AUGMENTED REALITY – A GAME CHANGING TECHNOLOGY FOR MANUFACTURING PROCESSES?

Research paper

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Abstract

Companies are experiencing more and more pressure to increase productivity and quality while cutting costs in the digital era. The integration of innovative new technologies in the work process is crucial when transforming businesses to cope with these increasing requirements. In this research article, we investigate the current integration of such an innovative technology - augmented reality (AR) - in the manufacturing industry. For that purpose, we conduct a systematic literature review as well as a practically oriented search for augmented reality use cases in the field of manufacturing. We contribute to the current literature on augmented reality and digital transformation by analysing and synthesizing 95 articles and use cases to identify the current and the potential future role of augmented reality in the manufacturing industry and its impact on different work processes. We show that theoretical proof of concepts articles mostly focus on improving production operations, especially assembly processes, while the majority of practical use cases of currently applied AR solutions involve maintenance and inspection processes. Based on these findings, relevant future work opportunities for researchers as well as practitioners are derived.

Keywords: Augmented Reality, Manufacturing Industry, Digital Transformation, Systematic Literature Review.

1 Introduction

From the perspective of the customer, digital transformation is already an integral part of the consumer's everyday life in forms such as mobile Internet, social media, and e-commerce. At the same time, digital transformation is penetrating the industrial value chain as businesses are rethinking customer experience, business models and operational processes (Westerman et al. 2011). Since the digital revolution has blurred or even entirely eliminated former industry boundaries, the new digital world comprises neither predefined boundaries nor industry-based limitations and is hence spreading everywhere (Press 2015). Thus, more and more companies are seizing digital opportunities by investing heavily in transformation-enabling technologies in order to achieve competitive differentiation.

Businesses themselves are confronted with the fact that the digital revolution is forecasted to drive radical structural changes in business models and operational processes as increasing data, interconnectivity, automation, and enhanced digital customer interfaces are challenging currently existing value chains. As stated by Krylovetsky, a solutions architect at Walt Disney, "[w]e're in a space where if you don't transform, you don't survive" (Dell and IDG 2015, p.1). Failing to keep up with the digital transformation will result in decreased market shares and a shrinking customer base. It is estimated that 605 billion Euros in total could be lost to international competitors by 2025 if the manufacturing industries in the EU do not respond to the digital revolution appropriately (Bloching et al. 2015).

In 2011, Intel announced that a mistake in a companion chip for a graphics-processor chip for PCs will cost them 700 million dollars in repairs and 300 million dollars in lost sales (Takahashi 2011). This prominent example confirms that the tiniest mistake in manufacturing can cost several hundred million dollars. Hence, companies are reaching out to find solutions to reduce error rates, increase productivity, cut costs and ultimately gain a competitive advantage over global competitors. In the context of this situation, we explore the current and potential role of augmented reality (AR) in the digital transformation of manufacturing processes.

AR refers to overlaying virtual objects over the real environment. This is distinct from virtual reality (VR), which fully emerges its user in a computer-generated world without any real components. As shown in Figure 1, the distinctions are not clear cut but rather represented on a continuum. Mixed reality can refer to anything between a nearly virtual environment and a real environment augmented with virtual or real objects. This terminology is important for this paper since some mixed reality applications can be relevant use cases.

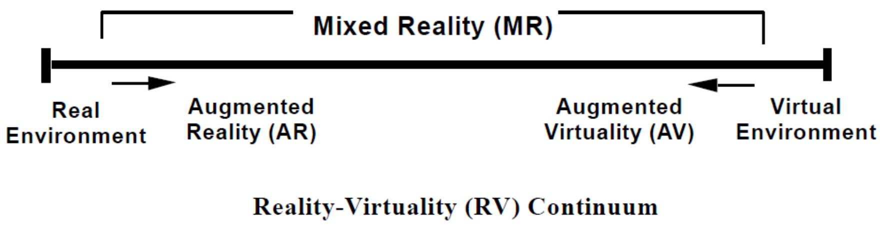

Figure 1. The Reality-Virtuality Continuum by Milgram et al. (1994)

Applications of AR in the business context include “designing medical implants, painting virtual images, training for construction procedures, treating phobias, exploring scientific models, viewing the activity within multiplayer games, and delivering telepresence and teleimmersion” (Rosenbloom 2004, p. 30). Experts estimate that the market for AR and VR will increase from 5.2 billion dollars in 2016 to 162 billion dollars in 2020 (Business Insider Intelligence 2016). AR will have an extensive impact on the future of work and some sources even say, that it is not just being increasingly used on factory floors, but that it will revolutionize it (Reuters 2017). According to Dan Arczynksi of Index AR Solutions “Augmented Reality isn’t a technology with incremental 2-5 percent savings. […] It’s a game changing application with measurable savings ranging from 25 percent to more than 90 percent“ (Greenfield 2016). He justifies this statement by arguing that with AR, one does not just buy equipment, but frees up cash flows by speeding up processes. It is important to determine whether AR is indeed able to improve manufacturing processes and how exactly these improvements look like.

