the role of comfort and fashionability to determine whether they play a significant role in XR adoption in the work context. This is particularly important since much of the extant research on this topic has been conducted in the consumer context (e.g., Herz & Rauschnabel, 2019). Such technology-specific factors may indeed have a clear influence on people's willingness to use highly visible devices like XR technologies in the professional context, as evidenced by anecdotal evidence (Hollister, 2022) and as indicated by Publication IV. However, these factors were not examined in detail within this dissertation.

This dissertation primarily focused on examining technology adoption from the organizational point of view. However, further investigations are necessary to compare managerial and employee beliefs regarding technology adoption, as these can vary significantly (Markus, 1983). Identifying areas of overlap and potential tensions between these perspectives could provide valuable insights. The examination of user resistance could also be expanded beyond the internal employee context to encompass external stakeholder groups, such as customers. This expansion could help ascertain how expected resistance from these groups might influence the intention of organizations to adopt XR technologies.

Other methods could also be employed in analyzing qualitative and quantitative data in future mixed methods research. For instance, fuzzy-set Qualitative Comparative Analysis (fsQCA) has gained popularity recently, and it could be utilized to reveal more nuanced relationships between quantitative variables beyond their direct relationships (Pappas & Woodside, 2021). XR technologies also offer intriguing opportunities for collecting highly granular insights about users, such as through the collection of eye tracking and other physiological data. These objective data could be compared with interview or self-reported survey data to identify specific stressors, such as privacy concerns (Kröger et al., 2020), which may contribute to user resistance. Such mixed methods approaches can also be utilized to identify tensions and incongruities between different types of data.

The data for this dissertation were primarily collected from Finnish companies (Publications I and II), while Publications III and IV primarily collected data from Europe. Consequently, caution should be exercised when generalizing the results to other cultural contexts, both at the country and organizational level. It is possible that factors such as the importance of user resistance in organizational adoption of novel technologies may have a different impact in cultures with more hierarchical and top-down management styles. Therefore, the applicability of the findings should be examined in various national and cultural contexts (Bagchi et al., 2004).

Lastly, the findings were derived from interviews and surveys conducted with private sector companies, particularly in the AEC and manufacturing industries. While many of the findings may have relevance in the public sector as well, it is important to apply them in this context with caution. It is crucial to consider whether the public sector context diminishes or amplifies the significance of different enabling factors and adoption antecedents. For example, competitive and mimetic pressures may be less influential in the public sector, while legal mandates may play a larger role.

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PUBLICATION
I

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How Can Collaborative Augmented Reality Support Operative Work in the Facility Management Industry?

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Keywords: Augmented Reality, Collaboration, Facility Management, Knowledge Management.

Abstract: Augmented reality (AR) enables effective knowledge transfer in synchronous and asynchronous modes of collaboration independent of the users' location. Researchers have emphasized that collaborative characteristics of AR could change how companies carry out knowledge management. However, there is little research about this subject. We address this gap specifically in the context of the facility management (FM) industry. A qualitative multiple-case study was carried out to explore how collaborative AR can bring value to FM companies. This study's contribution to research is a better understanding of the application of collaborative AR in the context of FM. As a managerial contribution, companies can better understand what type of collaborative AR solutions can be adopted in the short- and long-term. The factors that enable the adoption of these solutions are discussed.

1 INTRODUCTION

Augmented reality (AR) has previously had only limited use in industry and in the consumer market due to multiple technical limitations (Chi et al., 2013). However, the recent rapid technological advancements in AR-related technologies and new applications, such as Pokémon Go, have now brought AR into the public consciousness (Porter and Heppelmann, 2017). The use of AR is expected to grow rapidly. For example, Digi-Capital (2018) predicts the AR market will grow from less than $5 billion in 2017 to between $85 and $90 billion by 2022. Google and Apple are also investing heavily in AR with the releases of their ARCore and ARKit AR development platforms, respectively (Kharpal, 2017).

Because of these factors, AR technologies are likely to be adopted widely by industry within the next ten years (Chi et al., 2013; Irizarry et al., 2013). AR is also recognized as a significant technological trend, and it is beginning to move on from the hype and disillusionment phase to offering real business value (Gartner, 2017). More than ever, AR is now poised for a breakthrough.

According to Azuma et al. (2001), AR combines the real world with virtual objects in real time while being interactive. The core potential of AR is in combining relevant digital information with real-world objects. This can enhance the way people interact with the world and enable people to utilize digital information more intuitively and efficiently (Williams et al., 2015). AR can enhance the collaboration between a company's employees in many different ways resulting in cost-savings and better service for customers (Martínez et al., 2014). These aspects are especially relevant in the labor-intensive facility management (FM) industry (Lehtonen, 2006) where employees need to collaborate with each other while staying mobile throughout the workday as they maintain facilities they are not necessarily familiar with.

The current work methods in FM lack the infusion of technology and have been argued to be outdated (Irizarry et al., 2013). Most of the costs of a facility are incurred during the operation and maintenance phase (Becerik-Gerber et al., 2011). The potential for new efficiencies through the use of new digital solutions, such as collaborative AR, is significant in the FM industry (Zakiyudin et al., 2013). Collaborative AR has the potential to support effective knowledge transfer between multiple employees by enabling them to interact with each other in a context-sensitive manner.

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The use of AR in FM and especially its collaborative characteristics have not been studied extensively. This study aims to address that gap in research. *The research questions of this paper are:*

RQ1: What are the most relevant application areas of collaborative AR in the FM industry context?

RQ2: What added value can collaborative AR bring in the context of the FM industry?

In order to answer these research questions, a multiple-case study was carried out in several Finnish FM companies that are adopting collaborative AR solutions. This study context is particularly interesting because there are more than 100 highly active VR/AR studios in Finland that are offering innovative solutions to companies (Suominen et al., 2017). The FM industry's interest in digitalization has also increased in the last few years, and there are significant government efforts to aid FM companies in digitalizing their businesses (Ministry of the Environment, 2018).

The rest of the paper is organized as follows. First, the related theoretical background of AR and its collaborative characteristics are provided in section 2. Second, the research methodology of the study is described in section 3. Next, the results and findings of the study are presented in section 4. Finally, the findings are discussed with the theoretical and managerial implications of the study in section 5. The study's limitations and proposed future research are also discussed in this section.

2 THEORETICAL BACKGROUND

In this section, the adoption of AR within many industries is explored. Adoption of AR within the FM industry is specifically addressed. Finally, the collaborative characteristics of AR are synthesized.

2.1 AR Adoption

Previously, AR had been mainly used in military, medicine, industry, education, marketing and entertainment contexts (van Krevelen and Poelman, 2010; Bower et al., 2014; Mekni and Lemieux, 2014; Billinghurst et al., 2015; Porter and Heppelmann, 2017). AR technologies have been advancing rapidly within the last few years which have made adoption possible in many different application areas. However, AR is still largely in the development phase and has yet to reach its full potential (Carmigniani et al., 2011; Rankohi and Waugh, 2013; Murthi and Varshney, 2018).

AR can be utilized by handheld displays, such as smartphones and tablets, head-mounted displays (HMDs) and projection displays (Azuma et al., 2001). However, the vast majority of AR systems use video see-through devices, such as smartphones, rather than optical see-through devices found on HMDs (Wang et al., 2013).

Bringing assembly instructions into the view of a worker with AR is being piloted in thousands of companies (Porter and Heppelmann, 2017). When compared to a traditional manual, AR instructions can decrease the number of errors by up to 82% (Mekni and Lemieux, 2014). NASA uses Microsoft's HoloLens to bring in experts to remotely assist astronauts in maintenance tasks (Hachman, 2015). Boeing halved the error rate and shortened the production times in their pilot project with a Google Glass AR system (Sacco, 2016). Henderson and Feiner (2009) demonstrated that task localization for maintenance workers improved significantly with an AR solution when compared to previous methods. The commonality in all of these examples is that they represent AR adoption in a very specific use context. The complexity of FM brings significant challenges to adoption of new AR solutions.

2.2 AR in Facility Management

Employees working in the FM industry require access to a large amount of information from many different sources to complete their work tasks (Irizarry et al., 2013; Rankohi and Waugh, 2013). Gathering all the relevant information has been difficult and has required a lot of error-prone manual work due to the heterogeneity of the maintained facilities (Bae et al., 2013). This can also make collaboration challenging, as it can be difficult to ensure that that the employees are using the same and up-to-date information during collaboration. AR can provide solutions to these problems, but despite its potential benefits, it has not been widely adopted in the FM industry (Rankohi and Waugh, 2013).

One of the research areas within the construction and FM industries is the use of building information modeling (BIM) with the help of AR (Becerik-Gerber et al., 2011; Irizarry et al., 2013; Irizarry et al., 2014; Williams et al., 2015; Chu et al., 2018). However, most of the research in combining BIM with AR has focused on the design and construction phases of a facility (Gheisari and Irizarry, 2016). Enabling a remote collaborator to guide another user by allowing him or her to interact with the remote environment through AR has also been an area of interest (Gauglitz et al., 2014; Billinghurst et al., 2015; Lukosch et al., 2015). These solutions allow the users to feel as if they are virtually co-located (Lukosch et al., 2015). However, the applicability of these solutions has not been explored extensively in the context of FM.

Maintenance workers would benefit from using HMDs in utilizing AR because they leave both hands free for work-related tasks (Bimber and Raskar, 2005). However, the majority of existing AR solutions were developed for handheld displays, such as smartphones and tablets, because of their ubiquitous nature and higher mobility. Furthermore, HMDs are still quite expensive (Porter and Heppelmann, 2017) which limits their usage to solving problems in highly capital-intensive and time-critical tasks, such as repairing and maintaining industrial machinery, where even short work stoppages can incur high costs for companies.

This means that in the FM industry, AR solutions will be mainly used with smartphones, which are becoming ever more powerful and suitable for AR due to the many different sensors and upgraded functionalities (Carmigniani et al., 2011). A key benefit of AR is in reducing the user's need to shift his or her attention from his work task to supporting documentation (Woodward et al., 2014). For example, users could enhance their collaboration by embedding relevant digital information, such as a maintenance manual, in their shared view of a work task. Thus, a core value of AR is likely to reside in its potential for more effective collaboration.

2.3 Collaborative AR

Historically, most AR systems have made been for single users (Wang et al., 2013). AR has been developing toward a more collaborative direction with solutions that enable interaction between individuals. However, these collaborative characteristics and their research are in their infancy. This section provides an overview of those collaborative characteristics.

Collaborative AR is defined as an AR system where "multiple users share the same augmented environment" locally or remotely (Regenbrecht et al., 2002, p. 152) *and which enables knowledge transfer between different users*. Collaborative AR has significant potential because AR can be widely adopted within different functions in a company's value chain (Porter and Heppelmann, 2017). Some studies have also found that users prefer AR over virtual reality (VR) in collaborative situations (Billinghurst et al., 2001).

According to Ellis et al. (1991), collaboration and communication can be classified in four categories depending on whether the collaboration happens synchronously or asynchronously and whether the users are located in the same place or not. Collaborative AR solutions can also be classified by the participating stakeholders. Collaboration can happen inside a company, between companies or between a company and its customers.

The collaboration type can be further divided based on the number of participating users (Jensen, 2001). Collaboration types can be classified into one-on-one, one-on-many and many-on-many categories. The device used in the collaboration also has an effect on communication. For example, ensuring that every user has the same view and a shared understanding of the virtual content has been a challenge if the users view the AR content through their own devices (Azuma et al., 2001).

Collaboration in AR can happen in a multitude of ways. According to Azuma et al. (2001), all five human senses can be used in AR. However, thus far developers have focused almost entirely on the visual aspects of AR (Wang et al., 2013). Correspondingly, most AR functionalities utilize visual digital information, such as text, pictures, videos and information models. The available functionalities of the AR system also have an effect on collaboration. All these different factors should be taken into consideration in exploring collaborative AR. The key characteristics of collaborative AR are presented in Figure 1.

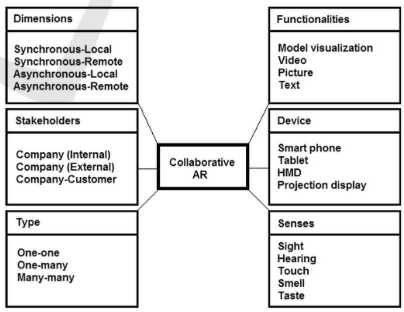

Figure 1: Characteristics of collaborative AR.

3 METHODOLOGY

Five Finnish FM companies participated in this study. We focused on companies that were adopting emerging collaborative AR solutions. Some of the companies participating in the study were more involved in the maintenance phase of a facility, while others were involved in a facility's whole lifecycle. This enabled us to explore the views of companies involved in different lifecycle phases of a facility. The study used a qualitative approach. The chosen research strategy was multiple-case study (Yin, 2009).

Semi-structured interviews were used as the data collection method (Ghauri and Grønhaug, 2005). Interviews were chosen because they are a useful method in exploring new research areas, such as collaborative AR, where limited research is available. This method also allowed us to explore interesting themes that emerged during the interviews more thoroughly.

The aim of the interviews was to find out what added value collaborative AR can bring to each FM company. Usage scenarios of new collaborative AR solutions pertinent to each company were explored during the interviews. In addition, a list of questions and themes were used in the interviews. The collaborative AR characteristics presented in Figure 1 were utilized in formulating the questions in order to explore the usage of AR. In the pilot tests, a remote AR video collaboration tool called POINTR was tested (Delta Cygni Labs, 2018).

In total, nine interviews were carried out between October 2017 and February 2018. The interviews lasted from 90 to 120 minutes. The interviews had one or more interviewees; therefore, some of the interviews can be classified as focus groups (Ghauri and Grønhaug, 2005). The interviewees consisted of senior leadership who are responsible for the company's digitalization strategy and of the end-users of the new collaborative AR solutions being adopted. In each interview, three to five members of the research team were present and acted as the interviewers. The interviewers and the interviewees were all Finnish.

The interviews were audio-recorded and then transcribed in Word documents as thoroughly as possible. The transcribed interviews were then analyzed iteratively where the themes arising from the interviews were constantly refined. The findings were grouped under different themes, such as FM industry specific challenges and application areas of collaborative AR. The characteristics of collaborative AR presented in Figure 1 were also utilized during the analysis. A list of the interviews is presented in Table 1.

Table 1: List of the interviews.

Interviewed company	Interview type	Interviewees
Company A	Focus group	CEO, CEO, Chief Real Estate Officer
Company B	Focus group	Chief Development Officer, Workspace Expert
Company C	Semi-structured interview	CEO
Company D	Focus group	CEO, Unit Manager, maintenance worker, landscape designer
Company C	Focus group/pilot test	CEO, 4 team leaders, 4 cleaners, maintenance expert
Company D	Focus group/pilot test	CEO, Unit Manager
Company E	Semi-structured interview	CEO
Company E	Focus group	CEO, Chief Real Estate Officer, Construction Manager, Construction Engineer, ERP Project Manager
Companies A, B and D	Focus group	CEO, CEO, Chief Development Officer

4 RESULTS

In this section, we present the results of the study. We first present the most relevant application areas of collaborative AR in FM. Then we present the use of AR in remote collaboration. After that, we present the use of AR in context-dependent asynchronous collaboration. Finally, five different enabling factors relating to the adoption of collaborative AR are presented.

4.1 Application Areas of Collaborative AR

According to the results, the companies were interested in utilizing AR in many different application areas. Of all the potential application areas, most interviewees considered that the main value of existing collaborative AR solutions was in enhancing the collaboration between the company's employees in operative work as highlighted in Figure 2. Educating the company's employees about different work tasks was also seen by many as a critical source of value.

A few companies were also interested in utilizing AR to bring their customers closer to their business processes. However, this was seen as challenging due to the heterogeneous customer profiles and their different levels of technological readiness to use new AR solutions. For example, a tenant and a professional service buyer differ significantly in this regard. A maintenance worker noted, *"So how does this work out when you require new devices for a tenant? I mean, can you give an 80-year-old a new device and tell him to give the next work order with it and tell him not to call us. The notifications are still very often written on the back of an old envelope and dropped in a mail box so it's quite a leap from that to this new solution."* Therefore, most interviewees saw the potential of collaborative AR to reside mainly in improving a company's internal business processes.

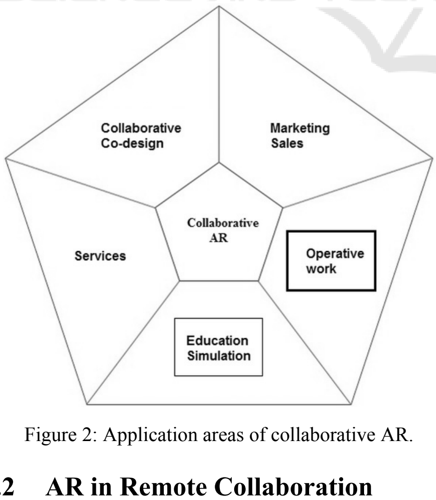

Figure 2: Application areas of collaborative AR.

4.2 AR in Remote Collaboration

The adoption of AR for remote collaboration was seen to have huge potential. Many interviewees saw AR to be useful for collaboration between maintenance workers, as well as between managers and workers. The interactive and visual nature of existing solutions (such as Delta Cygni Labs' POINTR) were seen as a big advantage when compared to traditional phone calls. Many interviewees thought that creating a remote video connection between two workers where the workers could augment the video stream with AR annotations and drawings could save the workers a lot of time by helping them avoid unnecessary site visits. As one CEO pointed out, *"The thing here is that because the solution is interactive and collaborative, if anything is unclear, we can go through it again and give more accurate instructions. That gives us a better chance to avoid unnecessary visits to facilities as their cost is especially high in the metropolitan area."*

The visual nature of the AR solutions was seen by some to enable more efficient collaboration between individuals who do not speak the same language. A team leader remarked, *"Then when you sometimes have these workers who do not speak Finnish that well, it's especially difficult to try to explain something to them verbally when you could just point to what you were referring to [in a video]."*

In addition to helping overcome the language barrier, the solutions were seen to give the expert a better understanding of whether the worker understood his or her instructions. One CEO said that *"reliability is probably a good thing about this because this gives us a better picture about whether the instruction was actually understood or not because there's a lot of guesswork involved with that right now."*

According to most interviewees, the FM industry has been very conservative in adopting new digital solutions when compared to other industries. However, many interviewees thought that significant changes in AR-enabled work methods were now possible because a new generation of workers is entering the industry. A CEO remarked, *"I believe more in change in the industry now because we've already had a massive generational shift happen in our companies."* Another CEO noted, *"Then you have to remember that people are constantly retiring, and new people are coming in. They all have smartphones, and they use it for everything in their lives. So it's not the problem anymore that people wouldn't know how to use or learn how to use them because it's taken for granted that everything is handled with a smartphone."* The readiness of FM industry employees to adopt new digital solutions was clearly seen to be improving.

