Augmented Reality in Support of Intelligent Manufacturing

A Systematic Literature Review

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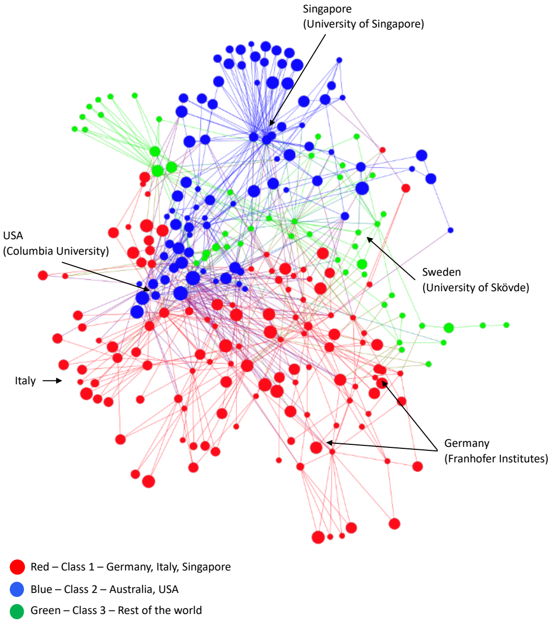

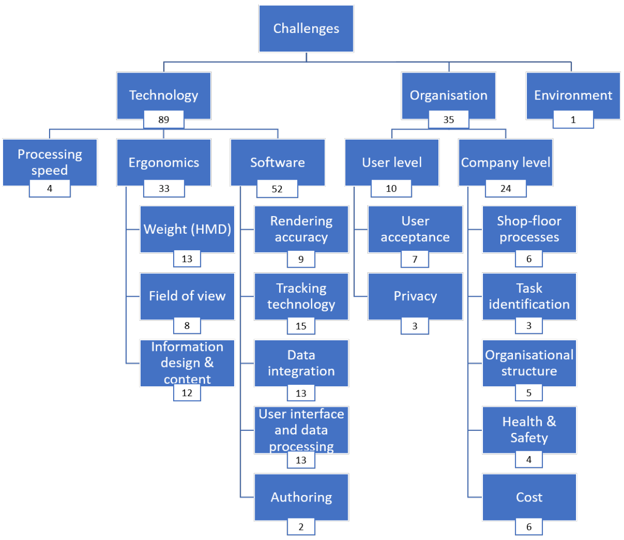

Highlights

- ○ Augmented Reality (AR) is a major part of industry 4.0 advancements
- ○ While AR is not ready yet for industrial deployment in some areas, it is already used in others
- ○ Hardware and software still require improvements in certain areas of AR
- ○ The context of research concerning AR is getting increasingly broader as its implementation rises
- ○ The future research needs to focus on intelligent manufacturing applications of AR

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Augmented Reality in Support of Intelligent Manufacturing – A Systematic Literature Review

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Abstract

Industry increasingly moves towards digitally enabled 'smart factories' that utilise the internet of things (IoT) to realise intelligent manufacturing concepts like predictive maintenance or extensive machine to machine communication. A core technology to facilitate human integration in such a system is augmented reality (AR), which provides people with an interface to interact with the digital world of a smart factory. While AR is not ready yet for industrial deployment in some areas, it is already used in others. To provide an overview of research activities concerning AR in certain shop floor operations, a total of 96 relevant papers from 2011 to 2018 are reviewed. This paper presents the state of the art, the current challenges, and future directions of manufacturing related AR research through a systematic literature review and a citation network analysis. The results of this review indicate that the context of research concerning AR gets increasingly broader, especially by addressing challenges when implementing AR solutions.

Keywords

Augmented Reality, AR, Intelligent Manufacturing, Systematic Literature Review, Challenges, Technology, Visualisation, Cyber-Physical Systems, Industry 4.0, Internet of Things, IoT, Smart Factory, Industrial Digitalisation

List of Abbreviations

AR	Augmented Reality
AV	Augmented Virtuality
CPPS	Cyber-Physical Production System
DOI	Digital Object Identifier
HHD	Hand-Held Device
HMD	Head-Mounted Device
IoT	Internet of Things
MR	Mixed Reality
RV	Reality-Virtuality
SCADA	Supervisory Control and Data Acquisition
TAM	Technology Acceptance Model
TLX	Task Load Index
VR	Virtual Reality

Introduction

Since the first industrial revolution, which introduced steam power and mechanised production, the manufacturing industry has always been subject to significant changes (Seki et al. 2013). The second industrial revolution brought assembly lines and electricity into factories. The advent of automation led to a third industrial revolution in the 1970s (Oztemel and Gursev 2018). The Industry 4.0 or similar initiatives (Li 2018) promote the incorporation of digital technologies into the manufacturing environment to enable an intelligent production system (Pacaux-Lemoine et al. 2017), powering a fourth industrial revolution (see Fig 1).