In summary, we address two main research problems in this paper. First, we synthesise and integrate theoretical and practical literature on AR in the manufacturing sector to identify research gaps. Second, we quantify improvements attributed to the incorporation of the AR technology based on current applications of AR in manufacturing businesses.

The remainder of the paper is as follows. First, a theoretical background on the manufacturing industry and its processes is given. Section 3 includes the systematic literature review based on scientific data. Section 4 follows with a practical search for use cases of AR in the manufacturing industry. The findings from the theoretical and practical search are synthesized in Section 5. Section 6 contains a summary of the main findings and the major contributions.

2 Theoretical Background on Manufacturing Industry

As part of the goods-producing industries super-sector, the manufacturing industry "comprises establishments engaged in the mechanical, physical, or chemical transformation of materials, substances, or components into new products" (United States Department of Labor 2017). These new products can either be sold as a finished good to costumers or serve as an intermediate good that is sold to other manufacturers who use it to produce more complex products. Within the global manufacturing industry, the largest sub-sectors by output are automotive, chemicals and pharmaceuticals, followed by regional processing such as printing, food and beverages (Manyika et al. 2012). Some of the largest manufacturing companies by revenue are Toyota, Volkswagen Group, Samsung Electronics, Daimler and General Electrics (Statistic Brain 2017).

While the service industry plays an increasingly important role in advanced economies, manufacturing still plays a key role for growth in developing countries (Szirmai 2009). From a global point of view, manufacturing businesses continue to grow and accounted for 16% of global GDP and 14% of employment in 2012 (Manyika et al. 2012). However, the sector is undergoing major changes in nowadays globalized world, as product development processes are getting more complex to account for the trend of mass customization and increasing product versatility (Ong and Nee 2013). Furthermore, customers are rapidly changing their demands, leading to shortened product life cycles for manufacturers (Pentenrieder et al. 2007).

The manufacturing process refers to the steps that are taken to transform raw materials into a product. One needs to ensure that the machinery and people have the right materials, components and information at the right time in the right place. In order to do so, one has to plan and coordinate the material and information flows, document the procedures and make constant improvements to avoid bottlenecks (Chang 1995).

From a manufacturing point of view, the product manufacturing lifecycle can be divided into the following steps. The first phase is the planning and design phase, where the product is engineered and design documents are created. Secondly, a prototype is built and tested to prepare for mass production. Work instructions are created and the workers are trained. During mass production, production operations such as assembly take place and the product is built. Subsequently, inspections and maintenance are done to maintain and constantly improve the produced product and control its quality (Drislane 2015). The last step is the product end of life which also requires careful planning to avoid any losses of resources. However, since this step is not relevant for the case of AR, we exclude it for the further analysis. We will use this lifecycle to categorize use cases for AR later on in this paper. At this point, it is important to distinguish between manufacturing and construction. While manufacturing - as explained above - refers to the production of finished products, construction refers to the creation of physical structures, for example buildings and roadways (Kokemuller n.d.). Therefore, use cases in the field of construction are out of scope of this paper.

3 Systematic Literature Review

We follow the approach by vom Brocke et al. (2009) to conduct the systematic literature review. Defining an appropriate keyword or an appropriate keyword combination for a literature review is essential. For this paper, a generic search for the keyword *Augmented Reality* would lead to an unmanageable number of results, most of which would not even be relevant for the manufacturing industry. Therefore, the keyword combination *Augmented Reality AND Manufacturing* is selected. Limiting the search further with additional terms does not make sense for this paper, since the number of results for the selected keyword combination is straightforward and a further limitation would unnecessarily increase the risk of missing relevant results.

Characteristic	**Categories**			
Focus	research outcomes	research methods	theories	applications
Goal	integration	criticism	central issues	
Perspective	neutral representation		espousal of position	
Coverage	exhaustive	exhaustive and selective	representative	central/pivotal
Organization	historical	conceptual	methodological	
Audience	specialized scholars	general scholars	practitioners/politicians	general public

Table 1. Taxonomy of the Literature Review following vom Brocke et al. (2009)

Table 1 depicts the taxonomy used for this papers literature review. The focus is clearly on applications since this paper aims at analyzing use cases of AR in manufacturing. The goal is to analyze central issues and integrate the findings to provide a common ground for future researchers. The structure of the results is supposed to be conceptual with a neutral representation of the results. A representative coverage allows to consider all relevant literature while an exhaustive coverage would be unrealistic and a pivotal search too narrow. The audience are specialized scholars in the manufacturing industry as well as practitioners and politicians due to the practical relevance of the discussed use cases.