4.3 AR in Context-dependent Asynchronous Knowledge Transfer

Many interviewees saw the cost of having a remote expert on standby when needed as a downside of synchronous remote collaboration. As one CEO explained, *"I'll emphasize again, this is fine during normal work hours, but then you have these night shifts where you would need recordings because otherwise, it just becomes impossible when you think of the Finnish working time legislation and the costs of having someone constantly on duty for different expertise areas."*

Therefore, AR was also seen to be potentially useful in asynchronous local collaboration. A core advantage of collaborative AR is in enabling the availability of context-dependent knowledge for workers asynchronously. For example, a worker could attach digital maintenance instructions to a particular machine for other workers to read later. This was seen to be crucial, as one CEO remarked: *"Actually, it is very common that when the worker does not know how to do something or how to use some machine that he just leaves the task alone. The worker also does not tell anyone about it, and it might resurface after a month, and then we wonder why this was not done already."*

Asynchronous local collaboration was also seen to save managers' time if workers could solve problems independently more often. A CEO explained, *"The idea here is that in the beginning we take these different machines of ours because they always have some top-5 problem list which the worker could go through before he calls us that something does not work."*

The availability of different types of instructions was also emphasized by one CEO: *"I think that partly it can just be an instruction video that you can tap open when you scan a machine. But then we also have to think that a person has to have options about what kind of instructions he wants to see. For some, the video is not enough, someone manages with just a picture, and written instructions are enough for others."*

According to one CEO, one of the major problems with the current work methods is that they are extremely prone to errors and mistakes. He explained that *"there's a lot of room for error right now. For example, whether a worker remembers to bring back the documents for billing purposes once he is finished with a task. Or if he gets a call about a new task. He quickly writes it down while he is driving somewhere, and then the note perhaps falls down during a braking situation, and then he completely forgets it. There's lots of opportunities for errors, and naturally, because I'm responsible for this operation as a whole, when people forget to bill something or don't know that they should bill about something, those errors are very concerning."* Collaborative AR was seen to have potential in solving these problems by automating and digitalizing the current work methods. For example, if a worker could find all relevant documentation for a machine by simply pointing a smartphone at it, the need for manual information gathering would decrease substantially.

Asynchronous local collaboration between a company and its customers was also seen as a possibility according to one CEO: *"Educating tenants is one area where I see a use for AR. Because no one reads that instruction folder, you need to translate that into an AR form where you can just take out your smartphone and check how something works."* Collaborative AR was generally seen as an update of the current outdated methods. However, adopting these new solutions in the customer context was seen to be highly dependent on the companies' customer profile. The younger the company customers, the more likely they were thought to be to adopt new digital solutions.

4.4 Enablers of Collaborative AR in Facility Management

According to the findings, multiple developments need to take place to pave the way for smooth adoption of collaborative AR in the FM industry. Most interviewees saw the integration of information systems as a critical factor in enabling the adoption of new collaborative AR solutions. The value of AR comes from showing relevant digital information to the user in his or her immediate context. For example, a maintenance worker could look at a malfunctioning machine (e.g. an air conditioning unit) with a smartphone and see different sensor information digitally attached to relevant parts of the machine. This is naturally extremely difficult if the different information systems do not transfer essential data between them. The FM industry utilizes many types of information systems of which many are extremely outdated. Integrating these systems has been challenging, as one CEO said, *"We banged our heads against a wall for two years with information gathering, and you just could not get it done. What happened in the end was that we have eight or nine different software solutions which get information from the cloud, and every software had a closed interface and different file format. Then there are fourteen different automation systems that we cannot* *get into. That is precisely the problem with us that our information is so fragmented."*

Open interfaces of information systems (application programming interfaces, APIs) were also seen to be critical for AR because AR solutions often require real-time information to be shown to the user. Ownership of different information systems in the FM industry is also extremely fragmented. One CEO pondered that *"it will likely be somewhat of a problem, because most of our clients do not own the facility where they operate so they do not have the authority to do that [give access to information]. I think this is a huge question that who gives permissions and how everyone earns with it, I think it's still unsolved. Because there is a lot of data in the facilities, but if they say that these are our systems, you cannot use them, then what can you do?"*

If these challenges are to be overcome, increased and open collaboration was seen to be needed between different companies throughout the whole lifecycle of a facility. A CEO succinctly encapsulated the problem: *"In that sense, it's true that digitalization and AR/VR are now coming through very quickly, but we're such a small company that it's difficult for us to utilize anything like this on our own."*

Many interviewees saw further advancements in building information modeling and indoor location technologies as a necessity for collaborative AR solutions. These technologies are key enablers for context-dependent knowledge transfer, as they are needed to save information to a specific location inside a building. For example, they would make it possible to provide direct access to a facility's maintenance manual in the actual use context. Several interviewees had already seen what these technologies make possible. A CEO remarked, *"I actually have experience with this. You had these glasses on, and then they had already made the information models in the design phase so that when I went into a place I could see the pipes inside the walls. That would, of course, be ideal, but that is a long way off, especially in old buildings."* A chief development officer also remarked that *"this indoor location technology is at least one of the preconditions because it opens up so many possibilities."* Table 2 summarizes the key factors that enable adoption of more comprehensive collaborative AR solutions. These key factors were mentioned frequently by different interviewees.

Table 2: Five key factors that enable adoption of collaborative AR.

Factor	Description	What has to happen
Integrated information systems	The different information systems need to easily provide information for the AR solutions	Companies need to undergo integration projects with their current information systems or change to new ones
Open information systems interfaces (APIs)	AR solutions need open access to real-time information from different information systems	Companies need to open their information to each other in a reciprocal manner
Open cooperation between companies	Companies from different stages of the lifecycle of a facility have to be willing to cooperate more openly	The companies require incentives and demonstrated benefits from cooperation
Building information modeling (BIM)	The use of BIM in construction needs to be adopted more widely	BIM has to become more efficient and intuitive to use; the models also need to be passed on to FM companies for later use
Indoor location technologies	Users' location has to be easily determined indoors to enable context-dependent knowledge transfer	Indoor location technologies need further technical advancements and large-scale ubiquitous adoption

5 DISCUSSION

In this section, we discuss the key findings of this paper. We also present the paper's theoretical implications and discuss the managerial implications for companies about to adopt collaborative AR solutions. Limitations of the study and suggested future research areas are also discussed.

5.1 What Value Can Collaborative AR Bring to the FM Industry?

AR is a cutting-edge technology to which the context of the FM industry brings its own challenges and opportunities. Digitalization efforts have been relatively minor in FM when compared to other industries. Therefore, adopting new digital solutions, such as collaborative AR, has the potential to give companies a competitive edge. Adoption of AR solutions is becoming increasingly relevant even in this conservative industry.

In the light of our first research question, we found that the most important application areas of collaborative AR in the FM industry can be found in the FM industry's operative work and in educating a company's employees. In these use contexts, collaborative AR can provide new methods for enhancing a company's internal business processes.

Based on our findings, the adoption of collaborative AR solutions can be divided into short- and long-term adoption. Relating to our second research question, these solutions can bring added value to FM companies in different ways, which will be explored in the following paragraphs concerning short- and long-term adoption of collaborative AR solutions.

In terms of short-term adoption, companies can enhance their internal business processes in synchronous one-on-one remote collaboration between maintenance workers and managers. The current work methods are extremely prone to errors and misunderstandings as problems on-site can be difficult to explain to others via a phone call. Collaborative remote AR solutions utilize video, audio and digital annotations which makes it much more likely for remote collaboration to succeed.

Because workers in the FM industry have to stay mobile during a typical workday, there is significant potential for new efficiencies through improved remote collaboration. The usefulness of AR in remote collaboration has also been recognized in scientific literature (Billinghurst et al., 2015; Lukosch et al., 2015). Remote collaboration between companies and their customers with the help of AR will likely become more popular in the future as AR solutions become cheaper and more widely used in the consumer market.

A key advantage of remote AR collaboration solutions is that they do not have to be integrated with any of the company's other information systems. This is critical as the integration level of the information systems was at a relatively low level in the companies participating in this study.

Remote AR collaboration solutions can be adopted immediately to replace traditional phone calls in technical communication with little need for tailoring as the solutions are off-the-shelf. The current devices in use were also seen to be largely sufficient for these solutions although companies should pay attention to the capabilities of new smartphones to utilize AR when the companies replace their old devices with new ones.

Smartphones are the most likely devices to be utilized as the current HMDs are still too bulky and expensive. Utilizing the more mobile smartphones is also advantageous because employees do not have to learn how to use new devices and interaction techniques with new devices, such as HMDs. However, companies should pay attention to advancements in HMDs as they have the benefit of leaving both hands free for operative work when compared to smartphones (Bimber and Raskar, 2005).

AR solutions are generally seen to be easy to learn and use (Martínez et al., 2014). This was also confirmed in the pilot tests as the employees saw the AR solution as easy to learn. This is beneficial because of the relatively low level of education and IT skills of employees in the FM industry.

The financial benefits of these remote collaboration solutions start to accrue immediately as employees save time in decreased site visits and fewer misunderstandings and errors in communication. Customer satisfaction is also likely to rise as problems more often get solved with a single visit. At a minimum, the other employee participating in the collaboration is better prepared for the site visit if he or she has already seen the problem visually.

In terms of long-term adoption, the companies stressed the need for better access to context-dependent and location-based knowledge. According to the literature, more comprehensive AR solutions appear to be potentially useful in accessing location-based knowledge (Irizarry et al., 2013; Wang et al., 2013; Chu et al., 2018). These solutions have the potential to provide significant added value in asynchronous collaboration. These solutions have the potential to enhance collaboration in many different aspects. For example, employees can view the hidden structures of a building in co-located collaboration or access and modify location-based knowledge for other employees to access asynchronously in the real use context.

Currently, employees have to manually gather all the information they need from different information sources to complete their work tasks. This requires a lot of work and is prone to errors. Centralizing digital information in fewer systems to be accessed with AR solutions appears potentially beneficial for successful completion of work tasks in FM.

Open APIs are also required from information systems if these solutions are to be implemented. This was seen to be difficult to implement currently although the trend was clearly seen to be toward more open APIs.

Adopting these more comprehensive AR solutions was seen to be challenging currently as there are few off-the-shelf solutions and the needed enabling technologies, such as BIM and indoor location technologies, have not been adopted widely at this time. The indoor context of most tasks of the FM industry is a significant challenge. However, BIM is being adopted ever more widely in construction (Irizarry et al., 2013). Apple, Google and Microsoft, among others, are also investing heavily in indoor location technologies (Pichler, 2017). Thus, the opportunities for more comprehensive AR solutions are likely to increase in the coming years. Therefore, adoption of these solutions should be a long-term focus for FM companies.

A single company in the FM industry does not have sufficient power to advance the spread of these technologies for use in different lifecycle stages of a facility, which, thus, necessitates more open cooperation between the companies for this to be achieved. FM companies are especially reliant on the decisions of construction companies concerning digitalization. The significant heterogeneity of the facilities and the amount of available digital information is also a challenge as this requires the FM companies to utilize different solutions in different facilities depending on their level of digitalization. The fragmented ownership of buildings also requires FM companies to negotiate access to digital information on a case-by-case basis.

5.2 Theoretical Implications

The present study has two main implications for theory. First, the study contributes to research by exploring the concept of collaborative AR in the context of FM. The study clarifies the use of collaborative AR in different application areas in the FM industry. The findings indicate that collaborative AR has the most potential in operative work and in educating a company's employees in the FM industry.

Different characteristics of collaborative AR are also emphasized depending on the industry. According to the present findings, collaborative AR has potential in enabling effective knowledge transfer in synchronous remote and asynchronous local collaboration in the FM industry.

Second, the study identified five key factors that pave the way for comprehensive collaborative AR solutions in the FM industry. These findings extend our understanding of the adoption of AR in the FM industry with collaboration-specific factors.

5.3 Managerial Implications

This study helps FM companies understand how collaborative AR can be used in operative work and what factors they have to take into consideration when adopting collaborative AR solutions. Because of these findings, companies do not have to undergo as much trial and error because they can easily chart which of the enabling factors they already fulfill. This makes it clear what solutions they can adopt immediately and what progress they have to achieve in other areas in order to adopt more comprehensive collaborative AR solutions.

5.4 Limitations and Future Research

The main limitation of this study is that it is based on only a few case organizations. Generalizing these findings to the FM industry as a whole, therefore, should be done cautiously. More longitudinal research should be conducted to explore the specific measurable benefits that can be achieved through adopting collaborative AR solutions in FM companies. The use of collaborative AR should also be researched in other industry settings to gauge whether the findings presented in this paper are applicable in other settings as well.

The willingness and readiness of construction companies for more open cooperation with other companies in the different lifecycle stages of a facility should also be explored. This will likely be a critical factor in adopting more comprehensive AR solutions in the future. Customers' readiness to use new AR solutions also needs further study.

As HMDs become smaller and more powerful, their usage in the highly mobile work tasks of the FM industry should also be studied more thoroughly. Currently, the use of HMDs is largely restricted to design tasks in a limited location.

The use of collaborative AR in the context of the FM industry has not been researched extensively yet. This study addresses that gap and contributes to research in this area. This study can act as a starting point for future research.

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Enabling factors of social virtual reality diffusion in organizations

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Research paper

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Abstract

Social virtual reality (SVR), or multi-user virtual reality, is an emerging technology that enables new ways of collaboration in industrial use. However, relatively little is known about the factors leading to the diffusion of SVR in organizations. This paper examines the diffusion of SVR in the context of architecture, engineering, and construction (AEC). Specifically, this paper identifies enabling factors that moderate the effects that the technological attributes of SVR have on its diffusion. Qualitative empirical data were collected in 12 semi-structured interviews and 14 focus groups with AEC organizations. The data were initially categorized in relation to Rogers' diffusion of innovations (DOI) theory's three most predictive technological antecedent factors of diffusion (relative advantage, compatibility, and complexity) and then iteratively refined based on a qualitative analysis. This study contributes to information systems literature in two ways. First, it identifies eight critical enabling factors that moderate the diffusion effects of the DOI antecedent factors of SVR. Second, propositions are derived concerning the specific effects these moderators have on the relationship between the DOI antecedents and SVR diffusion. As a practical contribution, organizations can better support SVR adoption efforts by evaluating the importance of these identified moderators in their organizational contexts.

Keywords: Virtual Reality, Social Virtual Reality, Adoption, Diffusion.

1 Introduction

Organizational use of virtual reality (VR) began in the 1990s when the first viable VR devices were introduced (Walsh and Pawlowski, 2002; Berg and Vance, 2017). However, the diffusion of VR—that is, the *collection of adoptions by individual users* (Straub, 2009)—was limited due to the low technological maturity and high costs of VR hardware and software (Hilfert and König, 2016; Mütterlein and Hess, 2017). After these initial attempts, VR was largely forgotten by industry for over a decade (Mütterlein and Hess, 2017). However, VR has recently experienced rapid development as prominent companies (e.g., Facebook and HTC) have started investing heavily in VR hardware and platforms (Kugler, 2017). These developments have now laid the groundwork for cross-sectional and extensive VR diffusion. Currently, the VR market is expected to grow significantly. For example, Digi-Capital (2019) predicts that the VR market will grow from approximately $3 billion in 2018 to $10–15 billion by 2023. VR is used in multiple industries, such as architecture, engineering, and construction (AEC; Whyte, 2003; Wang et al., 2018) and product design and manufacturing (Berg and Vance, 2017). These advancements warrant a fresh look into VR diffusion, since many organizations are now seriously considering adopting VR to support their work processes (Berg and Vance, 2017).

In VR, the user is effectively immersed in a completely synthetic and responsive virtual environment (Brooks, 1999; Bastug et al., 2017). In the past, VR use has mainly been considered to be an isolating experience, as most solutions were designed for single users (Kim et al., 2013). However, new multi-user VR solutions, which are referred to here as *Social Virtual Reality* (SVR), have now begun to emerge (Perry, 2015; Marr, 2019). In SVR, multiple users can interact with each other simultaneously in the same virtual space via avatars (Perry, 2015). Enhancement of professional collaboration has been identified as one of the more promising applications of SVR (Mütterlein and Hess, 2017). In the AEC industry, for example, SVR can enable more efficient collaboration between end-users and designers through better shared spatial understanding of proposed building design plans (Portman et al., 2015; Paes et al., 2017). Overall, practitioners and researchers have identified numerous value-adding use cases for SVR as richer collaboration is becoming increasingly possible within the virtual environment (Perry, 2015). Thus, SVR has the potential to increase organizational performance by improving collaboration between different stakeholders in industry value chains and by enabling efficient collaboration in situations in which physical meetings are not possible. However, wide diffusion of SVR is necessary if it is to create value for organizations, as business processes cannot be extensively adapted to utilize SVR with a limited number of users.

Much of the earlier VR research has focused on the technological development of VR systems and on single-user rather than multi-user VR systems (Walsh and Pawlowski, 2002; Kim et al., 2013). Although some research on VR adoption in industry has been carried out (e.g., Fernandes et al., 2006; Berg and Vance, 2017), there is still relatively scant research on the factors affecting the diffusion of SVR in organizations. In single-user VR, the user typically enters the virtual space alone to engage in specific work tasks (e.g., reviewing building designs). However, the focal technology of SVR is different, as SVR essentially involves multiple users collaborating in a shared virtual space wherein they share knowledge and create shared understandings with each other along the key business processes of an organization. This means not only that organizations have transferred and adapted business processes to SVR but also that multiple users can handle their collaborative efforts in that same space. Due to this technology use environment, SVR diffusion is likely influenced by factors other than those that influence single-user VR environments. Therefore, prior findings relating to VR adoption (e.g., Fernandes et al., 2006; Berg and Vance, 2017) are only partially applicable to SVR. Accordingly, identifying specific enabling factors that help SVR to reach a critical mass of users is imperative for effective SVR adoption in organizations. The present study focuses on this research gap by addressing the following research question: *Which factors enable effective diffusion of SVR in organizations?*

The present study draws on Rogers' (2003) diffusion of innovations (DOI) theory and focuses on its three most critical technological antecedent factors affecting diffusion: relative advantage, compatibility, and complexity (Tornatzky and Klein, 1982; Vagnani and Volpe, 2017). Although the DOI theory and the aforementioned antecedents have been found to be helpful in explaining the diffusion of various technologies (e.g., e-business) in organizations (Vagnani and Volpe, 2017), the applicability of DOI has also been criticized in the literature in the context of complex technologies that connect multiple users and information systems within organizational business processes due to its lack of suitable factors for addressing collective adoptions (Lyytinen and Damsgaard, 2001). Given that organizational SVR adoption fits this characterization, we aim to address the aforementioned criticism by enriching DOI with specific enabling factors that make SVR diffusion more effective in organizations.

The enabling factors of SVR diffusion were identified in a qualitative multiple-case study (Yin, 2009). Empirical data were collected through 12 semi-structured interviews and 14 focus groups in the AEC industry context. The data were then analyzed qualitatively in an iterative manner (Walsham, 1995). We propose the identified enabling factors as moderators for the relationships between the DOI antecedent factors and SVR diffusion in organizations, and we derive propositions on the effects of these moderators. We chose the AEC industry as the context of the study for three key reasons. First, the AEC industry has shown an increasing interest in SVR (Du et al., 2018). Second, a variety of multi-user SVR solutions (e.g., IrisVR and InsiteVR) are available for AEC, demonstrating the applicability of SVR within this industry context. Third and foremost, SVR is perceived to have great potential to solve communication difficulties between the highly fragmented AEC stakeholder groups by enabling efficient collaboration around 3D content in a 3D environment (Dubois and Gadde, 2002; Goulding et al., 2014; Du et al., 2018). Our study contributes to information systems (IS) literature by enriching the DOI theory in the AEC context with eight critical moderators for the relationships between the DOI technological antecedent factors and SVR diffusion. We further contribute to IS literature by deriving propositions on the effects of these moderators. As a practical contribution, organizations can use these findings to evaluate their readiness to adopt SVR and support their SVR adoption efforts.

