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

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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.

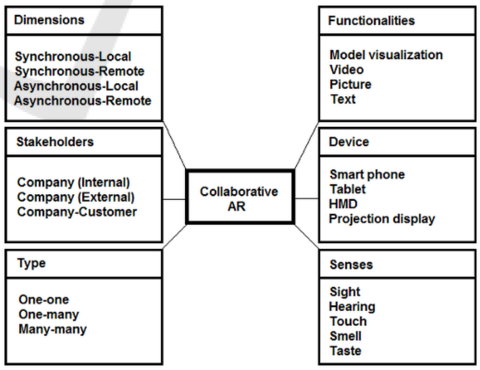

Figure 1: Characteristics of collaborative AR.

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.

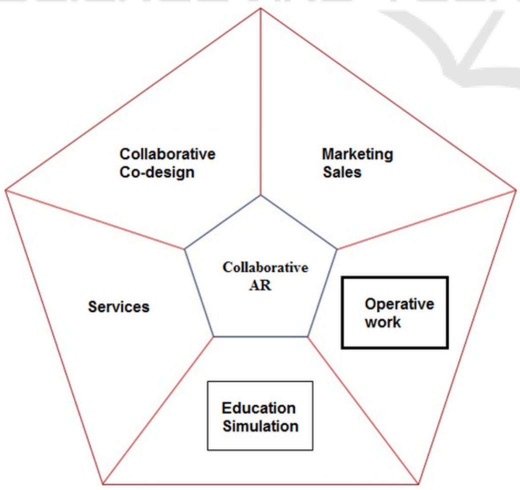

Figure 2: Application areas of collaborative AR.

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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