We chose two major databases for the literature review. Firstly, we considered ACM conference proceedings and journals. Secondly, we used the IEEE digital library. This combination allowed us to discover the applications of AR in manufacturing that we focused on. Subsequently, we conducted a backward search to discover further relevant scientific literature and to ensure that the most relevant literature resources were detected. The literature review was conducted between 8th March 2017 and 19th March 2017. We searched the two selected outlets using the defined keyword combination. As illustrated in Table 2, we marked all results as hits. For each one we analyzed weather or not it is relevant to AR in manufacturing and whether or not it is in alignment with the characteristics defined in the taxonomy. If this is the case, we marked it as a final hit.

Database	**Search**	**Coverage**	**Hits**	**Final Hits**
ACM Digital Library	“all fields”	since 1993	67	16
IEEE Xplore	“author keywords”	since 1992	5	4
IEEE Xplore	“abstract”	since 1992	79	18*
Backward Search				42
Total			**151**	**80**

Table 2. Summary of the Literature Review Findings (: 3 more hits were relevant but they were already included in the final hits of the “author keywords” search)*

In order for a hit to be eligible for the final hit list, it must be relevant for the manufacturing industry as defined in Section 2. Sometimes it is difficult to decide what is still considered to be part of the manufacturing industry and what belongs to a related industry such as construction or logistics. For example, some papers (e.g. Reif et al. 2009) describe AR assisted order picking systems which are part of a logistics warehouse process rather than a manufacturing process. Gamification of industrial work processes (e.g. Korn et al. 2015b) is also out of scope.

Furthermore, the respective result must focus on AR rather than VR. In cases of mixed reality, we further investigated whether it is acceptable to consider it an AR application. When a paper describes a technology that could improve manufacturing processes but AR just plays a small part in it, it must be decided if this is sufficient to make the paper a final hit. For example, Foursa et al. (2006) describe a project where AR plays just a small part and it is just presented as an idea rather than a use case, which is why it is not considered a final hit.

It is also important that the result focuses on the application of AR. Relevant papers must present at least a proof of concept with a field experiment, a user study, a trial implementation or a discussion about the application of AR in a real-world environment. For example, papers that theoretically discuss technical details behind an AR related technology (e.g. a location tracking system) are not considered relevant if they do not explain its application in a manufacturing environment. For example, Kim et al. (2010) just mention that their ideas might be applicable in the manufacturing industry, without further describing or testing this statement. Therefore, this is not sufficient to make this literature relevant for this paper.

Several results mostly focus on a technology or technique that could be applied to build a use case, without focusing on the latter. We clearly distinguished whether a technical result has a sufficient practical relevance to be considered relevant for this paper. For example, when test scenarios of the described technology, technique or method are carried out and described, the respective result is considered relevant after all (e.g. Knopfle et al. 2005) since this shows a sufficient level of application.

For the literature search in IEEE the search of *Augmented Reality AND Manufacturing* lead to 4,784 results which included many irrelevant results. Therefore, we selected the search field "author keywords" instead of "full text & metadata". After this change, we found 5 results. Afterwards, we conducted a search using "abstract" instead of "full text & metadata", leading to 79 results, 4 of which we already found with the "author keywords" search. We applied the same criteria as described to ACM to assess whether a hit is indeed in the scope of our research goal.

After this selection process, the references of the 38 final hits are checked for further relevant literature (backward search). The same criteria already described for the ACM and IEEE search are applied to identify whether or not an article is relevant. One results found through the backward search (Regenbrecht et al. 2005) is considered especially relevant for this paper since it introduces many manufacturing related AR projects. Therefore, we conducted an extra backward search for this paper alone, which led to 2 new relevant articles.

3.1 Analysis and Synthesis of Literature Review Results

We scanned each AR application in the articles with respect to the manufacturing process it supports (according to the phases described in Section 2). Furthermore, it is analyzed how far in the testing process each result is and which technology it uses to render AR.

It can be seen that 79 of the 80 results represent proof of concepts that have been evaluated in small scale field tests and user studies. Only one result can be described as a real use case since it has already been applied in several industrial settings within a pilot project of the Volkswagen Group Research (Pentenrieder et al. 2007).