This paper is structured as follows. First, the relevant theoretical background concerning SVR and DOI is presented in Section 2. Second, the methodology of the study is described in Section 3. Third, the findings of the study are presented in Section 4. Finally, the findings, propositions, contributions, and limitations of the study are discussed in Section 5 along with suggestions for future research.

2 Social Virtual Reality and Diffusion of Innovations

VR can be categorized into immersive VR, which can be experienced with special equipment such as head-mounted displays (HMDs) and cave automatic virtual environments (CAVEs), and non-immersive VR, which is experienced through 2D desktop interfaces (Brooks, 1999; Slater and Sanchez-Vives, 2016; Paes et al., 2017). In the present study, we focus on VR that utilizes HMDs to achieve a truly immersive VR experience, since this type of VR has been the central focus of the most recent VR developments. HMDs can be separated into three categories: mobile VR, stand-alone VR, and tethered VR (Anthes et al., 2016; Elbamby et al., 2018). Mobile VR refers to VR devices in which a smartphone is used as the display by plugging it into a VR HMD (Anthes et al., 2016). However, as some of the most prominent mobile VR devices are being discontinued (Protalinski, 2019), their relevance for organizations is decreasing. Stand-alone VR devices are also wireless, but they come with their own dedicated displays and processing power (Elbamby et al., 2018). Tethered VR devices are connected to and powered by an external laptop or personal computer (PC), enabling high-end VR experiences (Perry, 2015). Tethered VR HMDs are still required for many use cases since current wireless technologies are not sufficient for more demanding VR experiences. However, future 5G networks may partially help to solve this problem (Bastug et al., 2017).

Besides the technical improvements in VR devices (Kugler, 2017), the multi-user (or social) aspects of VR have also advanced significantly (Perry, 2015). SVR allows users in different locations to communicate in a virtual space via customizable virtual avatars as if they were face-to-face and manipulate virtual objects together (Bailenson et al., 2006; Perry, 2015; Bastug et al., 2017). SVR can help geographically distributed teams to work more efficiently and reduce unnecessary travel (Walsh and Pawlowski, 2002; Perry, 2015). The immersive nature of SVR can also increase organizational efficiency by helping stakeholders achieve mutual understanding in collaborative situations (Du et al., 2018).

Organizational use of SVR has great potential (Perry, 2015), but extant research on VR adoption is limited (e.g., Fernandes et al., 2006; Berg and Vance, 2017). Initial findings have stressed the importance of demonstrating the business value of VR to end-users (Berg and Vance, 2017). The importance of a champion for VR adoption has also been found to be crucial (Berg and Vance, 2017). Fernandes et al. (2006) emphasized the importance of securing top management support and clearly defining the objectives of VR adoption. Lack of vision and lack of clear measurable benefits of VR adoption have also been identified as obstacles for adoption (Suneson, 2014). Further, the lack of a dominant design for VR devices can slow down VR adoption (Whyte, 2003). This problem still exists, as can be seen with regard to the heterogeneous VR HMDs that are currently available. Motion sickness is still also an issue with VR HMDs, and women have been found to be more susceptible to it than men (Sharples et al., 2008; Munafo et al., 2017). The level of social interactions in SVR has been found to promote user enjoyment and positively influence users' intention to use SVR (Lee et al., 2019). However, relatively little is known about factors affecting SVR diffusion in organizations.

Diffusion is defined as a "process by which an innovation is communicated through certain channels over time among the members of a social system" (Rogers, 2003, p. 35). Rogers' DOI theory can be used to study diffusion by examining the attributes of the technology itself, the communication channels by which the technology is spread among individuals, time (the rate of adoption), and the social system in which the technology is adopted (Rogers, 2003). Utilizing DOI to study how the technological attributes of SVR affect its diffusion has also been suggested in the literature (Fernandes et al., 2006). Since the utility of SVR depends on the number of users interacting with each other in the virtual space, it is important to reach a critical mass of users as quickly as possible in order to increase the value of SVR (Rogers, 2003). Although certain solutions (e.g., tethered HMDs) might provide more value for individual SVR users, the likelihood of their extensive diffusion in organizational settings over a long period is low, as they require a high level of technical competence. Thus, with regard to SVR use, organizations need to compromise between high task-specific performance, fit for individual users, and overall ease of use for end-users. Moreover, even if the decision to adopt SVR is ultimately made by management, the need to identify the needs of the collective in the organization is crucial because authority-based decisions do not guarantee successful adoption (Rogers, 2003).

According to the DOI theory, a technology's perceived attributes—relative advantage, compatibility, trialability, and observability—positively affect its diffusion, whereas the complexity of a technology is negatively associated with its diffusion (Rogers, 2003). Meta-analyses by Tornatzky and Klein (1982) and Vagnani and Volpe (2017) showed that relative advantage, compatibility, and complexity are the most critical antecedent factors in predicting a technology's diffusion in organizations. Although prior research has not specifically focused on the technological antecedents of diffusion of SVR, it is possible to identify the three key antecedents from existing literature. Relative advantage refers to the degree to which an innovation is perceived as better than earlier innovations (Rogers, 2003). The relative advantage of SVR can be seen in its more efficient means of knowledge transfer in comparison to existing solutions (e.g., video conferencing; Du et al., 2018). Compatibility relates to the degree to which an innovation is consistent with the values, experiences, and needs of its adopters (Rogers, 2003). Difficulties in transferring different design software file formats into SVR have posed integration issues with business processes in the AEC industry (Du et al., 2018). However, the increasingly prevalent use of building information modeling (BIM) has alleviated this problem (Miettinen and Paavola, 2014). Complexity refers to the perceived difficulty of understanding and using an innovation (Rogers, 2003). SVR can have high initial complexity due to its high immersion potential and novel interaction methods in comparison to traditional information technology (IT) devices (Mütterlein and Hess, 2017). Although particular antecedent factors of SVR diffusion can be identified in the literature, the specific factors that enable the effective diffusion of SVR remain missing. Our study aims to identify such factors in relation to the aforementioned DOI antecedents and thus address the limitations of DOI in explaining the diffusion of complex technologies such as SVR in organizations (Lyytinen and Damsgaard, 2001).

3 Methodology

This study was conducted as a qualitative multiple-case study (Yin, 2009). Case studies provide rich descriptions of phenomena in the specific context of inquiry and are therefore suitable for the exploration of new research areas of which little is known (Benbasat et al., 1987; Eisenhardt and Graebner, 2007). In addition, with multiple cases, it is possible to compare different findings and determine whether an emergent theme applies to a single case or to many cases (Eisenhardt and Graebner, 2007). Qualitative empirical data were collected from 20 case organizations in Finland (11 small and medium-sized organizations with under 250 employees and 9 large organizations with over 250 employees) by five researchers through 12 semi-structured interviews and 14 focus groups in three publicly and privately funded national VR research projects between 2017 and 2019. Purposeful sampling was used to gather rich data with relevance to our research (Patton, 2002). Interview participants were chosen from organizations that were already using SVR to some degree (9 organizations) or were in the process of exploring and adopting SVR to support their work processes (11 organizations). Gathering insights from organizations that had experience with SVR allowed us to obtain a thorough, accurate overview of issues related to SVR diffusion in the AEC industry.

The interviews and focus groups explored the perceptions and experiences of the interviewees in relation to SVR diffusion. The interviewees represented both public and private organizations and consisted of executive and management-level personnel, experts (e.g., construction engineers), and other employees (e.g., operative personnel) engaged in work in which SVR played an important part. The interviewees had varying levels of experience with SVR. In the semi-structured interviews, 42% of the interviewees were in senior management positions, 42% were in middle management, and 16% were experts. The focus groups included 49 participants in total, of which 33% were in senior management, 22% were in middle management, 30% were experts, and 15% were other employees. The focus groups also included pilot tests of both custom-developed and commercial multi-user VR products (e.g., InsiteVR) with different VR devices (e.g., Oculus Go). Observation notes on user behavior were taken in these test situations. Data were collected until we believed a point of saturation was reached.

The interviews and focus groups were conducted in Finnish, lasted from 30 to 90 minutes, and were audio-recorded with the consent of the interviewees. The relevant parts of the audio-recorded interviews and focus groups were transcribed for analysis. Although the data were primarily analyzed by one researcher, we also utilized investigator triangulation by exchanging detailed notes concerning the findings and interpretations for comparison between researchers (Patton, 2002). We drew on the DOI theory and categorized the data in relation to its three most critical technological antecedent factors. Once the data were grouped in relation to these initial categories, smaller pieces of data were given labels, which were then compared for overlap and redundancy and finally combined under higher-level labels (Creswell, 2015). Observation notes were used for confirming and disconfirming evidence from the interview data (e.g., interviewees' statements regarding their experience with VR were contrasted with their behavior in the VR testing situations). This process was iterated as new data was collected (Walsham, 1995). Specific moderators that strengthened or mitigated the effects of the DOI antecedent factors emerged as the final labels. Propositions about SVR diffusion were then derived from these moderators. Interview data from multiple case studies is considered to be suitable for generating theoretical propositions since the data is grounded in varied empirical evidence (Eisenhardt and Graebner, 2007). Altogether, eight moderators and propositions were derived from the data.

4 Findings: Eight critical moderators affecting SVR diffusion

In this section, we introduce the specific enabling factors that align with the three antecedent factors of SVR diffusion. These enabling factors are presented as moderators that affect the relationship between the DOI antecedents (relative advantage, compatibility, and complexity) and SVR diffusion. We base the DOI antecedents on the prior literature as follows: SVR's key relative advantage is *efficient knowledge transfer*, SVR's compatibility is *ease of business process integration,* and SVR's complexity is *perceived technology utilization difficulty*.

4.1 Collaboration intensity variables moderating relative advantage

Collaboration intensity refers to variables that depict the types of collaborative work activities in which the potential for multifold, active application of the opportunities provided by SVR are higher, thus strengthening the effect of SVR's key relative advantage (i.e., efficient knowledge transfer) on SVR diffusion. We identified two specific collaboration intensity moderators, namely collaboration around complex visual information and geographically distributed teamwork.

Collaboration around complex visual information. Most interviewees estimated the main relative advantage of SVR to come from the users' ability to comprehend the dimensions of 3D content and objects better than with 2D desktops, which can lead to more breakthrough moments. Consequently, SVR was seen to enable more effective reviewing of proposed building designs. This was considered to be especially relevant for non-professionals, who have difficulties comprehending 2D plans, but collaboration between different professionals could also be improved by SVR because many stakeholder groups (e.g., public officials) also need to give their input on design plans. Comparing different design options was also thought to be quicker and more effective with SVR than with physical models. Communicating design plans to stakeholders with SVR was thought to facilitate a better understanding of what was being delivered. Involving users in the early phases of the design process was seen as one of the most interesting areas for SVR use since this would enable different end-user needs to be taken into account more accurately. In one hospital case, for example, the architects were able to reduce the size of the rooms after the nurses had seen the design model in SVR and told the designers that the room dimensions were too large for their intended use.

"...when we send the floor plan as a PDF, relatively few truly comprehend how the space works even if they are experts in their own profession, when instead we could tell them to put on these glasses and tell them to wander around [the model] and think about how their process would work in the space... It's easier to think about how I would act and what I would need [in the space] in VR." [Architect]

Many interviewees considered the user experience to be much more intense in SVR than with 2D desktops, and some said that the designers often do not even have to ask questions from the users as they usually start giving feedback on their own initiative. Some interviewees thought that SVR would also make it easier to make observations about the needs of users, especially ones who are unable to explain their design improvements in an abstract form, since in SVR the designer can go through the review asynchronously from the user's point of view. However, SVR was not regarded as a panacea, as exemplified by one interviewee noting that *"Co-design is tricky, whether it's virtual or not"* [Architect/BIM Consultant]. Still, most interviewees thought that the more the organization's work tasks include collaboration around visual information, the more SVR could be utilized in the organization.

Geographically distributed teamwork. Many interviewees said that SVR enables a more natural way of communicating that is superior to other technologies, such as videoconferencing, giving it a relative advantage when compared to many existing solutions. The feeling of presence provided by SVR was seen by many as an advantage when compared to other existing solutions, as it is not as easy to get distracted with other work in SVR. Accordingly, the more remote teamwork is being performed in an organization, the more SVR could be utilized to enhance collaboration. Many interviewees considered SVR to be highly interesting for internal design coordination because designers and engineers currently spend a lot of time traveling. With SVR, it would be possible to hold regular and ad-hoc meetings more often because it usually takes a whole workday to attend a meeting at a separate physical location. This would increase the iterations that can be carried out in the design process. As building designs are becoming more complicated, bringing different design experts from different locations into SVR was seen as a way to increase quality, and save time and money.

"This makes it possible that when someone gets an eureka moment, he can then call a couple of designers and tell them to put the glasses on to check out the idea. This can be done live anytime problems or solutions arise, and the issues can be processed instantly." [Architect]

For social interaction, some interviewees thought that utilizing even basic VR HMDs, where the user's head and hands are tracked, could create sufficient social cues for interaction, although they believed that bringing facial expressions into SVR would further improve collaboration because it would allow users to gauge the interest of the different participants more efficiently. Some interviewees also noted that participating more anonymously in SVR with avatars could also make it easier to generate ideas when compared to videoconferencing or CAVEs, where the interaction is more formal.

4.2 SVR-technical infrastructure fit variables moderating compatibility

SVR-technical infrastructure fit refers to variables that depict the extent to which the current technical infrastructure can be integrated with SVR, thus strengthening the effect of SVR's compatibility (i.e., ease of business process integration) on SVR diffusion. We identified two specific SVR-technical infrastructure fit moderators, namely intra- and interorganizational IS integration and multi-device participation in SVR space.

Intra- and interorganizational IS integration. Some interviewees considered it to be difficult for small organizations to utilize SVR on their own, and many considered finding partner organizations with the readiness and willingness to use SVR to be a challenge. Different file formats and constantly changing industry partners were seen to pose compatibility issues in integrating SVR into work processes. Many interviewees thought that the possibilities for using SVR would increase tremendously if data were made to flow more efficiently in the AEC industry value chain. The interoperability of information systems was identified as a critical challenge. Many also stressed that the process of generating the VR model from design software would need to be as streamlined as possible. Currently, the visual models and the information that is attached to them do not transfer between programs easily in most organizations. Furthermore, organizations often use mutually incompatible design software, which forces them to create the models again at different building lifecycle phases.

"In order to create VR, you have to have some data points that will be part of VR, and those data points are quite often lost, or there is no data. We can start taking this [SVR] further with new buildings, but it's difficult to get to many of the data layers, especially in our industry." [CDO]

While many interviewees saw the need for BIM as self-evident at this point, they acknowledged that the knowledge management issues associated with BIM were a significant challenge. Many organizations currently employ BIM coordinators, who have to actively police users in order to keep relevant information up to date. Integration of native information models and the related design tools is also a problem, and many interviewees wondered whether it is possible to add their own design tools to the virtual space. Moreover, many software vendors have only recently started offering their design tools for SVR. This was seen to be critical if real interactive professional work is to be done in SVR. Recent developments were also seen to increase the level of interaction in SVR between users and the digital content. Currently, feedback is often collected by sending stakeholders PDFs and asking them to comment on them by email. Collecting user feedback directly to the virtual model rather than with traditional methods (e.g., post-it notes and email) was seen as an interesting possibility to collect more specific user feedback. This was also seen as a way to eliminate unnecessary documentation work.

Multi-device participation in SVR space. Many interviewees said it was not feasible to get every user to utilize a VR HMD to access the SVR space due to their limited availability and because of user reluctance. Appreciating the IT preferences of the users was seen as a key success factor for SVR diffusion and having the possibility to participate in SVR collaboration with multiple different devices was seen to moderate its compatibility with users. Many interviewees mentioned that motion sickness was still a significant barrier and holding meetings only with VR HMDs was not considered to be possible if some of the users start to feel unwell. Thus, many interviewees stressed that there must be multiple ways for users to participate in viewing the digital content in SVR.

"Is VR compatible with everyone? Not necessarily, that's the thing. You have to be able to join [the SVR space] with many different devices." [BIM/VDC Manager]

The interviewees also indicated that the current lack of a dominant design for VR HMDs highlights the importance of multi-device participation in SVR. Many interviewees stressed that organizations should be able to upgrade their VR HMDs without significant compatibility issues with SVR solutions as many organizations were currently evaluating which of the currently available VR HMDs were the best fit for their organizations. In this regard, the newer stand-alone VR HMDs were seen to bring new possibilities because they are already adequate for many tasks, such as for demonstrations for end-users and for basic design work. More advanced tethered VR HMDs were seen to be suitable for intense visualizations and for presenting designs for executive-level personnel.

4.3 Mitigating action variables moderating complexity

Mitigating actions refer to variables that depict measures that organizations can take to dampen the negative effect of SVR's complexity (i.e., perceived technology utilization difficulty) and thus increase SVR diffusion. We identified four specific mitigating action moderators, namely utilizing younger and more innovative users as lead users, testing SVR simultaneously with multiple users, aligning stand-alone VR HMDs for suitable work tasks, and increasing organizational competence with 3D models.

Utilizing younger and more innovative users as lead users. Most interviewees described the AEC industry as conservative and not very innovative. This was seen as an important factor that could slow down the diffusion of SVR. Many interviewees explained that only the most innovative users usually participate in SVR design sessions, and most design meetings are still held in a physical office. However, some interviewees predicted that the coming generational change in the industry would bring more openness to new solutions. One interviewee explained that younger managers and clients have shown increasing interest in new innovations, whereas the older cohorts are very conservative.

"Why we are interested in this is because of the coming generational change, younger folks are starting to take the reins and are more open towards these things." [CEO]

In many AEC organizations, the age demographics are quite old, and it often takes a while for many of the users to learn the basics of VR hardware and software. One interviewee highlighted the fact that only a few of the employees and clients have used a VR HMD for more than 15 minutes. Organizations also have limited opportunities to test VR hardware. However, in the test situations, most users found VR to be quite easy to learn and to use, and one architect even started explaining in detail about the coming installation work in the explored SVR space. Still, it was evident that only a few of the testers used VR daily, and none of them were immediately comfortable and efficient with VR use, indicating that they have also had little chance to use VR devices in non-professional contexts.

Testing SVR simultaneously with multiple users. In situations in which SVR could be tested, many of the participants expressed considerable hesitation about trying it out due to the perceived initial complexity of SVR. Furthermore, a problem that was identified in the test situations was that the other participants in the room could not see and hear what was going on in SVR, and hence the test user was isolated from others and could not be efficiently instructed in SVR use. Due to SVR use being highly observable in the physical setting, potential user embarrassment was also seen to be a barrier for adoption, especially if there is only one VR HMD for the group to test. Thus, when testing and learning how to use SVR, multiple users need to do it simultaneously to not put undue focus and pressure on a single tester. This also enables the users to assist each other in the use of SVR.