Digital technologies are central to realisation of intelligence in the manufacturing industry of the future. Examples of digital technologies include but are not limited to AR (Masood and Egger 2019; Masood and Egger In press), virtual reality (Malik et al. In press), predictive maintenance (Yan et al. 2017), cloud computing (Zhang et al. 2017), IoT (Xu et al. 2014), big data (Xu and Duan 2018; Belhadi et al. 2019) and digital twins (Malik et al. In press). Through adoption of digital technologies, data gathering and information creation reaches unprecedented levels. The vision of Industry 4.0 is to build cyber-physical production systems (CPPS) which connect the physical and the digital world seamlessly to make manufacturing increasingly intelligent, thus, to increase (autonomous) adaptability, autonomy, and flexibility (Smith et al. 2013; Serrano and Fischer 2007). Despite this focus on technology, humans still play an important role in manufacturing operations (Kagermann et al. 2013; Longo et al. 2017; Peruzzini et al. In press; Segura et al. In press).

AR comes into play to make vast amounts of data created by CPPS contextually accessible in real time for humans (Yao et al. 2017). Hence, AR is central to enabling this human centred Industry 4.0 manufacturing approach (Cheng et al. 2018; Kong et al. 2018) by supporting humans within an intelligent manufacturing environment. AR is classified by the European Union as one of the main technologies that will drive the development of smart factories (Davies 2015). In order to facilitate collaboration and interaction between humans and production systems based on digital data, researchers focus on AR to achieve that goal (Oztemel and Gursev 2018).

While a lot of technologies play their part in the fourth industrial revolution (Davies 2015), AR is the only of those technologies focusing on improving the interaction between humans and machines and, thus, between humans and intelligent manufacturing systems. Hence, it is crucial to understand the current state of research concerned with AR in manufacturing.

The most recent literature review article focusing on AR in the manufacturing industry was published in 2012 (Nee et al. 2012). However, that review was not systematic. In general, most of the reviews are not conducted rigorously through a systematic review. One exception to that focuses only on maintenance operations (Palmarini et al. 2018). Similarly, Fraga-Lamas et al. (2018) only focussed on shipbuilding. Nee and Ong (2013) and Nee et al. (2012) showed a broad range of applications in industry; especially the manufacturing industry. However, the broader context of current challenges or future research directions, for example, the organisational challenges, are not considered in those studies. Table 1 shows the gaps in other relevant reviews which this paper aims to fill.

This paper examines the present research status and challenges connected to AR in support of (intelligent) manufacturing applications. The focus of this paper is broader than a particular manufacturing sector, or a particular manufacturing related task, e.g. maintenance. Based on the reviewed studies, challenges and future research directions are identified. Here, not only technological issues are analysed but the broader organisational contexts of current challenges are also taken into account. To do so, a systematic literature review was conducted. The rigorous methodology ensured the repeatability of the study. While having a similar methodology as Palmarini et al. (2018), this review paper does not only focus on maintenance operations.

The rest of the paper is organised as follows. After providing a background to AR, the methodology applied in this review paper is described. The next section elaborates on the current status of research. Then, the current challenges hindering the adoption of AR in manufacturing are discussed. Based on those challenges, future research directions are explored.