Half of the identified concepts aim at improving production operations (especially assembling processes), while 12 articles focus on the planning and design stage, 10 on inspections and maintenance, 7 on training and only one result on prototyping. 10 results do not target a single phase but clearly aim at improving at least 2 of the introduced processes, mostly including production operations and planning and design.

Some papers describe in detail the underlying technology of the AR system from image processing to tracking to rendering. However, analyzing all technical layouts for each individual final hit is out of scope for this paper. Therefore, only the aspect of how AR is rendered is analyzed for each result since this part is the most relevant to the integration of the technology in the work places and processes. There are three basic options for rendering AR (Funk 2015).

The first one is using head mounted displays (HMDs) which are also referred to as smart glasses or digital eyewear. While optical see-through HMDs use an optical beam splitting element to combine real and virtual worlds on a transparent display, video display HMDs directly project the content on an opaque display (Kiyokawa et al. n.d.). Amongst other things, HMDs differ in size, weight, power, resolution. However, they all share the common advantage of providing a unique hand-free viewing experience (Melzer 2010). The second option are handheld displays such as tablets and smartphones. One major advantage are lower costs than customized HMDs. The third option are spatial displays which are also referred to as projectors since they project virtual items in real environments.

HMDs are the most popular option among the identified proof of concepts (30 results) followed by projectors (18 results). Handheld devices are only used in 8 results. For 15 of the 80 results it is not specified which technology is used to render AR, mostly because the results found through the literature review are only proof of concepts which can be applied in multiple scenarios with different rendering options. 5 results compare the effectiveness of different rendering methods. For example, Büttner et al. (2016) find that HMDs are less effective than projectors in providing instructions for production workers. Similarly, Yuan et al. (2003) find that the assembly time using HMDs is relatively longer than the monitor-based method. 4 results use other technology that cannot be attributed to one of the three introduced rendering options since they use an innovative hybrid option (combination of HMD and touch panel display system) (Wiedenmaier et al. 2003), an integrated animation system (Balcisoy et al. 2000) or stereoscopic video see-through displays (Iwamoto et al. 2015a and 2015b).

4 Practical Search

Since the topic of this paper is very current and has a high practical value which is not sufficiently reflected in scientific sources, we conducted a practical oriented search using the Google search engine. Press articles and other online sources are scanned for AR applications and use cases in the field of manufacturing. The relevant findings are summarized and it is identified for each use case how AR helps improve the respective manufacturing work processes. We applied the same criteria as in the systematic literature review to decide whether or not a result is relevant. It is also important to notice that speculations about a company's usage of AR are not considered relevant for this paper, since there is no solid evidence and thus no details about how they might use AR to improve their manufacturing processes.

When we searched for *Augmented Reality manufacturing use cases*, 801,000 results appeared. Obviously not all results can be checked individually, which is why we needed to develop a search strategy. One strategy would be to use this keyword and check the first few result pages. However, the results might be too generic and it might be difficult to draw conclusions about existing research gaps etc. Therefore, we decided to first search for *Augmented Reality X*, where X stands for the respective manufacturing process identified in Section 2. This more specific keyword search has the advantage that we also find results for manufacturing areas in which AR plays a minor role (and thus do not appear first when generally searching for *Augmented Reality and manufacturing*). For each phase, the first results page is considered since the most relevant findings appear there.

First, we searched for *Augmented Reality Manufacturing Planning*. However, we did not find any specific use cases for this category on the first results page. Nevertheless, we found some generic use cases which are presented in the second part of this section. Similar results occurred when we searched for *Augmented Reality Manufacturing Design*, *Augmented Reality Manufacturing Prototype*, *Augmented Reality Manufacturing Inspection* and *Augmented Reality Manufacturing Maintenance*. While in the literature review most proofs of concept belong to the production operations phase, the respective search results mostly refer to other phases. This probably occurs because the term *production operation* is too broad to find relevant results. Therefore, the search for this phase is repeated with the keyword *Augmented Reality Manufacturing Assembly*, since we discovered in the literature review that assembly is a huge field for AR within production operations. Surprisingly, we did not find any new relevant results specific for the assembly process. We additionally conducted a more generic search process using keywords like *Augmented Reality Manufacturing, Augmented Reality Manufacturing Use Cases* and *Augmented Reality Manufacturing Examples* and compared the results with the already found ones to ensure that no relevant results are missed. However, no new relevant results appeared.

Overall, we identified 15 relevant use cases in the manufacturing industry (cf. Table 3). 8 use cases aim at improving inspection and maintenance processes while 4 use cases focus on production operations, 2 on training and one on prototyping. We did not find any use case that aims at improving the planning and design process in manufacturing.