"...the social aspect has been a bottleneck earlier when I have been demoing the [VR] glasses. I can almost say that they have actually made communication worse because the social aspect has not been implemented in them. So, when someone puts on the glasses, I ask them what they see. Well, they say they got lost, they are in some kind of space. Then, I ask them what kind of space, and finally I just take the glasses from them and take them to the right place." [BIM/VDC Manager]

Some interviewees explained that they had experienced extremely positive or negative reactions to SVR in their work, which had affected other users' inclination to try it out. However, when SVR was actually tried in a test situation, every tester thought it was very simple to use. Many interviewees believed that users might be more eager to test SVR if others were doing it with them simultaneously.

Aligning stand-alone VR HMDs for suitable work tasks. Most interviewees stressed that the chosen VR HMDs need to work smoothly so that the user's attention can be focused on the actual content and on collaboration. They believed that this would reduce the negative effect that the complexity of SVR has on its diffusion in organizations. Stand-alone VR HMDs were considered to be easier to use than tethered devices since the updates are handled in a centralized manner by the VR HMD provider. In contrast, there are still very few complete end-to-end solutions available for tethered VR HMDs, which necessitates a certain level of technical expertise in handling VR hardware and SVR software. In one company, VR had been tried previously, but the tethered VR HMDs had been sitting on a storage shelf for the last two years due to multiple problems with the graphic cards and constant software updates, which made it difficult to use them daily with different stakeholder groups in a quick and efficient manner. Many interviewees saw the performance level of stand-alone VR HMDs as a critical issue because it limits what kind of digital content can be examined in SVR, and that tethered VR devices were still required for many of the more advanced SVR use cases.

"...those [tethered VR HMD] are more suitable for demonstration use, whereas these [stand-alone VR HMD] are starting to be sufficient for design work, architects and structural designers for example can fill in the blanks with their imagination..." [Architect]

However, since SVR is still new to most people, using SVR requires considerable facilitation. Many interviewees thought it required too much work and know-how to maintain tethered VR HMDs, whereas stand-alone VR HMDs could be adopted with relatively little effort since they do not have any external cables and beacons. Furthermore, the lack of available training in SVR use made stand-alone VR HMDs a more attractive choice for many interviewees.

Increasing organizational competence with 3D models. Large-scale adoption of BIM was considered to be a necessity for SVR adoption in the AEC industry. If model-based work becomes the standard, many interviewees thought that SVR use would follow quite naturally since this would reduce the complexity that users face in preparing the digital content for SVR. Many interviewees reported that relatively few organizations have adequate competence to set up and use SVR and its related technologies completely independently, and thus must use consultants to create and set up the 3D models. However, some of the organizations were already quite sophisticated with 3D models and SVR.

> *"Because all of our work is model-based, we can now make VR models from the design models very quickly. It [SVR] can easily be adopted as part of the design process because there is no one-week intermediate phase where the VR model is prepared, it can now be made in an hour and it's ready for viewing [in SVR]."* [BIM/VDC Manager]

In some of the interviewed organizations, there were only a few PCs capable of smooth BIM and SVR use. The used 3D models in the AEC industry are often quite complicated, and therefore a powerful PC and a tethered VR HMD are often required to view them without performance issues. However, some interviewees noted that automatic model optimization was now helping to mitigate this issue. Currently, much of the content is also modeled on a case-by-case basis, which is expensive, and model reuse was still not as common as many thought it should be. In order to increase the utilization of 3D models, many interviewees also considered their gamification and interactivity to be crucial.

5 Discussion

In order to answer our research question, "*Which factors enable effective diffusion of SVR in organizations?"* we carried out a qualitative multiple-case study and identified eight critical factors that moderate the diffusion effects of SVR's relative advantage, compatibility, and complexity. These moderators and their effects are presented in Figure 1. Although these moderators may have multiple effects, we only included the main, or most effective, influences of the moderators in our model. The identified moderators for relative advantage and compatibility promote their positive effects on diffusion, whereas the identified moderators for complexity mitigate its negative effect on diffusion.

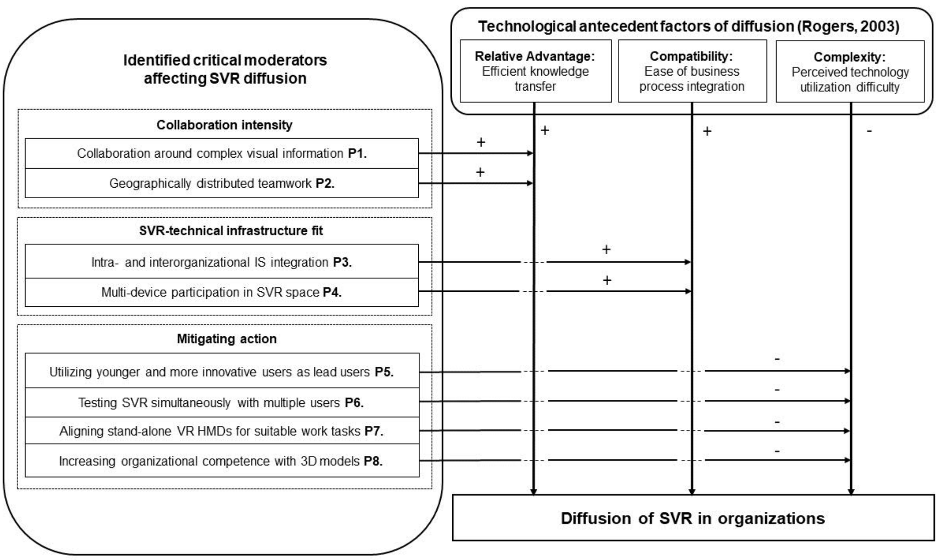

Figure 1. Eight critical moderators affecting the diffusion effects of SVR's relative advantage, compatibility, and complexity (Rogers, 2003).

Next, we examine the influences of the moderators on the relationships between the DOI antecedent factors and SVR diffusion. Based on this, eight propositions are derived and discussed.

5.1 Propositions on the effects of the moderators on SVR diffusion

The relative advantage of a technology is a positive factor in its diffusion (Tornatzky and Klein, 1982). We focus on the relative advantage of SVR in relation to its efficient knowledge transfer (Du et al., 2018). In the context of SVR diffusion, we identified two collaboration intensity variables that moderate the positive effect of this relative advantage: collaboration around complex visual information and geographically distributed teamwork. Since SVR is a highly visual technology, SVR diffusion in organizations will increase as more of its beneficial attributes, such as better spatial understanding of 3D models (Paes et al., 2017), are used in work tasks. We thus derive the following proposition.

Proposition 1: *Collaboration around complex visual information moderates the relationship between efficient knowledge transfer and SVR diffusion such that, as the level of collaboration around complex visual information increases, the positive effect of efficient knowledge transfer on SVR diffusion in the organization becomes stronger.*

In highly geographically distributed industries, such as AEC, SVR was seen to make it possible to hold meetings more often and perform more iterations on designs, thus creating value and time savings (Slater and Sanchez-Vives, 2016). The social interaction in SVR was also thought to be more natural than with video conferencing, making collaboration more efficient (Kugler, 2017). The findings indicated that many organizations aimed to reduce the number of physical meetings to create efficiencies and that SVR was seen as a potential solution in this regard. Thus, we offer the following proposition.

Proposition 2: G*eographically distributed teamwork moderates the relationship between efficient knowledge transfer and SVR diffusion such that, as the level of geographically distributed teamwork in the organization increases, the positive effect of efficient knowledge transfer on SVR diffusion in the organization becomes stronger.*

The compatibility of a technology has a positive effect on its diffusion (Tornatzky and Klein, 1982). We focus on the compatibility of SVR in relation to the ease of business process integration (Du et al., 2018). We identified two SVR-technical infrastructure fit variables that moderate compatibility's positive effect on SVR diffusion. First, compatibility was found to be moderated by the easy availability of digital content since handling and collaborating around visual content is crucial in enabling the use of SVR (Whyte, 2003). Furthermore, augmenting visual content with additional information sources would support decision-making and make collaboration more efficient in SVR. However, in the AEC industry, interorganizational IS integration between companies is at an even lower level than intraorganizational IS integration due to the fragmented nature of the industry (Gann and Salter, 2000; Dubois and Gadde, 2002). Organizations can therefore initially adopt SVR internally in a more limited fashion to improve internal processes and collaboration. However, interorganizational SVR collaboration was seen to emerge more slowly since different IS's would first need to be highly integrated to provide easy access to digital content. The following proposition is drawn from these findings.

Proposition 3: *Intra- and interorganizational IS integration moderates the relationship between ease of business process integration and SVR diffusion such that, as integration of different IS's both within the organization and between its partners increases, the positive effect of ease of business process integration on SVR diffusion in the organization becomes stronger.*

Second, making it possible to participate in collaboration in SVR with devices other than VR HMDs (e.g., laptops) was found to promote the positive effect of compatibility on SVR diffusion. The present findings indicated that users have different preferences regarding the use of VR devices, and many users still reported experiencing motion sickness with VR. The prevalence of these symptoms varies significantly between individuals (Sharples et al., 2008), and recent estimates have suggested that 25–40% of users experience some degree of motion sickness when using VR (Samit, 2017). This has significant implications for collaboration, as it can completely deter any collaborative SVR use with relevant stakeholders if some of them cannot use SVR because of these symptoms. Thus, SVR diffusion in an organization should increase as it becomes easier for users to participate in SVR collaboration with devices of their choice. Consequently, we derive the following proposition.

Proposition 4: *Multi-device participation in SVR space moderates the relationship between ease of business process integration and SVR diffusion such that, as the possibility for users to participate in SVR space with devices of their choice increases, the positive effect of ease of business process integration on SVR diffusion in the organization becomes stronger.*

The complexity of a technology is negatively associated with its diffusion (Vagnani and Volpe, 2017). We focus on the complexity of SVR in relation to its perceived technology utilization difficulty (Mütterlein and Hess, 2017). We identified four mitigating action variables that moderate the relationship between complexity and SVR diffusion. First, the present findings indicate that the coming generational change in the AEC industry should accelerate the diffusion of SVR since younger users were found to be more open to adopting SVR. The younger generation's experiences with video games and hedonic SVR use might also increase their capabilities in technical and creative SVR use (Portman et al., 2015). Furthermore, the current lack of available training for SVR exacerbates these factors since users have to engage in considerable self-learning to utilize SVR. However, gaining these skills also enables these users to act as champions of SVR in their organizations (Fernandes et al., 2006) and to provide effective peer support in the actual job context (Sykes, 2015). Since younger and more innovative users were not found to perceive the complexity of SVR to be as high as it was perceived by many other stakeholders, the negative effect of complexity could be diminished by utilizing these stakeholders as lead users in SVR adoption. Consequently, our fifth proposition is as follows.

Proposition 5: *Utilizing younger and more innovative users as lead users moderates the relationship between perceived technology utilization difficulty and SVR diffusion such that, as the utilization of these stakeholders as lead users increases, the negative effect of perceived technology utilization difficulty on SVR diffusion in the organization becomes weaker.*

Second, the perceived initial complexity of SVR was mitigated by simultaneous multi-user testing. The present findings revealed that most users learned how to use SVR very quickly despite their initial reservations, which helped them overcome their initial reluctance to use SVR. This is crucial to overcoming this initial barrier since the importance of trialability vanishes after an innovation is already in use (Karahanna et al., 1999). Multiple VR HMDs should thus be made available in the initial testing of SVR so as not to isolate a single user from other users. This would also allow users to more effectively perceive the multi-user nature of SVR and observe the benefits of SVR directly. Mütterlein and Hess (2017) also found that having only one VR HMD in a test situation could isolate a user from the group and distract the user from the VR experience. Thus, the sixth proposition is as follows.

Proposition 6: *Testing SVR simultaneously with multiple users moderates the relationship between perceived technology utilization difficulty and SVR diffusion such that, as the level of simultaneous multi-user testing of SVR increases, the negative effect of perceived technology utilization difficulty on SVR diffusion in the organization becomes weaker.*

Third, the present findings indicated that stand-alone VR HMDs possess the greatest potential for large-scale diffusion in organizations due to their better form factor and ease of use in comparison to tethered or mobile VR HMDs. For SVR to diffuse in industry, organizations need to find as many use cases as possible for SVR throughout the industry value chain to motivate users and organizations to overcome its initial complexity. Thus, organizations need to align stand-alone VR HMDs with work tasks in which their performance is sufficient to carry out the work activities. Berg and Vance (2017) also stressed the importance of the portability of VR devices for their large-scale adoption. Furthermore, as the most popular mobile VR devices are being discontinued (Protalinski, 2019), stand-alone and tethered VR HMDs will become the most important options available for organizations. Even though stand-alone VR HMDs will be essential for large-scale diffusion, tethered VR HMDs will still be required for certain demanding high-end tasks. This conclusion leads us to the seventh proposition.

Proposition 7: *Aligning stand-alone VR HMDs for suitable work tasks moderates the relationship between perceived technology utilization difficulty and SVR diffusion such that, as the alignment of* *stand-alone VR HMDs for suitable work tasks increases, the negative effect of perceived technology utilization difficulty on SVR diffusion in the organization becomes weaker.*

Fourth, increasing organizational competence with 3D models was seen to reduce the negative effect of complexity on SVR diffusion by making SVR content preparation easier. BIM and other digital solutions are increasingly being adopted in AEC to support design processes (Bryde et al., 2013). The task of converting design models between different design software and file formats has posed significant problems in the past (Suneson, 2014). However, the findings indicated that considerable progress has occurred in the automation of these steps. Moreover, a variety of SVR software dedicated specifically to the needs of the AEC industry have recently become available, making it easier for organizations to gain sufficient competence in handling 3D models. This has strengthened the foundation on which SVR can begin to diffuse in the AEC industry. Thus, our eighth proposition is as follows.

Proposition 8: *Increasing organizational competence with 3D models moderates the relationship between perceived technology utilization difficulty and SVR diffusion such that, as organizational competence with 3D models increases, the negative effect of perceived technology utilization difficulty on SVR diffusion in the organization becomes weaker.*

5.2 Theoretical and practical contributions

Our study makes two contributions to theory. First, this study contributes to the nascent literature on SVR adoption by enriching DOI with eight critical moderators of SVR diffusion in the AEC context. Drawing from Rogers' (2003) DOI theory and its following meta-analytical examinations (Tornatzky and Klein, 1982; Vagnani and Volpe, 2017), we focused our findings on the three most critical technological antecedent factors of diffusion: relative advantage, compatibility, and complexity, which we conceptualized for SVR with the help of prior literature as efficient knowledge transfer (relative advantage; Du et al., 2018), ease of business process integration (compatibility; Du et al., 2018) and perceived technology utilization difficulty (complexity; Mütterlein and Hess, 2017). Previous research has posited that DOI has limitations in explaining the diffusion of complex technologies (e.g., SVR) in organizations, and researchers have been invited to extend DOI to account for these contexts (Lyytinen and Damsgaard, 2001). Our study answers to this need arising from the literature by addressing the enabling factors of SVR diffusion in a qualitative multiple-case study. Our findings indicate that moderators relating to collaboration intensity, SVR-technical infrastructure fit, and mitigating actions affect the relationship between the DOI antecedents and SVR diffusion. These findings are important because they reveal detailed, multi-faceted ways in which organizations can reach a critical mass of users for SVR, thus enabling them to extensively adapt their business processes to exploit SVR.

Second, our study generated eight propositions that explain the effects of the identified moderators on SVR diffusion. Relative advantage is a critical positive antecedent of diffusion (Tornatzky and Klein, 1982). Our findings highlight that collaboration around visual information and remote teamwork further promote the positive effect of efficient knowledge transfer (relative advantage) because the beneficial attributes of SVR are utilized extensively in these use contexts. Regarding the positive diffusion effect of compatibility (Tornatzky and Klein, 1982), our findings indicate that IS integration and the users' ability to access SVR with multiple devices were found to moderate the effect of ease of business process integration (compatibility) on SVR diffusion because they enable a greater number of stakeholders to participate in the collaboration. Complexity is negatively associated with the diffusion of a technology (Vagnani and Volpe, 2017). Our findings indicate that multi-user testing, younger lead users, applicability of stand-alone VR HMDs, and organizational competence with 3D models mitigate the negative effect that perceived technology utilization difficulty (complexity) has on SVR diffusion. These factors enable more efficient handling of the examined content in SVR as well as an easier user experience due to more effective peer support and more easily operated VR hardware.

As a practical contribution, organizations can utilize the findings of this study to evaluate their readiness to adopt SVR. Effective SVR adoption requires significant resources and commitment from an organization and its stakeholders. The present findings indicate that organizations need to identify the task areas that best match the strengths of SVR in collaboration around visual content and in geographically distributed teamwork. Furthermore, integration of different IS's and competence with 3D models are important in enabling easy access to digital content. Users' initial impressions are also critical in adopting SVR, and SVR adoption should be efficiently facilitated to enable teams to overcome initial reluctance and the perceived complexity of using SVR. Furthermore, stand-alone VR HMDs should be used whenever possible to mitigate the complexity of SVR. Organizations should also identify champions for SVR adoption from among their younger and more innovative users. Overall, organizations can evaluate the relevance of these identified moderators in their organizational contexts and thus identify the relevant issues that they must focus on improving before adopting SVR.

5.3 Limitations and future research

The present study has some limitations. First, the qualitative study is limited to Finnish organizations and, therefore, the findings might not be fully transferable to other countries. The data were also collected from organizations that had shown an interest in SVR by participating in VR research projects. Therefore, organizations that had not yet considered SVR as a technology with the potential to be used in the AEC industry were not represented in this study. However, since the study aimed to understand the enabling factors of SVR diffusion, this sampling strategy was deemed necessary to gain insights into experiences with SVR technology. The AEC study context might also stress different aspects of SVR diffusion than other industry contexts. For example, the importance of SVR's ease of use might be more pronounced in the AEC industry due to its age demographics. There might also be limitations to the interpretive and theoretical validity of the study (Maxwell, 1992), as the iterative qualitative analysis process was carried out primarily by a single researcher. However, the co-authors reviewed the findings of this analysis periodically to mitigate such limitations.

Although this study has identified important moderating variables of SVR diffusion, the effect sizes and interrelationships of these variables were not examined in this study and thus could be examined in future quantitative and experimental research. We encourage researchers to operationalize the propositions generated in this study and evaluate them in future studies in different industry contexts. Future studies could specifically examine successful cases of SVR adoption in order to validate the proposed moderators or examine ways to deal with user resistance to SVR adoption, as proposed by Kim and Kankanhalli (2009). Our findings can act as a starting point for identifying enabling factors of SVR diffusion in other industry contexts and in examining whether similar moderators affect the diffusion of other complex technologies in organizations.