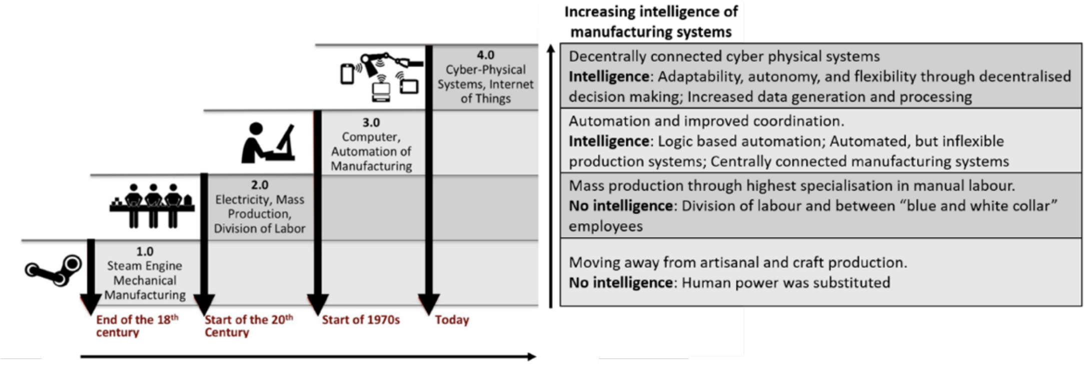


***Fig 1** The four industrial revolutions (based on Forschungsunion (2012, 13) and Hallward-Driemeier and Nayyar (2018, 41–44).*

***Table 1** Review articles with the application and the focus of studies. The last column indicates which gap this paper tries to close compared to the other literature*

Authors	Year	Title	Application	Focus	Gap
Dey et al.	*2018*	A Systematic Review of 10 Years of Augmented Reality Usability Studies	Collaboration, Education, Entertainment, Industrial, Interaction, Medical, Navigation, Perception, Tourism	Technology usability	- No current challenges highlighted - Only 30 out of 291 reviewed papers have an industrial context - No in depth analysis of the current research of industrial AR - No studies after 2014 considered
Fraga-Lamas et al.	*2018*	A Review on Industrial Augmented Reality Systems for the Industry 4.0 Shipyard	Shipbuilding	Hard- and software solutions, possible architecture for AR in shipbuilding	- No systematic review - Focus only on shipbuilding industry - No in depth analysis of future research directions - Review focuses on hard- and software solutions, not on current research
Palmarini et al.	*2018*	A systematic review of augmented reality applications in maintenance	Maintenance	Current research status and future research directions	- Only maintenance operations considered - Does not consider broader context of current challenges or future research directions (organisational or environmental)
Nee et al.	*2013*	Virtual and Augmented Reality Applications in Manufacturing	Manufacturing	System architecture, technological challenges	- No systematic review - Does not consider broader context of current challenges or future research directions (organisational or environmental)
Nee et al.	*2012*	Augmented reality applications in design and manufacturing	Manufacturing and Design	Technology, industrial applications, human factors	- No systematic review - Does not consider broader context of current challenges s or future research directions (organisational or environmental)
Carmigniani et al.	*2011*	Augmented reality technologies, systems and applications	Advertising and Marketing, Entertainment, Education, Medical, Navigation	Focus on end-user friendliness and end-user applications	- No systematic review - Does not consider broader context of current challenges s or future research directions (organisational or environmental) - No industrial applications reviewed

Augmented Reality

Contrary to common perception, AR has been around for the last five decades (Sutherland 1968). Recent leaps in miniaturisation and increased computing power made it possible to develop AR systems with capabilities relevant to consumers and industry. AR systems enable humans to access digital information through a layer of information positioned on top of the physical world (Kong et al. 2018). According to the widely used reality-virtuality (RV) continuum (Milgram et al. 1994), AR is positioned between the real environment and the virtual environment (see Fig 2).

The real environment and the virtual environment (also called virtual reality (VR)), are the two extreme points of the RV continuum. All the information is either real or virtual. Everything in between those extremes incorporates virtual and real elements and is called mixed reality (MR). MR incorporates AR, which augments the real world by adding virtual content. It also incorporates augmented virtuality (AV). AV augments the virtual world by adding real-world content. The differentiation between AR and AV is not distinct along the continuum. However, as long as the real content is dominant, it is AR. This contrasts the concept of AV and VR, where a dominant proportion or all the information is presented virtually. Some researchers relate to AR only when the content is displayed in 3D (Azuma 1997). Within this document, the term AR is used for 2D and 3D solutions.

The basic components of an AR system are the visualisation technology, a sensor system, a tracking system, a processing unit, and the user interface (Wang et al. 2016). The interaction between those components, their function, and the technologies used are shown in Fig 3.

Visualisation technology

This component visualises digital information within the context of the real environment. Four main visualisation technologies are available for AR systems, namely head-mounted displays (HMDs), handheld devices (HHDs), static screens, and projectors (Milgram et al. 1994). The visualisation system can either be stationary or mobile.