The use case for the prototyping phase refers to the Unifeye Prototyping software developed by Metaio which is currently used by Volkswagen, Audi and Ford to simplify and accelerate workflows in the area of prototype design and construction (Assembly Magazine 2010).

The two training related use cases are from Bosch and the United Nations Industrial Development Organization (UNIDO). At Bosch, 10,000 service technicians train for braking and direct injection technology using AR technology rendered through the Oculus Rift headset (Sanjiv 2016). This is an example of the partially ambiguous terminology of AR, VR and MR, we described in Section 1. Although the Oculus Rift is a VR headset, it can also be used in the context of AR by using external cameras that capture the real world and project it to the display of the VR headset. Thus, the company refers to it as AR. At UNIDO, students learn the basics of diesel engine maintenance using AR on tablets (Netland 2016).

There are four use cases in the field of production operations. At Lockheed Martin, engineers use AR glasses during the assembling process for the F-35 aircraft. This increases their accuracy to 96%, while working 30% faster (Sanjiv 2016). Similarly, an AR technology is currently being implemented in the assembly line of the A330 cabin furnishing operations at Airbus. Final assembly line technicians wear connected glasses that enable precise positioning during the cabin installation marking process. By incorporating this AR technology, the "time spent per aircraft on marking operations is divided by six with an error rate reduced to zero, regardless of the user's experience" (Aerotime 2015).

At Boeing, the Google Glass is used to assist aircraft wire harnessing which cuts production times by one-fourth and error rates by half (Netland 2016). Another company that incorporates AR in their production operations is Volvo, which uses Microsoft HoloLens in their assembly lines (Wright 2017). When it comes to inspection and maintenance, a relatively large number of use cases can be found. Bosch Automotive Service Solutions has an app called *Common Augmented Reality Platform (CAP)* which allows people to do exactly what their mechanics can. Figure 2 shows a view from *Bosch Flex-Inspect* which allows for live diagnosis using AR. With the help of AR, information (e.g. text instructions or 3D objects) can be blend in the real world when the camera of a tablet or a smart glass turns to a vehicle. This reduces the time needed for complex repair work by 10-15 percent (Robert Bosch GmbH 2016).

Since 2011 Airbus is using AR technology in manufacturing processes for several purposes under the brand Smart Augmented Reality Tool (SAugmented RealityT). Approximately 1,000 employees use SAugmented RealityT on more than 130 tablet devices which reduces the inspection time by 80% and helps avoid costly corrections later in the manufacturing process, leading to a high return on investment (Airbus Group n.d.). BMW uses smart glasses to diagnose where a fault is and to instruct the wearer step-by-step on how to fix it (Woollaston 2014). MAugmented RealityTA (Mobile Augmented Reality Technical Assistance) is an innovative service support tool for the Volkswagen XL1, which Volkswagen uses to identify work items quicker and more accurately (Volkswagen AG 2017). ThyssenKrupp is conducting field tests with a Microsoft HoloLens based AR system that enables field service technicians to see what went wrong and how to fix it when looking at a piece of elevator equipment (cf. Figure 2). This enables them to perform a job in 20 minutes instead of 1-2 days.

Mitsubishi introduced an AR system that enables a technician wearing smart glasses to confirm an order of the inspection on a display and then enter the results by voice, which helps reduce the workload and avoid entry errors (Mitsubishi Electric 2016). In a pilot program at Porsche, professionals in the field of quality assurance can take pictures of assemblies on vehicles under inspection and then compare them with images provided by the companies' suppliers. Through the AR overlay quality gaps can be detected more easily, resulting in significant time savings (Wright 2017). Newport News Shipbuilding has introduced mobile based AR technology to more easily identify the structures one needs to work on (Greenfield 2016). One inspection process that usually takes 36 hours could be trimmed to 90 minutes (LaWell 2017).