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PUBLICATION
III

Extended reality technologies in small and medium-sized European industrial companies: Level of awareness, diffusion and enablers of adoption

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ORIGINAL ARTICLE

Extended reality technologies in small and medium-sized European industrial companies: level of awareness, diffusion and enablers of adoption

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Abstract

Augmented reality (AR) and virtual reality (VR), collectively referred to as "extended reality" (XR), have begun to diffuse in industry. However, the current levels of awareness, perceived limitations, and use of AR and VR, as well as the potential differences on these aspects between these technologies are still not well known. Moreover, it is unknown whether small and medium-sized enterprises (SMEs) differ from large companies on these issues. This research employed a mixed methods research design to address this gap by carrying out a cross-sectional survey ($n=208$) to gauge European industrial companies' level of AR and VR awareness and adoption, and by interviewing 45 companies in nine European countries in order to identify critical enabling factors in the adoption of XR for SMEs. Results show no statistical difference between the respondents' perceptions toward AR and VR or in their use levels. Thus, examining AR and VR under the umbrella term XR seems justified, especially in the context of their organizational use. However, larger companies were found to be using XR more than SMEs. Analysis of interviews based on the technology–organization–environment framework also yielded several enabling factors affecting XR adoption and specified whether they are particularly highlighted in the SME context. Overall, this paper contributes to XR research by providing a holistic multi-country overview that highlights key issues for managers aiming to invest in these technologies, as well as critical organizational perspectives to be considered by scholars.

Keywords Augmented reality · Virtual reality · Extended reality · Technology adoption · Industry 4.0 · Small and medium-sized enterprises

1 Introduction

In recent years, the augmented reality (AR) and virtual reality (VR), collectively known as extended reality (XR), markets have been predicted to grow significantly (e.g., Grand View Research 2021; IDC 2020). However, these predictions usually pertain to all types of use, both consumer and enterprise. Accordingly, the current level of XR use in organizations, and, more specifically, in small and medium-sized enterprises (SMEs), is still not clear, and further investigation is needed. Due to the slowness of diffusion in consumer use, many XR developers have also begun pivoting toward the enterprise sector. For example, Google Glass and Magic Leap were initially aimed at the consumer sector, but later began focusing their offerings toward enterprise clients (Hammond 2020; Miller 2015). Moreover, many of the major technology companies are now developing XR solutions specifically for enterprise use (e.g., Microsoft Mesh and Nvidia Omniverse).

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Accordingly, both AR and VR have been identified as technologies that organizations could potentially capitalize on (see e.g., Berg and Vance 2017; Porter and Heppelmann 2017; Torro et al. 2021); this fits as part of the overall trend of digitalization, which has been critical for the competitiveness of companies during recent decades. Companies' interest in utilizing XR has also increased consistently, especially among larger companies (Porter and Heppelmann 2017). However, SMEs have been lagging behind larger companies when it comes to digital transformation (OECD 2021), due to lack of resources and more focused competencies, which affect their innovation capability and readiness to digitalize their operations (Denicolai et al. 2021). As the pace at which technology is adopted increases (Denning and Lewis 2020), SMEs risk being left behind. This can have dire consequences for societies as SMEs constitute the majority of all businesses and employ the majority of people (European Central Bank 2021). It is therefore crucial to understand the overall organizational situation and the challenges that accompany XR in order to support companies in their adoption efforts.

Interest in XR is also growing from the research viewpoint. Nevertheless, most of the extant organizational XR studies have focused on a single industry or country; very few overall quantitative accounts exist on the topic of how widespread their use is. Due to the rapid developments in XR, it is important to assess how much these technologies have diffused into enterprise use and what issues companies perceive to be critical in their adoption. This paper aims to examine the overall diffusion of XR in European industrial companies as of 2020, with a specific focus on SMEs. The twofold research question of this paper is:

1. Do the current levels of XR awareness, use, and perceived limitations differ between European SMEs and larger companies?
2. What are the critical enabling factors of XR adoption for SMEs?

We employed a mixed methods research approach to get a wider and more complete perspective on XR adoption (Venkatesh et al. 2013). Firstly, quantitative data were collected via a cross-sectional online survey with 208 respondents from European companies belonging to different sectors. The analysis examined the potential differences in perceptions toward AR and VR and investigated whether it is empirically justified to examine AR and VR conjointly under the recently popularized umbrella term XR. In addition, 45 semi-structured interviews were carried out in nine European countries to explore XR adoption in more depth. The interviews were framed and analyzed by using the Technology–Organization–Environment (TOE) framework (DePietro et al. 1990). The analysis identified relevant XR adoption enabling factors for companies and evaluated whether the enabling factors were specifically highlighted in the SME context.

This paper contributes to research by providing a comprehensive overview about the current level of AR and VR adoption and use in European industrial companies. We found no statistical difference in the respondents' perceptions or level of use between these technologies. However, AR and VR use levels were found to differ between SMEs and large companies, although the levels of awareness and perceived limitations of adoption were similar for both types of companies. We also uncovered 13 important enabling factors affecting XR adoption, eight of which were noted to be especially important in the SME context. This contribution is valuable, as these technologies have had several previous waves which failed to materialize into widespread industrial use (Walsh and Pawlowski 2002). These findings help to illuminate the most important determining factors affecting their adoption that organizations (especially SMEs) would benefit from investigating.

The rest of the paper is structured as follows. First, the theoretical background on AR and VR as well as their adoption is examined in Sect. 2. Second, the methodology relating to the survey and semi-structured interviews is described in Sect. 3. Third, the results of the survey and the findings from the interviews are presented in Sects. 4 and 5. Finally, the results and findings are discussed in Sect. 6, along with the contributions and limitations of the study. The paper ends with suggestions for future research.

2 Literature review

AR can be defined as a technology that *combines or superimposes digital information into the user's view of the real world* (Azuma 1997), and VR as a technology that *replaces the user's view of the real world with an immersive and interactive 3D virtual environment* (Bryson 1995; Jerald 2015). Both AR and VR utilize head-mounted displays (HMDs) to achieve these outcomes for the user; however, smartphones and tablets are also widely used to create AR experiences (Jalo et al. 2020; Porter and Heppelmann 2017). AR and VR can essentially be seen as tools with which one can present digital information to the user in a more immersive and interactive fashion (Davila Delgado et al. 2020). This is achieved either by transplanting information into the real-life context with AR, or by examining it in a completely virtual space in VR. AR and VR are also often researched in conjunction (see e.g., Cipresso et al. 2018; Li et al. 2018; Ong and Nee 2013; Steffen et al. 2019), and, more recently, the umbrella term XR has been used to refer to both AR and VR together (Bujić et al. 2021; Chuah 2019; Dwivedi et al. 2021; Gong et al. 2021). However, it is uncertain if the use levels and perceptions of industrial companies differ between these technologies, or whether common adoption factors affect their implementation in the organizational context.

Recent years have seen an increase in empirical research on industry adoption of XR from the organizational point of view. Ten articles examining organizational XR adoption were identified in total for this literature review. Three of these articles examined XR adoption with a cross-industry sample (Berg and Vance 2017; Masood and Egger 2019, 2020). Berg and Vance (2017) qualitatively surveyed the use of VR in the US; they found measuring the return on investment (ROI) of VR to be important for maintaining top management support. Tailoring the VR solution to focus either on visual fidelity or interactivity and technical details depending on the user group was found to be an important factor for leveraging the affordances of VR for specific use cases. Masood and Egger (2019) conducted a survey on the importance of various adoption factors for AR. They found organizational fit, technology compatibility and hardware maturity, and tailoring of the system to fit the organization's needs via piloting and user training to be statistically significant factors affecting AR adoption. Masood and Egger (2020) further examined AR adoption factors based on practical field experiments using AR HMDs with organizations from the UK and found user acceptance to be crucial for AR adoption; the study also confirmed the importance of system configuration and organizational fit.

Five articles examining XR adoption in the architecture, engineering, and construction (AEC) context were also identified (Badamasi et al. 2022; Davila Delgado et al. 2020; Jalo et al. 2018, 2020; Noghabaei et al. 2020). Jalo et al. (2018) identified different factors affecting the adoption of AR in the Finnish Facility Management industry via interviews and focus groups. They found the compatibility of information systems (IS) and AR and wider interorganizational cooperation to be crucial for their organizational use. Jalo et al. (2020) researched different enabling factors relating to social virtual reality (SVR) diffusion in AEC organizations in Finland via interviews and focus groups. They found that identifying visual work tasks that rely on remote collaboration leads to an increase in adoption. IS and software compatibility with SVR and ensuring multi-device access to SVR were also found to aid in SVR diffusion. Lastly, the perceived complexity of SVR could be mitigated by utilizing more user-friendly stand-alone VR HMDs, as well as by training users in 3D modeling skills, by carrying out initial testing in a group, and by designating VR lead users. A survey study conducted in the UK by Badamasi et al. (2022) found that the high cost of VR devices, employees' lack of VR skills, and the required cultural change brought about by VR adoption were the most crucial barriers hindering the adoption of VR. Davila Delgado et al. (2020) identified relevant XR adoption factors in the UK via focus groups and ranked them based on a quantitative survey. Similar to Badamasi et al. (2022), high costs and low maturity of XR technologies, lack of XR skills, and general reluctance regarding new technologies were identified as the most critical limiting factors in their study. Lastly, Noghabaei et al. (2020) carried out a two-wave survey in the USA and found lack of financial resources and lack of knowledge about XR within top management and design teams to be the most important barriers for XR adoption.

The two final articles examined XR adoption in the retail context (Chandra and Kumar 2018; Alam et al. 2021). Chandra and Kumar (2018) examined the adoption of AR in e-commerce in Singapore, India, and the USA with a survey. Their results highlighted the key roles of relative advantage, securing top management support, the readiness of customers to use AR, and a sufficient level of technological competence to implement and maintain AR in increasing organizational adoption intention. Alam et al. (2021) used a survey to assess which factors influence the adoption of AR in Malaysian retail companies. They found that pressure from competitors and customers, and the managers' technological knowledge and awareness of AR to be key drivers of AR adoption, whereas high costs relating to AR were hindering adoption. Moreover, the perceived usefulness of AR and the managers' self-efficacy influenced managerial attitudes and adoption intentions.

The literature review shows that this stream of research has largely focused on a single country or industry, so studies containing larger multi-country and multi-industry samples could enhance the transferability and generalizability of the findings for industry in general. Moreover, key issues for SMEs are often not considered. Our study thus aims to provide a more holistic perspective on the current stage of XR adoption in industry, as well as to identify which adoption enablers are specifically critical for SMEs.

3 Methodology

This study was carried out according to a mixed methods approach (Venkatesh et al. 2013), including a cross-sectional online survey and semi-structured interviews. Both the survey and interviews were carried out between April 2020 and October 2020. This research had a specific focus on SMEs due to their prominent role in the European manufacturing industry, and the related need to understand the current gaps in SMEs' innovation processes in order to properly understand and support the implementation of new digital technologies such as AR and VR. However, larger companies were also included in the sample to provide a more complete and possibly contrasting view on the adoption of AR and VR. First, possible differences in the companies' situations and perceptions between AR and VR were investigated and SMEs' and large companies' situations with these technologies were compared via the survey. Second, a set of relevant adoption factors relating to both technologies emerged from the semi-structured interviews. Their importance for SMEs was then evaluated and corroborating evidence for the enabling factors was sought from the extant literature.

The online survey statements were exploratory in nature and were formulated to address the respondent companies' awareness and perceived limitations pertaining to AR and VR and their current level of use. In the survey, each respondent answered identical questions related to AR and VR according to a 7-point Likert scale ranging from "strongly disagree" to "strongly agree," or a 5-point Likert scale ranging from "never" to "a great deal," based on the specific question. The statements are listed in Tables 2 and 3. All of the statements were first asked about AR, followed by VR. The order of the statements was not randomized, however, as the identical questions were not placed directly after each other, the respondents were less likely to be induced to answer them similarly (Nederhoff 1985). The survey was revised based on feedback from pilot tests with two SMEs in Finland and Italy. The final survey instrument was then translated into German, Italian, and Spanish. The survey included questions about the background of the respondents, followed by questions about the overall status of AR and VR use in their companies.

The survey was carried out in the context of a European research project and distributed among the professional networks of the research consortium. As we had no means to secure responses from each potential respondent, we acknowledge the possibility of some degree of selection bias, as those who are already familiar with AR or VR to some degree or are interested in these technologies are possibly more likely to answer such a survey (Armstrong and Overton 1977). However, based on the results of the survey, this bias is likely not significant, with approximately 60% of the respondents still answering that their companies do not use AR or VR. We also aimed to reduce nonresponsiveness by assuring the respondents that their anonymity would be protected (Armstrong and Overton 1977). The survey was opened by 451 people; 208 people provided valid complete responses to the survey (159 of these were from SMEs). We thus had a response rate of 46.1%, which is consistent with prior IS adoption studies (see e.g., Kim and Kankanhalli 2009; Wolf et al. 2012). We also assessed nonresponse bias by carrying out a Levene's homogeneity of variance test with respondents from the first and last 33% of the responses to the statements in Tables 2 and 3 (Armstrong and Overton 1977). The early and late groups did not differ from each other in a statistically significant way ($p > 0.05$ for all group comparisons), suggesting that nonresponse bias was not a significant threat to the results.

The survey respondents were quite evenly distributed between lower (24%), middle (31.3%), and top management (30.8%), with 13.9% choosing the option "other" (indicating they were experts or other employees). A clear majority (79.8%) of the respondents were male and the rest (20.2%) were female. As for the age of the respondents, 31.2% of them were 18–34 years old, 52.8% were 35–54 years old, and 16% were 55–74 years old. A majority of the respondents (61.5%) had an advanced degree (Master's, Ph.D., M.D.), 22.6% had a bachelor's degree, and the rest (15.9%) had a lower level of education (e.g., a high school degree).

Table 1 provides background information about the companies of the respondents. As shown in Table 1, no single industry or country dominated the responses. Most of the responses (76.5%) were from SMEs (with under 250 employees), with the remaining responses coming from larger companies. Most of the companies were also internationally focused (58.5%) or operated at least at the national level (29.3%). The companies were also mainly focused on providing products and solutions to other companies (60.6%) or consumers (16.3%).

IBM SPSS Statistics version 27 was used to perform the data analysis. The survey data was first tested for normality with the Shapiro–Wilk test, which indicated that all of the data were non-normally distributed ($p < 0.001$). After the data were logarithmically transformed, they were still found to be not normally distributed. Therefore, the nonparametric Wilcoxon Signed-Rank (WSR) and Mann–Whitney U tests were adopted to carry out the analysis, as recommended in the literature (Blair and Higgins 1985; Rasmussen and Dunlap 1991; Serlin and Harwell 2004). The WSR test was used to compare the differences between AR and VR within the entire sample ($n = 208$). A within-subjects repeated measures design was thus used for this test. We also carried out a Spearman's nonparametric correlation test on the answer pairs. The differences between the SMEs ($n = 159$) and large companies ($n = 49$) were examined with the Mann–Whitney U test, which can be used to compare two independent samples with different sample sizes (George and Mallery 2019).

The semi-structured interviews were also carried out as part of the activities of the same European research project involving several researchers from different countries, with the lead author providing the interview protocol for the other researchers. The interviews represented multiple case-studies involving 45 companies from nine European countries (five from Austria, Belgium, Cyprus, Estonia, Finland, the Netherlands, and Spain, six from Italy, and four from Germany). Of these companies, 31 were SMEs (below 250 employees) and 14 were large companies (over 250 employees). Interviewees consisted of senior management (16), middle management (18), lower management (4), and experts (7). The interviewees were selected by the project partners from their professional networks. Purposeful

Table 1 Information about the respondents' companies ($n = 208$)

	Frequency and percentage		Frequency and percentage
Location		*Industry*	
Austria	24 (11.5%)	Aerospace	5 (2.4%)
Belgium	25 (12.0%)	Architecture and construction	32 (15.4%)
Cyprus	27 (13.0%)	Automotives and vehicles	17 (8.2%)
Estonia	11 (5.3%)	Biotechnology	1 (0.5%)
Finland	28 (13.5%)	Chemicals	3 (1.4%)
Germany	20 (9.6%)	Clothes and textiles	1 (0.5%)
Greece	2 (1.0%)	Computers and electronics	14 (6.7%)
Ireland	1 (0.5%)	Electrical equipment	6 (2.9%)
Italy	16 (7.7%)	Food and beverages	8 (3.9%)
Netherlands	24 (11.5%)	Furniture	3 (1.4%)
Romania	1 (0.5%)	Healthcare and pharmaceuticals	14 (6.7%)
Spain	29 (13.9%)	Industrial installation and maintenance	12 (5.8%)
Employees		Machinery and equipment	21 (10.1%)
1–9	39 (18.8%)	Metals	19 (9.1%)
10–49	66 (31.7%)	Plastics	3 (1.4%)
50–250	54 (26.0%)	Other (e.g., Consulting)	49 (23.6%)
251–500	13 (6.2%)		
501–1000	5 (2.4%)		
> 1000	31 (14.9%)		

Table 2 Survey responses on AR and VR awareness and limitations ($n = 208$)

	Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree
Our organization is well-aware of the potential of AR [1]	18 (8.7%)	33 (15.9%)	15 (7.2%)	18 (8.7%)	47 (22.6%)	39 (18.8%)	38 (18.3%)
Our organization is well-aware of the potential of VR [1]	17 (8.2%)	31 (14.9%)	16 (7.7%)	20 (9.6%)	42 (20.2%)	43 (20.7%)	39 (18.8%)
There are many limitations to using AR in our organization. [2]	17 (8.2%)	34 (16.3%)	21 (10.1%)	53 (25.5%)	40 (19.2%)	31 (14.9%)	12 (5.8%)
There are many limitations to using VR in our organization. [2]	16 (7.7%)	37 (17.8%)	23 (11.1%)	43 (20.7%)	38 (18.3%)	37 (17.8%)	14 (6.7%)

Table 3 Survey responses on AR and VR use levels ($n = 208$)

	Never	Rarely	Occasionally	A moderate amount	A great deal
Our organization is making use of AR [3]	123 (59.1%)	27 (13.0%)	30 (14.4%)	16 (7.7%)	12 (5.8%)
Our organization is making use of VR [3]	119 (57.2%)	24 (11.5%)	25 (12.0%)	21 (10.1%)	19 (9.1%)

sampling was thus used at this stage to gather insights from companies that were either considering using XR or had already adopted such solutions (Patton 2002). The information collected through these interviews was also integrated with secondary sources, including internal documentation provided by companies, as well as data available on the internet (e.g., company websites), in order to triangulate data and assure the consistency of related findings (Yin 2013).

In order to provide a comprehensive accounting of factors affecting the adoption of XR in organizations, the TOE framework was utilized in structuring the interviews and in analyzing the collected data to illuminate relevant technological, organizational, and environmental adoption factors (DePietro et al. 1990). The TOE framework provided a good basis for further identification of enabling factors from the data, as it does not predetermine the particular factors influencing adoption. The application of the TOE framework has also found wide empirical support in the context of many Industry 4.0 technologies (e.g., Borgman et al. 2013; Chandra and Kumar 2018; Martins et al. 2016), and it has been argued to be useful for analyzing the adoption of novel technologies in the context of a wide variety of organizations (Schiavone et al. 2022), attesting to its suitability in our research context. The interview protocol (see "Appendix") was developed based on the themes highlighted in the literature review described in Sect. 2 and the lead author's experience on several XR research projects. The interview protocol was also circulated among the researchers and refined based on their feedback. The interviews were carried out via remote video conferencing software (such as Zoom and Microsoft Teams) due to the COVID-19 pandemic. The interviews lasted between 45 and 75 min and were recorded with the consent of the interviewees. The semi-structured nature of the interviews allowed the interviewers flexibility to ask follow-up questions and follow the natural flow of the conversation, while still following a common structure (Gillham 2005). The interviewers created a summary of all the interviews and transcribed insightful quotes from each interview into English. The qualitative analysis of the interviews adopted an interpretive approach (Walsham 1995). The analysis process began by giving codes to smaller pieces of data, and then grouping them under the TOE framework categories (Creswell 2015; DePietro et al. 1990). These codes were iteratively combined into higher-level main codes to develop themes (Creswell 2015). Disconfirming evidence for the themes was also sought from the data (Creswell and Miller 2000). Illustrative quotations for each main code are included in the findings. The coding was mainly done by the lead author; however, co-authors later reviewed the findings to confirm their accuracy, as they also participated in the data collection (Creswell 2015).