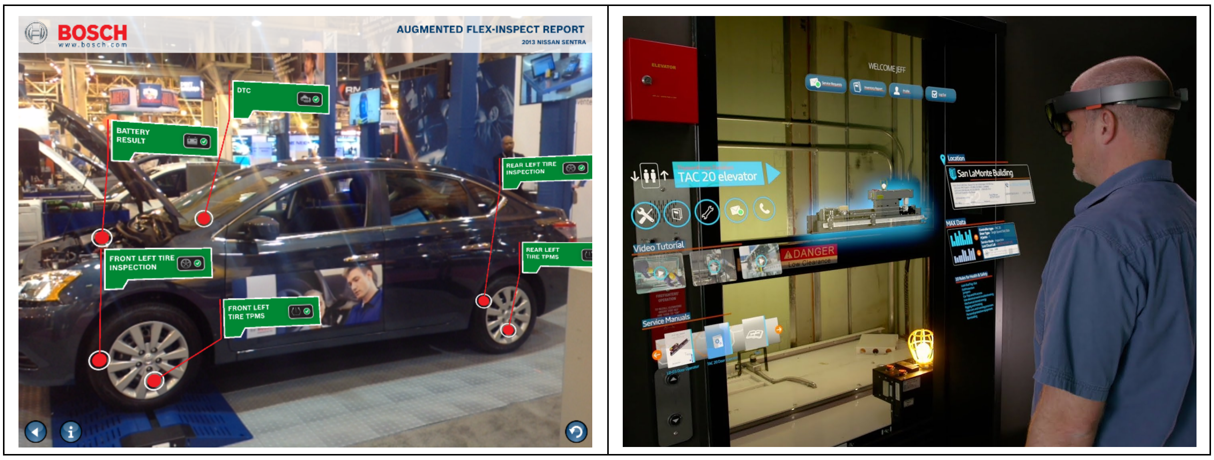

Figure 2. Bosch-Flex-Inspect (RE'FLEKT n.d.) and ThyssenKrupp's Elevator Maintenance System (Weinberger 2016)

It is interesting to notice that most results are from the automotive and aerospace industry. It can also be noted that most companies do not quantify the improvements related to AR (at least not publicly available) but speak generally well about the advantages related to AR. Table 3 summarizes the main findings from the practical search.

Phase	Company	Rendering Technology	Improvement quantifications
Prototyping	Volkswagen, Audi, Ford	Display	Not quantified
Training	Bosch	Oculus Rift headset	Not quantified
Training	UNIDO	Tablet	Not quantified
Production Operations	Lockheed Martin	Smart glasses	Increases engineers' accuracy to 96%, increases work speed by 30%
Production Operations	Airbus	Google glasses	Cut production times by one-fourth, cut error rates by half
Production Operations	Boeing	Microsoft HoloLens	Not quantified
Production Operations	Volvo	Smart glasses	Not quantified
Maintenance	Mitsubishi	Smart glasses	Not quantified
Inspections & Maintenance	Bosch Automotive Service Solutions	Tablet or smart glasses	Increases speed by 10-15%
Inspections & Maintenance	BMW	Smart glasses	Not quantified
Inspections & Maintenance	Volkswagen	Tablet	Not quantified
Inspections & Maintenance	ThyssenKrupp	Microsoft HoloLens	Not quantified
Inspections & Quality Insurance	Porsche	Tablet	Not quantified
Inspections & Error Prevention	Airbus	Tablet	Time reduction of 80%
Inspections & Error Prevention	Newport News Shipbuilding	Mobile devices (e.g. tablet or smartphone)	Time reduction from 36 hours to 90 minutes

Table 3. Overview over Augmented Reality Use Cases in Manufacturing

5 Synthesis of Theoretical and Practical Results

In theory, businesses can plan their production and assembly process in an augmented world right from the start. In this phase, AR has the potential to help refine and optimise design specifications, review concepts and opinions and quickly adjust and modify plans. Products can be manufactured more efficiently through a rapid, iterative design cycle aided by AR (Advice-Manufacturing 2017). While we found proof of concepts that take advantage of this in the systematic literature review, no use case in the planning and design phase could be identified in the practical search (cf. Table 4). This is an interesting result for practitioners because it shows that there is an unexplored potential for the use of AR in this phase. The identified articles can serve as a good starting point for developing respective applications.

Applying AR in the prototyping phase is not very popular neither in theory nor in praxis despite its potential for increasing the speed and accuracy of creating and evaluating prototypes inexpensively. Thus, future researchers should try to provide AR solutions that specifically address this phase in order to make them more tangible for the industry.