Next, we will first present the analysis of the survey data, followed by the findings from the interviews.

4 Companies' perceptions and adoption levels of AR and VR

The WSR test (Table 4) was carried out on the survey data to determine if there were statistical differences between the answers to similar statements in terms of awareness, limitations, and use of AR and VR (depicted in Tables 2 and 3). Overall, if the companies were to perceive these technologies to be very different, we would expect the distribution of the responses to change between AR and VR statements.

In the WSR test, if the significance levels of the paired samples reach statistical significance ($p < 0.05$), the test would indicate that there is a statistically significant difference in the medians between the two samples. From Table 4, we can see that none of the pairs reach this level of significance. We can therefore conclude that there was not a statistically significant difference between AR and VR perceptions or use for the respondents in this sample. The correlations between the answer pairs were also significant at the $p < 0.01$ level, with the first pair having a strong positive correlation and the last two having a moderately strong positive correlation (Dancey and Reidy 2007). The respondents' answers were thus significantly paired in regard to AR and VR (i.e., if they were well aware of the potential of AR, they answered similarly with regards to VR). These analyses provide further evidence justifying examining AR and VR conjointly as XR, as has already been done in previous literature (e.g., Davila Delgado et al. 2020; Steffen et al. 2019). Thus, the following analysis in Sect. 5 will also examine these technologies collectively as XR.

Finally, we also tested for differences between SMEs and large companies within the sample with the Mann–Whitney U test. As can be seen in Table 5, SMEs and large companies differed significantly in their AR use ($p = 0.011$, $p < 0.05$) with a small effect size ($r = 0.175$) and statistically more

Table 4 Wilcoxon signed-rank test and Spearman's correlation test results ($n = 208$)

	Z	p	Spearman's correlation
Our organization is well-aware of the potential of [AR/VR]	− 0.724	0.469	0.745**
There are many limitations to using [AR/VR] in our organization	− 0.447	0.655	0.652**
Our organization is making use of [AR/VR]	− 1.449	0.147	0.455**

**$p < 0.01$

Table 5 Mann–Whitney U test results comparing SMEs ($n = 159$) and large companies ($n = 49$)

	Median (SME)	Median (Large)	*U*	*Z*	*p*
Our organization is well-aware of the potential of AR	5	5	3853	−0.117	0.907
Our organization is well-aware of the potential of VR	5	5	3734	−0.445	0.656
There are many limitations to using AR in our organization	4	4	3578.5	−0.875	0.381
There are many limitations to using VR in our organization	4	5	3594.5	−0.829	0.407
Our organization is making use of AR	1	2	3068.5	−2.530	0.011
Our organization is making use of VR	1	2	3272.5	−1.882	0.060

marginally with VR use ($p = 0.06$, $p < 0.1$) with a small effect size ($r = 0.13$; Cohen 1988). However, there were no differences in their awareness levels or perceived limitations to using these technologies.

5 XR adoption enabling factors

In this section, the qualitative findings of the study are described by distinguishing technological, organizational, and environmental enabling factors for XR adoption, based on the TOE framework.

5.1 Technological factors

Main technological enabling factors that emerged from the findings include: the extent of the XR hardware install-base and related network effects, finding the right balance of features in XR hardware (depending on the business process), securing XR testing opportunities, and ensuring XR and IS compatibility as well as rapidness of IS-XR workflows.

5.1.1 Technological install-base and network effects

Many of the interviewees noted that the required install-base for widespread XR use was often missing. For instance, one interviewee noted that their customers do not have VR HMDs which could be used in business processes. If XR hardware are still not widely diffused, the network effects which can induce others to adopt XR are also lower. Specialized XR applications are also often unavailable for various industry contexts.

> "I had great hope that somebody in the VR community would have provided apps for our profession to improve safety at work. I know some apps for [our] industry, but unfortunately, they are not suitable for our needs." Development Manager, Austria

Overall, companies show a higher readiness in the AR context as AR can often be utilized with existing smartphones with both internal and external stakeholders. Nevertheless, smartphones with the required features for advanced AR solutions are still not widely in use in industry. However, this issue was seen to automatically improve over time as stakeholders switch to newer devices.

5.1.2 Balancing performance and ease of use in XR hardware

The companies widely noted the challenge of finding the correct balance between visual fidelity, performance, ease of use, and quick setup of the XR devices. For VR, standalone HMDs were widely seen to be the preferred option due to their simplicity and smooth user experience, which were seen to be especially important factors in customer-facing business processes. However, tethered VR HMDs were still preferred in use cases that require more advanced functionalities and higher visual fidelity (e.g., high-end presentations).

> "I see that there's a divide [on what type of VR will be used]. For example, the design cases, work site, and design meetings will use stand-alone [VR] because they need to be as easy to use as possible. The cost is also an issue […]. Then again, if we want to sell something specific to clients, in that case it tilts toward the higher quality [VR] glasses." Manager, Finland

For AR, the interviewed companies had mainly focused on using smartphones and tablets (hand-held devices, or HHDs); HMDs (e.g., Microsoft HoloLens) were preferred in tasks where freedom of movement for both hands was needed. However, some interviewees noted that AR HMDs were still often not robust enough for industrial use, especially in more demanding conditions (e.g., dust and rain). In the short term, HHDs were seen to offer the most potential due to their wide install-base, low costs, and minimal training needs. The AR capabilities of these devices were also expected to increase automatically over the years; however, more advanced AR use cases (e.g., fitting wiring schematics in a building site) still had accuracy and reliability challenges.

> "We have to be sure about the reliability and precision of these technologies before their use. Is the presented information and data accurate? There is no room for

big mistakes in construction. Small mistakes can cost a lot of money." Manager, Cyprus

5.1.3 Opportunities to test XR devices and software

Many of the interviewed companies had been testing a wide variety of XR devices. Practical opportunities to test the XR devices were seen as one of the crucial enablers to understand their potential and challenges. The main limitation here was seen to be with hardware, as, on the software end of things, most enterprise XR solutions in fact frequently offer free trial periods. Due to their novelty, relatively high cost, and initial complexity, many interviewees found that facilitated and supportive settings (such as industry and university events) provided the best opportunities for experimenting with the newest solutions. However, in particular the interviewed SMEs were often unaware of these possibilities. A crucial limitation that was widely reported in the testing situations was that they did not enable multi-user testing, a feature that is judged to be fundamental to using these tools collaboratively.

> "We would like to be offered a demonstration or a free trial before we use these technologies, in order to be sure about the results and if it actually produces profit for the company." Manager, Cyprus

5.1.4 XR compatibility with information systems and software

Recent improvements in XR hardware were seen to be essential for their usefulness, however, their compatibility with organizational IS was still a barrier for their widespread adoption. Consequently, many interviewees had decided to first focus on modernizing their IS to enable later XR adoption and to ensure that application programming interfaces (APIs) were available for easy data access. Some interviewees also noted the difficulty of integrating legacy assets into XR processes (such as 2D design drawings), and thus judged the path-dependence from earlier choices with organizational IS to be a key limitation. Due to the challenges and work required in this area, especially with highly customized IS, many interviewees expected that many legacy assets would remain siloed and would not be incorporated into XR environments. For instance, the AEC industry has been transitioning toward using digital design tools (namely building information modeling, BIM), but very little digital information was reported to exist for many of the older properties. Accordingly, an AR maintenance app, for instance, could thus only be used in the context of new buildings.

> "The issue with this technology [XR] is the lack of compatibility and integration with current systems and CAD software." Business Operations Manager, Germany

5.1.5 Fast workflows between information systems and XR

Many interviewees noted that they had experienced significant difficulties with the speed of workflows between XR and their existing IS. As an example of the importance of this factor, the CEO of one of the interviewed companies reportedly changed his mind completely about VR after he saw the design information being transferred quickly between their design software and a VR software. This was seen to be crucial for the practicality and efficiency of new VR-enabled business processes. Some interviewees also reported that digital content can often already be accessed in AR or VR from the software with a single click, and that the cumbersome and time-consuming file transformations between several different software were not needed anymore. Automatic bi-directional workflows from software and IS to XR (and back) were seen as a key enabler in reducing work redundancy and in ensuring the reliability of the decisions and work being done in XR.

> "Historically the workflows have been more custom [for VR], so we've exported the model into something else, then something more was done to it in some other software, and only then it became viewable, and even then not necessarily in a multi-user setting. Whereas now when we have the model, there's a button which says 'View in VR,' and we can then go view it with a group." Manager, Finland

5.2 Organizational factors

Five organizational enabling factors were identified, including: securing top management support via practical XR testing, availability of XR development resources, ability to recruit XR experts, mitigating potential employee resistance toward XR, and effective facilitation of the initial XR adoption and use situations.

5.2.1 Top management knowledge and first-hand experience with XR

In many of the interviewed companies, the top management was generally aware of the potential of XR, but most companies had not yet actively begun implementing it. Top management interest and willingness to promote XR in the company was thus seen as a critical enabler. Practical experience and testing of XR devices and software by top management was seen to help them better understand their applicability and limitations in their company and thus secure the needed adoption resources. However, finding the time for upper management to learn how XR could transform organizational business processes was still a limitation.

> "The CEO's view on these technologies has become much more positive, he's really taken this whole development thing as his own. He's been complaining that we've been talking about this for years and years, (I've been working here for a year now), and we've just refined these things further but haven't gotten to the practical part yet. Now it's much more like 'Let's take this app into use,'; 'Show this to the people at the building site and ask them whether this could be a good thing.'" Manager, Finland

5.2.2 Availability of resources and personnel for XR research and development

The perceived complexity of XR adoption was seen to require that key employees familiarize themselves with XR in detail and evaluate its effects on the company's business processes, or even the overall business model. Most of the interviewed companies reported struggling with this issue and found it to be a limiting factor in adopting XR or expanding its use. In particular, SMEs felt this to be a key challenge as they reported already being stretched thin on personnel; however, larger companies did not feel this to be as serious of an issue.

> "The pitfall however is that management doesn't free up time for the employees to delve deeper into this technology and to do some experiments. As a consequence, only the most basic features of the software are used and the other features remain unexplored." Manufacturing Engineer, Belgium

5.2.3 Ability to recruit people with XR expertise

Another challenge faced by the interviewed companies was in finding employees with XR experience. In the short term, XR competences were seen to be achieved either by self-learning or at university courses. One interviewee also noted that many of the employees with XR skills would likely not have extensive industry experience and transforming the company's business processes with XR would thus need to be done in cooperation with senior employees.

> "One of the problems we have is that our age distribution is such that we have guys like me [younger generation] and then there are supervisors that are closer to 60. To get them to use it [XR], we have to balance for a while between two things; I handle the facilitating [relating to the use of XR], and the other guy handles the construction management side [...], and then we try to share [domain] knowledge between us, because we still don't have people who can handle both." Manager, Finland

Many of the interviewees also noted that they were still more familiar with XR in entertainment rather than industrial use. Accordingly, some interviewees noted that these hedonic experiences could be used as a good starting point for thinking about how XR could be used in their companies.

5.2.4 Mitigating employee resistance toward adoption

Employee resistance toward adopting XR, especially from older employees, was identified as a crucial barrier. As XR can be used to transform operations significantly (e.g., from physical design reviews to remote XR reviews), the readiness and proclivity from both the management and the employees to adopt new ways of working was seen to be essential. An organizational culture that supports innovation and testing of technologies with a low threshold were seen to be important for mitigating possible user resistance. Incorporating employees into the XR adoption process from the beginning was also seen as a one of the greatest potential mitigation strategies; as one interviewee explained:

> "Older employees were a bit skeptical about this technology [AR], but they have been consulted from the start, resulting in two equivalent systems they can choose from (Vuzix glasses or tablet) and finally, the whole technological change has been accepted and turns out to be successful today." COO, Belgium

Providing extra hands-on training both for XR use and other enabling technologies (e.g., digital model exporting from IS) were seen to be essential in ensuring a smooth adoption process. The employees were seen to need sufficient XR skills to operate the solutions independently in order to transfer the ownership for the solutions to the business units. Although support should be available when needed, the primary responsibility for using the XR solutions effectively should be with the end-users.

5.2.5 Facilitating the initial adoption and use

Due to the importance of overcoming the initial skepticism and inertia toward XR adoption, some interviewees noted the importance of designing the first XR testing and adoption events to be as practical and engaging as possible. These sessions should include hands-on testing of devices as well as identification of a few key users who would be trained to be able to provide peer support.

> "[...] it's the job of sales to train the sellers to use VR, I'll certainly be there to support as well, or I'll train the main users who will then take it into everyday use

so it'll come into use more effectively. Then the know-how and ownership are there too." Manager, Finland

Expectation management was also noted to be important due to the existing misinformation about XR caused by the hype surrounding these technologies. Choosing multi-user XR solutions with advanced user management features (e.g., gathering users to the event manager) was also identified to be important to ensuring smooth initial XR experiences. These solutions should also be multi-device compatible in order to enable reluctant users to participate in testing by viewing the XR event via, for example, desktops.

5.3 Environmental factors

Three environmental enabling factors were identified: XR capabilities and readiness of the company's stakeholders, competitor pressure from successful XR use, and the maturity of the XR vendor and training ecosystem.

5.3.1 Increased stakeholder XR capabilities and readiness

To enable large-scale XR use, many interviewees emphasized that their stakeholders need to increase their skills and readiness to use XR. Companies operating globally faced the largest limitations in this regard, because the significant heterogeneity of their stakeholders' XR capabilities constrained the use of XR to a few select partners. This meant that XR could currently mainly be used in internal operations or in facilitated settings with customers.

"I think the most needed skill would be to train our customers in using AR technology to report missing or damaged machinery parts and to order replacements. This is also one of the reasons why the use of AR in our customer service is currently not considered economically viable. […] The main problem with this is that our clients are located all over the world, sometimes in very remote places. Adopting AR technology does not happen overnight and requires some basic infrastructural elements." Clerk, Austria

Some interviewees also noted that their customers still often preferred to use smartphones or tablets rather than HMDs. Cultural factors were also seen to have a role in determining stakeholders' propensity toward XR use.

"Especially in Italy the customer prefers to see the service person face-to-face, physical meetings are still preferred to solve problems." Vice President, Italy

5.3.2 Observed XR benefits achieved by competitors

Most of the interviewees reported that their competitors and other relevant stakeholders were still not using XR in a significant way. Many interviewees noted that once XR use starts becoming more widespread, companies would start feeling the pressure to adopt XR solutions. However, it was seen to be easier for companies to identify competitors using XR in customer-facing business processes rather than in internal operations. Moreover, many interviewees noted that SMEs often wait for larger companies to successfully adopt and thereby demonstrate new technologies' applicability before they consider adopting it. This risk-aversion was mostly due to their limited resources when compared to larger companies.

"Extended use of these technologies by competitors or relevant partners can influence our company to adopt them." Manager, Cyprus

5.3.3 Maturity of XR vendor and training ecosystem

Many of the interviewed companies noted that they do not have many employees who would have the technological inclination to delve into XR to find out what solutions would work best for them. Generally, most of the information technology (IT) infrastructure and maintenance is outsourced in SMEs, decreasing SMEs' internal capabilities to adopt and integrate new technologies. In contrast, some of the larger interviewed companies felt they would be able to adopt XR independently. Many of the interviewees thus felt it was essential for them to identify a suitable external partner or vendor who could handle the required XR hardware and software installations.

"We would need to purchase full equipment (hardware and software) and we need external consulting in order to know which equipment is best for our needs and purposes." IT and HR Manager, Austria

Overall, there were significant differences between the companies in their abilities to adopt XR independently. For example, one interviewee noted that he could most likely carry out the installations independently because he had already spent a lot of time learning about XR devices, software, and the overall ecosystem; however, many of their competitors were still struggling with this. Moreover, in smaller countries XR vendors and consultants were seen to be not readily available, as XR was still seen to be a novel and niche market.

6 Discussion and conclusion

This mixed-methods study provides a holistic view on the current state of AR and VR adoption in European industrial companies and identifies key enabling factors affecting XR adoption. A cross-sectional online survey ($n=208$) was

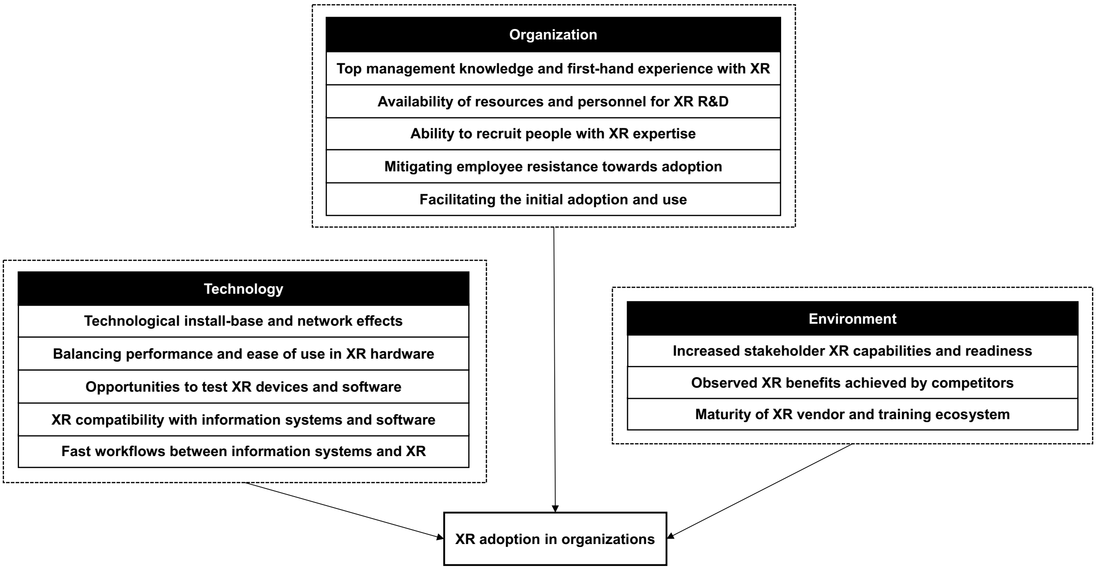

Fig. 1 The identified XR adoption enabling factors categorized under the TOE framework

carried out to answer the first research question: "*Do the current levels of XR awareness, use, and perceived limitations differ between European SMEs and larger companies?*" Our study revealed that, overall, there were no differences in perceptions or use levels between AR and VR. However, large companies positively differed from SMEs on AR use levels ($p = 0.011$, $p < 0.05$, $r = 0.175$) and more marginally with VR use levels ($p = 0.06$, $p < 0.1$, $r = 0.13$), even though there were no differences between SMEs and large companies regarding awareness or perceived limitations relating to AR and VR. In addition, we interviewed 45 companies and identified 13 enabling factors for XR adoption and categorized them under the TOE framework in order to answer the second research question: "*What are the critical enabling factors of XR adoption for SMEs?*" The summary of these findings is presented in Fig. 1. Further analysis presented in the next section found that eight of these enabling factors were specifically highlighted in the SME context.