	Planning & Design	**Proto-typing**	**Training**	**Production Operations**	**Inspections & Maintenance**	**Multiple**	**∑**
Theory	**12**	**1**	**7**	**40**	**10**	**10**	**80**
HMDs	Dangelmaier et al. 2005, Doil et. al. 2003, Fruend & Matysczok 2015, Klinker et al. 2002, Ong et al. 2007, Ong & Shen 2009		Boud et al. 1999, Gorecky et al. 2013, Hahn et al. 2015	Caudell & Mizell 1992, Feiner et al. 1993, Henderson 2011, Mizell 1994, Molineros & Sharma 1999, Paelkte 2014, Peppolonie et al. 2015, Quint & Loch 2015, Raghaven et al. 1999, Reiners et al. 1998, Rice et al. 2015, Sims 1994, Syberfeld et al. 2015, Tang et al. 2003	Goose et al. 2003, Platonov et al. 2006	Friedrich 2004, Luo & Ge 2015, Schwald & Laval 2003, Shen et al. 2006, Zhao & Shen 2015	31
Handheld	Oh et al. 2015			Billinghurst et al. 2008, Sagglomo et al. 2016, Sharma & Molineros 1996, Zhang et al. 2008	Domova et al. 2014, Zhang et al. 2010	Pentenrieder et al. 2007	8
Projectors	Otto et al. 2014	Porter et al. 2010		Büttner et al. 2016, Funk et al. 2002, Funk et al. 2015, Gorecky et al. 2011, Korn et al. 2015, Korn et al. 2013, Korn & Funk & Schmidt 2014, Korn & Schmidt & Hörtz 2013, Mendivil et al. 2013, Obinata et. al. 2016	Borrmann et al. 2016, Kosch et al. 2016, Lipson et al. 2015, Zhou et al. 2011, Zhou et al. 2012	Funk & Schmidt 2015	18
Comparison of different devices	Sharma et al. 1999			Büttner et. al. 2015, Xianjun et al. 2003, Yuan et al. 2003, Yuan et al. 2006			5
Other	Balcisosy 2000, Wiedenmaier et al. 2003		Iwamoto et al. 2015b	Iwamoto et al. 2015a			4
Not specified	Pan et al. 2006		Liu & Zhang 1998, Pathomarce & Charoenseang 2005, Zhang et al. 2011	Alt & Schreiber 2001, Eversheim et al. 2001, Hou & Wang 2013, Loch et al. 2016, Mizell 2001, Sharma & Molineros 1997, Wang et al. 2010	Knöpfle et al. 2005	Baratoff & Regenbrecht 2004, Navab 2004, Regenbrecht et al. 2005	14

	Planning & Design	Proto-typing	Training	Production Operations	Inspections & Maintenance	Multiple	∑
Praxis	**0**	**1**	**2**	**4**	**8**	**0**	**15**
HMDs			Sanjiv 2016	Sanjiv 2016, Aerotime 2015, Netland 2016, Wright 2017	Mitsubishi Electric 2016, Woollaston 2014, Weinberger 2016		8
Handheld			Netland 2016		Robert Bosch GmbH 2016, Volkswagen AG 2017, Wright 2017, Airbus Group n.d., Greenfield 2016		6
Projec-tors							0
Other		As-sembly Maga-zine 2010					1

Table 4. Synthesis of Theoretical and Practical Results aligned to the Manufacturing Cycle

However, it must be noted that sometimes the prototyping is integrated in the design and planning phase which is why AR might play a slightly bigger role than the numbers in Table 4 might suggest.

AR for training purposes in the manufacturing processes makes it more likely for the trainees to retain the learning since it is embedded in the same context in which the actual job task is performed later on. Furthermore, it reduces the risk of errors and delays when performing tasks and allows all employees to rapidly access the most current training modules (Hill, A. n.d.). In addition, an AR based training system allows the trainees to train as many times as they wish, allowing them to improve their skills through trial and error (Iwamoto et al. 2015b). Some companies - both in theory and in praxis - already take advantage of this. For AR in production operations we found a huge gap between its popularity in theory and in practical use cases. While in the literature review production operations were clearly the most popular application area for AR in manufacturing, this is not at all the case in practical business contexts. Researching the underlying causes for this discrepancy and identifying why it is especially difficult to apply the theoretically developed concepts in this area in the real world, could be an important endeavor in the future. This is also important since there are notably many advantages - such as accelerated assembly speed and improved quality - of incorporating AR in this area. Several sources confirm that AR-based assembly guidance is more effective than alternative instruction forms and one study even identifies that it can reduce the error rate of an assembly task by 82% (Tang et al. 2003). Nowadays many variations of each product are introduced to perfectly fit customer desires. For manufacturing this means that assembly line workers often encounter slight changes in the work processes or used materials. With the help of AR, critical information about the currently desired configuration can be delivered whenever and wherever needed (Hopkins 2016). Aiding production workers with AR also allows more workers to do high-skilled jobs. This is important since manufacturing job openings are already outpacing the supply of qualified candidates (Abraham and Annunziata 2017). AR can help counteract this growing gap in the workforce.

Applying AR to the inspection and manufacturing process allows for an early detection of discrepancies between the manufactured article and the desired order, using the latest digital models (Davies n.d.).

According to the literature review, AR in inspections and maintenance plays a minor to medium role. However according to the practical search, this is currently the most popular application area. Here again, it is important to research why this is the case.

As shown in the following table, the major application fields for AR in manufacturing in theory are production operations and planning and design, whereas in praxis inspections and maintenance and production operations are the most popular fields.