6.1 Theoretical contributions

The present study makes a twofold contribution to theory. First, the quantitative analysis based on an industry survey found there to be no statistically significant differences in organizations' AR and VR use levels or the awareness and perceived limitations regarding these technologies. These results give further evidence and justification for examining both of these technologies simultaneously, as has already been practiced in prior literature (e.g., Davila Delgado et al. 2020; Steffen et al. 2019). These results also bring into question whether or not AR and VR really are at different development stages from an organizational point of view, as has been reported previously (e.g., Gartner 2017). Even though HMD implementations of AR are still likely less mature than VR implementations, it is possible that organizations view AR as a whole to be at the same level of maturity as VR when smartphone- and tablet-based AR are included. Moreover, analysis of the survey data found that larger companies were using AR and VR more than SMEs, although both were similarly aware of their potential and perceived similar levels of limitations in their adoption. This further corroborates earlier findings that large companies are more likely to adopt emerging technologies first before they have become well established in industry (Porter and Heppelmann 2017) and confirms the need to support, especially, SMEs in the adoption of digital technologies through the identification of enabling factors that are specifically applicable to them.

Second, this study provides an organizational perspective on XR adoption based on the TOE framework with a specific focus on SMEs. The present study contributes to the nascent literature on organizational XR adoption by uncovering key technological, organizational, and environmental enabling factors and assessing their specific importance for SMEs. The identified enabling factors and whether their importance is highlighted in the SME context are summarized in Table 6. Moreover, the novelty of the enabling factors is compared against previous findings

Table 6 Summary of XR adoption enabling factors

Enabling factor	Corroborating research	Highlighted in SMEs?	
		Yes/No	Description
Technology			
Technological install-base and network effects	–	Yes	SMEs often work in larger networks; proliferation of XR in other companies enables the use of XR in additional business processes
Balancing performance and ease of use in XR hardware	Berg and Vance (2017), Jalo et al. (2020), Masood and Egger (2020)	No	Both SMEs and large companies need to be able to choose appropriate equipment
Opportunities to test XR devices and software	Jalo et al. (2020)	Yes	SMEs often do not have the slack resources to experiment with XR hardware and software, which makes ease of testing more crucial for them
XR compatibility with information systems and software	Jalo et al. (2018, 2020), Masood and Egger (2019)	Yes	SMEs will likely not start tailoring XR solutions to their IS and software
Fast workflows between information systems and XR	–	No	Efficiency of workflows important for both SMEs and large companies
Organization			
Top management knowledge and first-hand experience with XR	Alam et al. (2021), Berg and Vance (2017) Chandra and Kumar (2018), Masood and Egger (2019) and Noghabaei et al. (2020)	No	Top management support for XR adoption critical in all companies
Availability of resources and personnel for XR research and development	Davila Delgado et al. (2020), Noghabaei et al. (2020)	Yes	SMEs often lack slack resources which could be directed toward XR implementations
Ability to recruit people with XR expertise	Badamasi et al. (2022), Davila Delgado et al. (2020)	Yes	Due to the novelty of XR, finding experts is difficult for most companies. However, unlike large companies, SMEs likely cannot afford specialized XR experts
Mitigating employee resistance toward adoption	Badamasi et al. (2022), Davila Delgado et al. (2020), Masood and Egger (2019)	No	Inertia and resistance possibly even higher in larger companies due to increased bureaucracy and organizational complexity
Facilitating the initial adoption and use	–	No	Positive first impressions with XR important for all companies
Environment			
Increased stakeholder XR capabilities and readiness	Alam et al. (2021), Chandra and Kumar (2018)	Yes	Critical for interorganizational business processes, SMEs likely do not have the leverage to require other companies in the network to acquire XR expertise
Observed XR benefits achieved by competitors	Alam et al. (2021)	Yes	SMEs often wait for larger and more risk-tolerant companies to demonstrate the effectiveness of new technologies
Maturity of XR vendor and training ecosystem	–	Yes	SMEs will likely need more external support for implementing XR

from literature. This comparison provides a concise view on the state of extant XR adoption literature.

The identified technological enabling factors (Table 6) were found to be mainly focused on XR and IS compatibility, and in the diffusion of the technology in the larger ecosystem, which can enable the use of XR in external business processes due to increased network effects. As more organizations begin adopting XR, its value proposition for other organizations increases simultaneously, as it opens up new opportunities for collaboration. This is especially crucial for SMEs, as the intraorganizational application potential of XR will likely be wider in large companies. In addition, wider diffusion provides opportunities for organizations to test XR. This can be especially helpful for SMEs, which often do not possess the extra resources to obtain XR devices for experimentation purposes. Testing opportunities can also help companies in finding the right balance between performance and ease of use with their chosen XR solution. Last, although IS compatibility has been highlighted in extant literature (e.g., Davila Delgado et al. 2020), the rapidness of the IS-XR workflows is noted here as a distinct factor, as it can help in incorporating XR into everyday business processes. The off-the-shelf compatibility of XR with IS is also likely more relevant for SMEs, as tailoring of the solutions carries higher financial risks.

At the organizational level, the top management not only needs to be knowledgeable about XR (Berg and Vance 2017), but they also need to test these devices in practice due to their immersive and novel nature in order to grasp their enterprise-application potential. As SME managers can often also be the direct owners of the company, convincing them about XR's potential can significantly help in securing the required resources for XR. Berg and Vance (2017) also noted that the VR champion in an organization should encourage the end users to test VR in practice to fully recognize its potential. Securing the needed personnel and development resources for XR was also found to be crucial, especially for SMEs that are often limited in this regard. The required XR expertise can be found by recruiting the necessary talent from external sources or internally from employees who have self-learned how to use XR. Although XR is still often perceived to be more applicable in entertainment rather than demanding industrial and engineering use (Davila Delgado et al. 2020), its hedonic use can also develop skills that can be applied in the organizational context. Mitigating employee resistance toward XR was also found to be critical, a theme that has also gained increasing interest in recent literature (see e.g., Kim and Kankanhalli 2009). Some of the most promising ways to mitigate such resistance include involving the employees in the XR development process from the beginning and ensuring the initial testing and use of XR to be as practical and engaging as possible. An organizational culture supporting innovation can also lower the threshold for experimentation.

The maturity level of the XR vendor and training ecosystem was found to be an especially relevant environmental factor for SMEs, which often do not possess sufficient capabilities for independent system implementation and training. Successful XR adoption by competitors can also create pressure for adopting XR. Such mimetic pressures were also found to be critical for the adoption of virtual worlds by Yoon and George (2013). However, our analysis also noted that XR adoption by competitors was likely to be more visible in external customer-facing processes, which are already more difficult to implement in comparison to XR utilization in internal business processes. Thus, if companies wait for visible signs of XR adoption in their competitors, they are likely lagging far behind them in applying XR, as XR will likely be initially adopted in internal business processes that then create organizational capabilities for wider XR use. At this point, the required XR capabilities and readiness of other stakeholders will also probably be higher.

In summary, although the affordances created by AR and VR can be slightly different (Steffen et al. 2019), common factors can be identified that are relevant for adopting both of these technologies, as they are essentially both focused on presenting digital information to organizational users visually in an immersive manner, and in enabling new ways to interact with this digital content. However, this study also shows that the importance of specific enabling factors can vary depending on the size of the company and its business environment.

6.2 Practical contributions

From a practical point of view, the holistic multi-country overview provided by this study highlights key issues for industry managers aiming to invest in XR by highlighting critical technological, organizational, and environmental factors they need to focus on to ensure a smoother adoption process. The in-depth analysis of enablers based on the three dimensions of the TOE framework can represent a reference for organizational managers and decision-makers interested in identifying existing barriers in their companies and in leveraging the most relevant enablers to drive their companies toward effective adoption of XR. In particular, aside from the technological and organizational aspects, the multidimensional level of analysis includes essential environmental factors such as the maturity of the related innovation ecosystem, which can provide essential support for organizations considering adopting XR. The findings of the study can thus help companies in systematically addressing the key issues which can hinder organizational XR adoption.

SME managers and decision-makers can especially benefit from understanding which XR adoption factors are highlighted in their own context, thus enabling them to shape their digital transformation path according to the specific competencies, resources, and strategic goals pursued by their organization. As SMEs often do not have enough slack resources for experimenting with new technologies on their own, seeking external opportunities for testing XR solutions and acquiring expertise from the external innovation ecosystem can thus be specifically useful for SMEs. These trial opportunities can also help them choose appropriate XR equipment and enable their top management to test XR in practice to help them better understand how XR might fit in with their current IS and software, as well as their overall business strategy. As many SMEs often follow larger companies when it comes to adopting new technologies, the survey overview about the XR adoption situation in European companies can also help managers in evaluating the overall market situation and in determining whether their companies should start investing in XR. Monitoring how widely XR has already diffused within their stakeholders and what level of capabilities they possess can also help companies understand in which business processes XR can already be leveraged effectively.

6.3 Limitations and future research

This study has certain limitations pertaining to its quantitative and qualitative aspects. First, the survey data collection was placed at the beginning of the COVID-19 pandemic, which was a turbulent period for many companies. This may have influenced what types of companies were able to answer the survey. The shift toward remote work has also possibly spurred further interest in XR. Longitudinal studies on organizations' perceptions and situations after the pandemic might provide different results. As the pace of digitalization and adoption of technologies has increased more generally (Denning and Lewis 2020) as well as specifically due to the pandemic (OECD 2021), more research is needed on what company traits and capabilities are highlighted in the effective adoption of emerging technologies, both in SMEs and large companies. Moreover, even though both the quantitative and qualitative samples were mainly focused on SMEs, larger companies were also included. However, we view this choice as justified, as this sample is more representative of the overall enterprise market composition of the European industrial sector. This also allowed us to compare whether the situation with AR and VR differed between SMEs and larger companies and to assess the specific importance for SMEs of key technological, organizational, and environmental enabling factors identified in this research.

Second, although the semi-structured interview protocol was shared among the researchers and iteratively refined based on their feedback, it is possible that both the interviewers and the interviewees understood and interpreted the questions differently due to cultural and person-specific issues. Moreover, neither the relative significance nor the interrelationships of the identified enabling factors were examined in this study. Future research could thus operationalize the enabling factors and quantitatively evaluate their importance for organizations. Our findings are also mainly focused on the organizational level of adoption. As XR can be used to radically transform organizational activities and social structures, more research on employee perspectives on potential conflicts and changes that XR adoption can bring about could prove to be useful. Both quantitative and qualitative longitudinal pre- and post-adoption research designs could be employed to examine these issues.

Appendix

Interview protocol

The interview protocol below was phrased to be used with companies who have not yet used AR or VR. Another interview protocol was also developed to be used with companies who were already using AR or VR. The protocol had only slightly differed phrasings, so it was omitted here due to space limitations.

Familiarity with AR/VR

Shortly, how aware are you of Augmented Reality (AR) or Virtual Reality (VR)?

- Have you used them yourself? Or have you seen them being used somewhere?

Has your organization thought about using AR and VR? Which one has more potential for your organization?

- Where and how could you use them in your organization?
  - e.g., visualizations, information access, multi-user collaboration, remote support?
  - Which tasks and processes?
- Has your organization been testing any kind of AR or VR devices?
  - Do you know where you could test them?
- Why haven't you started using AR or VR yet?
  - Is the problem with the technology itself (e.g. cost, too complex…)?
  - Or are there some organizational barriers that prevent you from using AR or VR (e.g. ease of integration with business processes)?

- Or is the issue with the employees (e.g. lack of skills)?

Organizational issues

How knowledgeable is top management about AR or VR?

- Is someone in top management promoting their use?

Do you think your organization could start using AR or VR on your own (e.g., buy devices, install software, teach your employees on how to use the technology) or would you need external support?

- In what areas would you need support?
  - e.g. technological issues, adapting business processes, training employees to use the technology…
- Where would you want to get the support from?
  - University collaboration? Industry associations? Technology vendors?

What kind of skills would your employees and managers need to learn to use AR or VR effectively?

- Do you think your employees could learn to use AR or VR by themselves?
- Where do you think these skills could be learned?
  - Self-learning? Internal company courses? Vendor training? Consultant companies?

How could universities help your organization in the adoption of these technologies?

- What sort of cooperation would you prefer?
- What would increase your interest in adopting these technologies?

How well does your organizational culture support experimenting and testing new technologies?

Technological issues

What kind of content would you want to use in AR or VR (e.g. 3D models, visualizations, organizational data etc.)?

- How would you get this content to AR or VR?
- What kind of issues do you think you would face in integrating AR or VR into these systems?

Have you been able to test out different AR or VR solutions?

- Where did you test them? How was the experience?

What benefits do you think AR or VR would bring to your organization?

Do you think your employees would resist using AR or VR? Why?

Do you plan to use AR or VR in the future?

- When?
- What needs to happen with these technologies for you to start using them in your organization?

External issues

Have your competitors used and benefited from AR or VR?

- Is this creating pressure to adopt these technologies?

Are any of your stakeholders (e.g. suppliers, customers) using these technologies?

- Is this creating pressure to adopt these technologies?

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PUBLICATION IV

Effect of user resistance on the organizational adoption of extended reality technologies: a mixed methods study

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PUBLICATION V

Six reasons why virtual reality is a game-changing computing and communication platform for organizations

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Beyond the pandemic, organizations need to recognize what digital assets, interactions, and communication processes reap the most benefits from virtual reality.

BY OSKU TORRO, HENRI JALO, AND HENRI PIRKKALAINEN

Six Reasons Why Virtual Reality Is a Game-Changing Computing and Communication Platform for Organizations

THE COVID-19 PANDEMIC created unprecedented disruptions to businesses, forcing them to take their activities into the virtual sphere. At the same time, the limitations of remote working tools have become painfully obvious, especially in terms of sustaining task-related focus, creativity, innovation, and social relations. Some researchers are predicting that the lack of face-to-face communication may lead to decreased economic growth and significant productivity pitfalls in many organizations for years to come.[13]

As the length and lasting effects of the COVID-19 pandemic cannot be reliably estimated, organizations will likely face mounting challenges in the ways they handle remote work practices. Therefore, it is important for organizations to examine which solutions provide the most value in these exceptional times. In this article, we propose virtual reality (VR) as a critical, novel technology that can transform how organizations conduct their operations.

VR technology provides "the effect of immersion in an interactive, three-dimensional, computer-generated environment in which virtual objects have spatial presence."[5] VR's unique potential to foster human cognitive functions (that is, the ability to acquire and pro-

IMAGE BY GORODENKOFF VIDEO PRODUCTIONS

cess information, focus attention, and perform tasks) in simulated environments has been known for decades.[6,8,32] VR has, thus, long held promise for transforming how we work.[33]

Earlier organizational experiments with desktop-based virtual worlds (VWs)—3D worlds that are used via 2D displays—have mostly failed to attract participation and engagement.[34,37] Increasing sensory immersion has been identified as necessary for mitigating these problems in the future.[18] Therefore, sensory immersion in VR through the use of head-mounted displays (HMDs) can be seen as a significant step forward for organizations transferring their activities to virtual environments. In this regard, VR is now starting to fulfill the expectations that were placed upon VWs in the past decades, as per Benford et al, for instance.[4]

However, VR has only recently matured to a stage where it can truly be said to have significant potential for wider organizational use.[17] In 2015, Facebook founder and CEO Mark Zuckerberg described VR as "the next major computing and communication platform."[38] Although VR has received this kind of significant commercial attention, its potential in organizational use remains largely scattered or unexplored in the extant scientific literature.

Drawing on contemporary research and practice-driven insights, this article provides six reasons why VR is a fundamentally unique and transformative computing and communication platform that extends the ways organizations use, process, and communicate information. We relate the first three reasons with VR as a computing platform and its potential to foster organizations' knowledge management processes and the last three reasons with VR as a communication platform and its potential to foster organizations' remote communication processes.

VR as a Computing Platform: Transformative Knowledge Management

VR can be used to simulate many organizational activities, depending on an organization's goals and demands. However, VR can also be seen as a transformative knowledge manage-

» key insights

- **VR can solve many critical bottlenecks of conventional remote work while also enabling completely new business opportunities.**
- **VR enables novel knowledge-management practices for organizations via enriched data and information, immersive workflows, and integration with appropriate IS and other emerging technologies.**
- **VR enables high-performing remote communication and collaboration by simulating or transforming organizational communication, in which altered group dynamics and AI agents can also play an interesting role.**

ment system because it provides new ways to manage and enrich information and workflows, and it has significant potential as a platform for integrating other information systems (IS) and emerging technologies. Next, we articulate three reasons why VR is a game-changing computing platform.

Reason 1: Enriched data and information

The current methods for examining complex information via 2D displays impose obvious limitations on the presentation of information to users. For example, it is difficult for users to understand how a certain room layout might fit with their work tasks purely from architectural 2D drawings.[17] VR tackles this problem by enabling enhanced spatial understanding of 3D content and data when compared to traditional 2D displays.[6,27] In VR, users can examine immersive 3D content spatially from multiple perspectives, such as birds-eye view or 1:1 scale).

In general, the ability to view 3D content in an immersive 3D environment is a powerful tool for fostering users' understanding of complex issues and scenarios.[8] Users can immerse themselves in the virtual content, which can be anything from the molecular structure of a medicine or the design of a movie scene.[12] In comparison with 2D displays, the information in VR is perceived to be more real and explicit and, thus, less abstract and ambiguous. This has far-reaching consequences for many organizations across different fields.[33]

VR technology is also highly adaptable, allowing different layers of information about the same content to be shown according to users' needs or preferences.[35] For example, in a virtual building, an architect can work with a different layer of information than a construction engineer or a potential customer. Ideally, this requires the addition of relevant metadata to the digital content to present it to various stakeholders automatically and efficiently on the basis of user profiles. If needed, adaptations in VR can further be based on natural and intuitive user behaviors, such as gaze or body movements.[33] As individuals are able to immerse themselves in data and information, and increase their contextual cognitive functions, VR adaptability has the potential for organizations to foster stakeholder engagement and participation.

Information can also be stored, organized, and retrieved spatially in VR. Spatial awareness (for instance, viewing the world in 3D) has long been used to enhance our information-recall skills. For example, multiple 2D displays, such as virtual desktops or whiteboards, can be positioned to a virtual space in an organized manner to display vast amounts of information.[19] Thus, users, especially in knowledge-intensive work, can personalize their own spatial information management system and increase their productivity through better recall of relevant information.

Reason 2: Immersive workflows and training

Many work activities are still bound to a specific physical space, which can be especially inefficient when large amounts of complex information and multiple stakeholders are involved. Moreover, many organizations still rely on labor-intensive business processes that do not scale efficiently, such as building expensive physical prototypes during product design. For example, if a physical miniature model of a building or a vehicle is created, it can be only displayed at a certain location and at previously agreed-upon times. VR provides an ideal platform for scaling up many of these activities by enabling an organization's stakeholders to manipulate different digital assets directly in VR from anywhere in the world in a shared immersive environment. For example, existing physical assets can be replicated in VR as digital twins to support many different use cases and workflows relating to product development or training.[15]

VR's most obvious use cases have long been in different training scenarios, for example, for fire safety or surgeries.[33] These use cases undoubtedly have benefits, especially when substituting activities that are extremely dangerous or expensive.[15] VR provides a major advantage for virtual workflows and training because, in addition to the benefits of enriched data and information, users can have intuitive and natural interactions with the digital content. Mounting evidence over the past three decades shows that when the VR system realistically responds to the user's actions, the user is likely to react and interact realistically as well.[32,33] Furthermore, as users perceive training in VR as real, the benefits of VR apply not only in the practice of hard but also soft skills, such as customer engagement or public speaking.[3] Therefore, acquiring professional skills and knowledge via the use of VR holds exceptional potential when compared to many conventional IT technologies.

However, VR is not limited to experiences that imitate our real-world expectations. It can also simulate impossible interactions, such as teleportation and moving heavy objects without gravity. VR can, thus, be used to create experiences that are "better than reality,"[21] based on the desired organizational effect. Organizations can further improve performance by enhancing the user-flow experience and motivation to efficiently perform tasks by gamifying features of VR and aspects of work routines. The user's performance and progression in, for example, different training scenarios can be tracked and verified automatically as in many games. In the context of workflows, for instance, relevant changes in a virtual building can be presented to users with navigation and distance markers or with estimations about changes in costs and the construction schedule.

Another advantage of VR is that it becomes a living 3D document and a version-control system that is modified by user interactions. The information can persist in the virtual environment as long as needed. VR content can be made available anywhere in the world at all times, which enables far more iterative collaboration and knowledge transfer within projects.[17] Users can also return to the digital assets even years after they were last used if they, for example, need to learn how some earlier design challenge was solved. The superior spatial recall of information in VR can further increase user efficiency in these work tasks.[19]

Reason 3: Increasing synergies with other emerging technologies and organizational IS

Fluent information transfer between an organization's IS and its stakeholders is critical to the organization's success. Taking into account VR's capability to enrich information and workflows, using VR as a platform for integrating existing IS comes with many interesting synergies.

For example, architecture, engineering, and construction (AEC) professionals use building information modeling (BIM) as a process to manage all information relating to construction projects. BIM consists not only of the physical 3D characteristics of buildings and infrastructure but also vast amounts of other information, such as construction times, costs, energy performance, and safety aspects. Exporting complex 3D assets, such as BIM, to VR was earlier a limitation in many organizational settings, but the latest VR software has tackled many of these challenges, even enabling live editing of 3D models in VR.[23] As VR can host complex 3D information in an immersive and interactive fashion, integrating organizational digital content, such as BIM, with VR can foster the effectiveness of organizational decision-making and virtual workflows.

It is also important to ensure that the information processed in VR is transferred in the other direction as well (that is, back to relevant IS or software). For example, when a client makes a purchase decision in VR, this information should be directly imported to the customer relationship management (CRM) and enterprise resource planning (ERP) systems. This also eliminates the need to manually edit the assets outside of VR, which reduces mistakes and redundant work. Ideally, the feedback that is given in VR should also provide immediately actionable tasks in other systems. For instance, 3D model annotations in VR should translate to tasks in the design software.

VR has countless technological synergies with other rapidly evolving technologies, such as artificial intelligence (AI), blockchain, and robotics. High immersion, interactivity, and user engagement in VR leverage and compound the organizational potential of these other emerging technologies. For example, AI-supported data visualizations can be brought into VR to help decision-makers steer organizational actions according to different trends and scenarios. The use of digital voice agents (DVAs), such as Google Assistant or Microsoft's Cortana, can help users complete different routine tasks in VR. Additionally, blockchain holds potential for fostering secure ownership and transfer of digital assets in VR. 5G networks enable VR to be used as an immersive interface for robotic teleoperations where, for example, the user's body motions can help achieve utmost accuracy.[21] The possibilities are practically endless; in the future, advancements in brain–computer interfaces (BCIs) provide fascinating possibilities where the use of VR could be, at least partly, controlled by brain signals.[21,22,33]

Virtual reality as a critical, novel technology that can transform how organizations conduct their operations.

VR as a Communication Platform: High-Performing Remote Communication

Every meaningful action in an organization, such as knowledge creation or decision-making, tends to depend on the success of communication and information transfer.[7] Therefore, the content in VR with the most potential is other people. Implementing communication features even in the simplest use cases, such as a virtual sales meeting in VR, can significantly leverage their potential. Accordingly, when communication features are integrated in more complex use cases, such as industrial design, their potential benefits continue to grow. When VR is used as a communication platform, it can be referred to as social virtual reality (SVR).

Next, we extend our analysis with three reasons why VR is a game-changing communication platform. Specifically, we describe how SVR enables multi-user social interaction that simulates real-life communication and extends it to new forms of remote work.

Reason 4: Every communication process can be simulated

A lack of face-to-face communication deteriorates the richness of communication in organizations. Deriving the most out of current communication tools can mitigate this problem but not fix it. In general, discussions, dialogue, and problem-solving benefit from synchronous communication (for example, video conferencing), whereas the transfer of a large amount of diverse and new information tends to benefit from asynchronous communication (for instance, email).[9]

SVR supports both of these fundamental communication processes—synchronous and asynchronous—in an intuitive and natural manner. Most importantly, SVR can simulate and extend face-to-face communication in a spatial setting. For example, 3D models can be loaded for discussion and dialogue, which fosters users' shared sense-making and understanding of how others interpret the available information. In contrast, text- or voice-based annotations provide an important feedback mechanism, where users are able to guide, assist, or exchange ideas more elaborately without time constraints. Annotations that are placed directly on 3D objects also maintain the context in communication. Ideally, SVR substitutes many different communication channels by merging them into one. Instead of a plethora of email discussions or video conferencing sessions, every detail from, for example, a product design pipeline, can be discussed and commented on in SVR.

SVR that includes tools for presentations and brainstorming, such as file sharing, whiteboards, and sticky notes, extends a physical meeting room to a virtual sphere. Avatar-based interaction, natural 3D space, and spatial sound enable multiple real-time discussions, where participants interact and communicate spatially as opposed to looking at each other on a monitor. In general, authentic spatial collaboration significantly enhances an individual's acquisition of professional skills, because it allows them to observe how others behave and operate.[8] Thus, connecting spatial communication with task-related content can make VR an ideal platform for collaboration and learning. One of the biggest advantages of SVR is also that the context of communication can be filtered to precisely fit the task at hand, excluding any outside distractions[35]. Due to the sensory immersion provided by HMDs, the task-related focus can be strictly controlled and maintained in SVR.

Current methods for examining complex information via 2D displays impose obvious limitations on the presentation of information to users.

Theoretically, SVR can facilitate every communication process imaginable and, thus, potentially exceed communication effectiveness compared to real-world settings. For example, one can follow a live keynote presentation, rewind to watch parts of it again, and then catch up with others, just like pressing fast-forward on a television set[1]. Additionally, SVR provides communication tools that are not available in the real world, such as a laser pointer coming out directly from an avatar's fingertip. As another example, avatar profiles as "floating billboards"[1] can disclose a participant's name, role in the organization, competencies, or other relevant information that we sometimes fail to remember about our colleagues. Perhaps disclosing personal interests in avatar profiles would generate informal social bonding that is otherwise difficult to achieve remotely.

Informal communication is something that organizations struggle to maintain in remote work. It is well known that informality is critical in terms of networking and generating innovations and new ideas. Some top executives are worried that extensive remote work during the COVID-19 pandemic will lead to a decrease in informality.[25] SVR provides an especially promising position for tackling this issue with informal virtual spaces, which can be just like a virtual version of a company's physical break room, characterized by the richness of communication and lack of formal rules, roles, and timetables. Informal virtual spaces can be used anytime, anywhere, without disrupting formal work processes.[11] Similarly, SVR can also facilitate social networking and maintaining work-related social relations at virtual events.[10]

Reason 5: Transformed group dynamics

Organizational group dynamics, such as trust development, are extremely difficult to manage in conventional remote work.[29] However, one of the novelties of avatar-based communication in SVR is its ability to facilitate many fundamental conscious and subconscious social interactions in a spatial setting. Avatar-based communication mimics the sensation of participants being with distant others physically. Just like physical bodies, avatars are both communicative tools and display systems. We communicate via avatars and our behavior allows others to sense and predict our emotions and intentions. Research shows that this behavior is largely automatic.[2] Today, much of this behavior—posture, interpersonal distance, gaze, and facial movements—can be tracked and displayed in VR, which opens up interesting business possibilities (and data privacy issues) for exploiting the user's behavioral or even biometric[16] data in VR.[2]

Of course, current SVR technology is often based on cartoonish avatars that are not yet able to display fully realistic body language or facial expressions. However, even the most basic forms of nonverbal communication, such as the gaze, can have a significant effect on communication performance. For example, the gaze communicates points of interest and, thus, fosters turn-taking and dialogue.[1] Recent advances in VR-related tracking technologies suggest that the avatar gaze, just like realistic avatar hand and facial movements, will soon be a standard feature of SVR.[16] Developments in these tracking technologies are critical because they affect the avatar's behavioral realism and the user's nonverbal communication performance.

It is well known that collaboration performance in remote work is built on strong interpersonal trust. However, conventional remote communication tools have raised different trust-building issues due to individuals' inability to physically and spatially observe how others behave and operate.[29] Although SVR does not yet offer fully realistic social simulation, it already holds tremendous potential for enhancing different trust-building mechanisms. As different formal and informal activities are increasingly integrated into SVR, users are able to learn more from others' skills and personalities and build shared experiences that are comparable to the ones from the physical world. Interestingly, a brain imaging study shows that the trust-building process in avatar-based communication is quite similar to that in face-to-face communication, except that real facial information works better when forming initial trust (that is, trust between strangers or acquaintances).[28] There is already commercial interest in building photorealistic avatars for VR, and they are expected to arrive in the coming years.[30]

Recent studies also suggest that reciprocal communication and behavioral realism seem to mitigate the uncanny valley—the "eerie sensation" users get when viewing almost, but not perfectly, photorealistic artificial faces.[31] This development can have interesting implications for the adoption of SVR in a highly formal work context, such as business meetings. But for now, why not satisfy our natural tendency to trust real human faces by embedding video conferencing into SVR?

However, SVR also allows users to display an altered version of themselves by customizing their avatars. Avatar customization is not just a novelty issue or something that connects only with consumer VR and entertainment. It is a powerful tool for nonverbal communication and online identity management. Studies show that avatar characteristics may have psychological and behavioral implications—a phenomenon known as the Proteus effect.[36] For example, Yee et al[36] show that taller avatars performed better in a negotiation task and attractive avatars disclosed more personal information. Further, the avatar's nonverbal behavior can be modified, filtered, or automated to not display the user's actual nonverbal behavior.[1] For example, an artificial smile (that is, an avatar's smile that is enhanced with algorithms) can leave everyone in a better mood after a virtual conferencing session.[26] How the Proteus effect and nonverbal modifications can transform group dynamics and information transfer in SVR holds much promise for future remote work.

Reason 6: AI agents as organizational actors

A vast amount of relevant information gets lost in organizational communication due to our limited information-processing capabilities.[7] However, introducing AI avatars—or agents—into SVR allows completely new forms of collaboration and information-sharing practices for organizations. Technology's "human-likeness" can affect how individuals interact with and form attitudes toward technology. Thus, if a technological entity looks and acts like a human, it is more likely to be perceived as, for example, "competent" instead of "functional."[20]

A variety of AI capabilities that mimic the human mind (for example, reasoning, object and speech recognition, and a dialogue system) can be attached to agents, and these capabilities can be expanded further with, for example, big data analytics.[14,24] Especially in knowledge-intensive work, agents can take an interesting position in different knowledge-creation and decision-making activities when an organization's stakeholders interact with each other and agents. In SVR, interactive agents can be available at all times, and their communication and information-sharing capabilities will increase in parallel with different AI developments.

Of course, agents could conduct different routine or assistive tasks comparable with the use of current chat bots or DVAs. However, unlike conventional AI, agents are also perceived as physical entities. For example, agents can physically navigate users through a virtual event or illustrate how to perform various organizational tasks, such as machine maintenance. Some training activities, for example, could be scripted using activities performed by real human users, tackling some issues with scalable content creation. Furthermore, one especially interesting domain for agents is sales and marketing. Agents can represent organizations in the digital realm in a scalable manner. Even an agent's nonverbals can soon be simulated according to the potential client's cultural background and preferences. If needed, a human user can be summoned to replace the AI. For example, when a customer wants more detailed information in a sales situation, the right salesperson with proper language preferences can take control of the AI's avatar.

The potential of agents as organizational actors probably increases with their behavioral realism. Some scholars describe a future where agents display increasingly human-like behavior, such as being able to mimic our nonverbal cues and emotions.[22,31] For example, agents might be able to detect our emotions from our voice pitch and facial information (our facial movements can already be tracked in VR). Agents could also create believable reciprocal communication patterns, and communication with agents could, thus, become nearly indistinguishable from human-to-human communication.[22] As a practical example, see the Seymour et al[31] study that presents Baby X, a computer-controlled agent.

Conclusion and Implications

VR is finally reaching a point in its development where it can be widely used

Table 1. VR as a computing platform—key implications for organizations.

Key aspect of VR	Potential organizational benefits	Key actions for realizing the benefits of VR
1. Enriched data and information	► Enhanced organizational knowledge creation and decision-making ► Reduced misunderstandings and uncertainty ► Increased stakeholder engagement ► Enhanced stakeholder understanding and recall of complex or domain-specific information	**Content creation for VR** ► Discover existing and novel forms of digital assets that could benefit from being viewed, stored, organized, and retrieved in VR ► Adapt content in VR according to stakeholder needs and preferences **Capacity-building for VR** ► Map out and create awareness for an organization's stakeholders who could benefit from the use of VR ► Develop capabilities for novel knowledge-management practices required in VR
2. Immersive workflows and training	► Workflows and training with unrestricted participation and interactions ► Enhanced acquisition of professional skills and knowledge ► Highly iterative and effective collaboration and knowledge transfer ► Enhanced user-flow experience and motivation to perform tasks efficiently	**Workflow creation for VR** ► Discover existing and novel workflows that benefit from VR-enriched data and information and have a sense of natural interactions in a spatial setting ► Enable persistent content for iterative workflows and project management **Implementation of training and simulations in VR** ► Prioritize training or simulation scenarios that would be impossible, dangerous, or costly to perform in real life ► Introduce VR in both hard- and soft-skills training ► Enrich training and simulation scenarios with playful and gamified elements
3. Increasing synergies with other IS and emerging technologies	► Fluent information transfer between different IS and the organization's stakeholders ► Compounding the benefits of various emerging technologies by leveraging the immersive and interactive nature of VR ► Novel business opportunities and use cases when VR is integrated with other emerging technologies	**Integration of IS with VR** ► Enable essential information flows about the organization and users between existing organizational IS and VR ► Enrich real-time organizational data and information via VR **Integration of emerging technologies with VR** ► Identify synergies between emerging technologies and organizational data, information, and workflows ► Incrementally introduce VR solutions that exploit the technological development of emerging technologies

Table 2. VR as a communication platform—key implications for organizations.

Key aspect of VR	Potential organizational benefits	Key actions for realizing the benefits of VR
4. Every communication process can be simulated	► High-performing remote communication and collaboration ► Enhanced dialogue and shared understanding ► Enhanced transfer of context-bound data and information ► Possibility to control the task-related focus ► Remote, casual interactions and networking	**Facilitation of interpersonal communication in VR** ► Introduce real-time, avatar-based interaction ► Enable the use of customized avatar profiles with individualizing information ► Enable new ways of avatar-based interaction that are not possible in the real world **Facilitation of formal and informal meetings and events in VR** ► Integrate task-related communication tools into VR environment ► Filter the context of communication according to tasks ► Exploit the use of avatar profiles in networking ► Build content and interactions for informal bonding
5. Transformed group dynamics	► New forms of online group dynamics and social bonding ► Novel trust-building mechanisms in a shared spatial setting ► Enhanced online identity management with potential behavioral implications	**Creation of realistic avatars in VR** ► Increase avatars' behavioral realism via advanced tracking technologies, such as eye, face, and body tracking ► Increase avatars' photorealism for communication processes that are highly formal or emphasize trust-building between unacquainted individuals **Introduction of nonverbal avatar enhancements in VR** ► Enable rich avatar customization as an online identity management system and to exploit the Proteus effect ► Build algorithms that modify, filter, or automate a user's nonverbal expressions and gestures in VR
6. AI agents as organizational actors	► Novel remote collaboration and knowledge-creation practices ► Agent-supported training and tutoring ► Agents as scalable organizational actors and physical entities in the digital realm	**Creation of agents to support knowledge-intensive work in VR** ► Build agents that provide information and support in repetitive or routine tasks ► Build agents with advanced AI capabilities that provide support in problem-solving and decision-making activities **Creation of agents as physical entities in VR** ► Build reciprocal nonverbal communication patterns for agents ► Enable the control and learning of practical and task-related skills for agents

to support and enhance various work tasks in organizations. However, its uniqueness as a computing and communication platform is still not widely understood. Our article builds upon VR's well-known potential to foster human cognitive functions in simulated environments and specifically aims at shedding light on its organizational implications in the context of knowledge management and remote communication. Based on a review of scientific literature and practice-driven insights, we have outlined six reasons why VR is a game-changing technology for organizations. As a computing platform, VR enables novel knowledge-management practices for managing enriched data and information and immersive workflows, which both benefit greatly from integrations with appropriate IS and other emerging technologies, such as AI. As a communication platform, VR can simulate every communication process imaginable (some of which can be AI-supported), which has significant potential for fostering an organization's online communication performance, knowledge creation, and group dynamics.

One of the main takeaways of this article is that VR enables not just substituting the physical with virtual but also novel ways of working. VR can make existing work more effective, but it can also bring completely new business opportunities for organizations. We elaborate these potential benefits for organizations in Table 1 and Table 2. Due to rapid developments in VR technology, organizations have not yet exploited these various possibilities afforded by the newest VR hardware and software. It is important for organizations to identify the business processes where the easily capturable benefits of VR converge with ease of adoption. As with any new innovation, organizations will need to develop new skills and capabilities to export their relevant digital assets, interactions, and communication processes to VR.

With sufficient capabilities, VR can also be used to radically transform organizational operations. However, VR is not a one-size-fits-all solution. Its benefits often emerge in very specific use cases (such as a particular simulation) that do not necessarily translate to a monetizable VR service that could serve a larger group of companies. Instead, VR development is often based on customized solutions, which has made it difficult to scale and adapt them to different organizational contexts.

This article has identified the benefits of VR specifically for the context of knowledge management and remote communication in order to obtain key insights about the game-changing nature of VR for organizations. We also provide several key actions in Tables 1 and 2 that organizations can carry out to take full advantage of the six key aspects of VR we described and to realize the organizational benefits thereof.

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