The concept matrix also shows that HMDs are the most popular choice for rendering AR in theoretical proof of concept articles as well as in actual use cases. However, the second place differs, since projectors are much more popular in theoretical proof of concepts than in praxis. On the other hand, handheld devices such as tablets and mobile phones are more popular in use cases than in proof of concepts. This can probably be attributed to the practical goal of cost saving when faced with expensive alternative rendering technologies. However, investigating alternative explanations could be a potential research question in the future.

Another interesting research project for future work could be the investigation of how exactly process improvements related to AR are currently measured in each identified use case. This could help to better quantify the advantages related to the application of AR to individual manufacturing processes and it could also help to build guidelines on how companies can better measure this to motivate other companies to start shifting towards this technology for their manufacturing processes. However, this would require access for researchers to the currently applied solutions in companies.

After having identified questions for a future research agenda in this area, the respective limitations must be considered. First it is important to notice that there are also drawbacks to applying AR to improve manufacturing work processes. For example, the long-term use of AR technologies in the working place might cause stress for its user (Tumler et al. 2008). This might be related to the fact that AR technologies are relatively new and still have a lot of potential for improvement. AR involves placing graphical overlays over the real environment. For example, it has been reported that "every time you move your hand up and down, the actors and video overlay will shake in relation to the background, taking you out of the experience" (Mest 2016). Other limitations for companies to introduce AR to their manufacturing processes might be the involved costs of up to 300,000 dollars to build an AR application as well as the required experience in custom app development (Klubnikin 2015). In addition, security and privacy issues associated with AR technologies must be considered (Mendivil et al. 2013).

A major limitation of this paper is the dependence on publically available information and the representative search process of the same. By further investigating the identified examples and gaining insight to internal information - for example through interviews with employees - deeper knowledge concerning the quantification of AR benefits, limitations and the practical value of applying AR to manufacturing processes can be gathered. This limitation implies that our investigation of the quantification of improvements is only a first attempt and requires further research to fully disclose the value of AR applications. The issue of leaving some potentially important research out is inherent in representative literature reviews. However, we argue that we addressed this drawback by conducting the backward search.

6 Conclusion

This paper systematically analyzed existing literature and use cases to determine, which role AR currently plays in transforming manufacturing processes and what possible potentials for future work exist.

We identified that most theoretical work focusses on improving production operations, especially assembly processes, while the majority of practical use cases involve maintenance and inspection processes. Even though we found many advantages of applying AR to planning, design and prototype activities in proof of concepts, we identified nearly no use cases in this area. Furthermore, we discovered that most AR systems are based on HMDs, even though other technical alternatives are found to be more effective for certain tasks in theoretical papers. For the identified proof of concepts, the AR projector technology plays a much more important role than in real world use cases in which handheld devices are more popular than projectors. While most companies do not publicly quantify the benefits attributed to the usage of AR, some companies mention quantifiable process improvements. Most of them measure how much the work speed increases (i.e. how much the production time can be reduced) due to the application of AR. This ranged from a 10% to 15% time reduction (Robert Bosch GmbH 2016) up to a 80% time reduction (Airbus Group n.d.). In addition, some companies measure how much the accuracy increases (i.e. to what degree the number of errors can be reduced), which ranges from cutting error rates by half (Netland 2016) to increasing the accuracy to 96% (Sanjiv 2016).

Based on the synthesis of theory and praxis, research questions and potential research projects for the future were derived. This includes further investigations of the underlying causes for the identified discrepancies between theory and praxis, as well as of the development of measures to quantify benefits of AR. This is important to be able to assist companies in digitally transforming their manufacturing processes in order to profit from the theoretically identified potentials related to respective AR applications. Furthermore, existing limitations - such as technological and privacy issues - were discussed to identify challenges that must be overcome in order to increase the chance of establishing AR in the real manufacturing world.

We contribute to the current research and praxis on augmented reality by showing a large unexplored potential for future work, since a variety of AR related benefits stressed in diverse proof of concepts for all major manufacturing processes, has not yet been transferred to praxis. We show that first attempts in quantifying real-life process improvements through AR yield drastic increases in accuracy and work speed. Considering all findings of this paper, it is without doubt that AR will continue to impact businesses across all industries, including the manufacturing industry. However, at this point in time it is still too early to refer to augmented reality as a game changing technology in the manufacturing industry, since only a small number of companies actually implement it in their processes. Nevertheless, it remains interesting to observe how this role will change in the following years. If the technology experiences further improvements and existing use cases turn into established solutions, augmented reality will be able to transform the manufacturing industry as we know it.

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