Sensor system

The sensor system obtains information from the environment. For most of the AR system, the central input is one or several cameras. Stereo cameras provide depth perception. Other methods for obtaining depth information are ultrasonic, or infrared sensors (Wolfartsberger et al. 2017). When using mobile systems (HMDs or HHDs), different sensors, like gyroscopes or accelerometers are used to determine the position of the display (Fraga-Lamas et al. 2018).

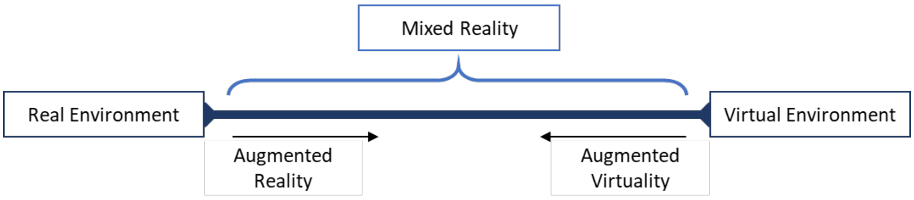


***Fig 2** Reality-virtuality continuum (based on Milgram et al. 1994)*

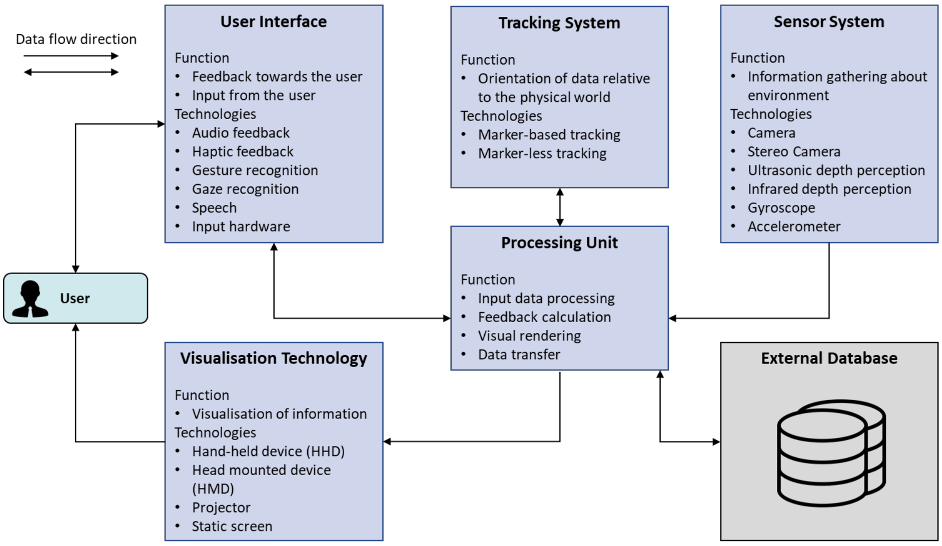


Fig 3 *Components and their interaction of an AR system (based on Wang et al. 2016; Azuma 1997)*

Tracking system

The AR tracking system enables digital objects to be placed accurately within the physical world. The most prominent AR technology is marker-based. Physical markers are attached to certain places. These AR markers are used to triangulate the correct position for a digital object. This technology is well understood and mature, but dirt, mechanical abrasion, or lightning conditions impede marker recognition. Natural marker or marker-less systems require no additional physical objects attached to the real world to determine the position of virtual objects (Wang et al. 2018; Wu et al. 2016).

User interface

The AR user interface enables two-way communication from the system towards and from the user. Technologies, like force feedback (Majewski and Kacalak 2016), or acoustic cues (Zhou et al. 2007) are used. Prominent user input methods are gesture recognition (Wang et al. 2016), the direction of gaze (Park et al. 2008), speech recognition (Majewski and Kacalak 2016), or discrete hardware solutions. Discrete user input hardware can range from mouse and keyboard to hand-scanners (Murauer et al. 2018).

Processing unit

The processing unit is responsible for executing the software to run the AR system. In addition, it is the connection to other sources of data which can be obtained or provided in real-time.

Methodology

In this section, the methodology of the literature is described. A seven-step approach was used to extract the relevant information. This methodology was based on 'Producing a systematic review' (Denyer and Tranfield (2009) and on 'Systematic approaches to a successful literature review' (Booth et al. 2016). Fig 4 shows the steps and the outcome of each phase.

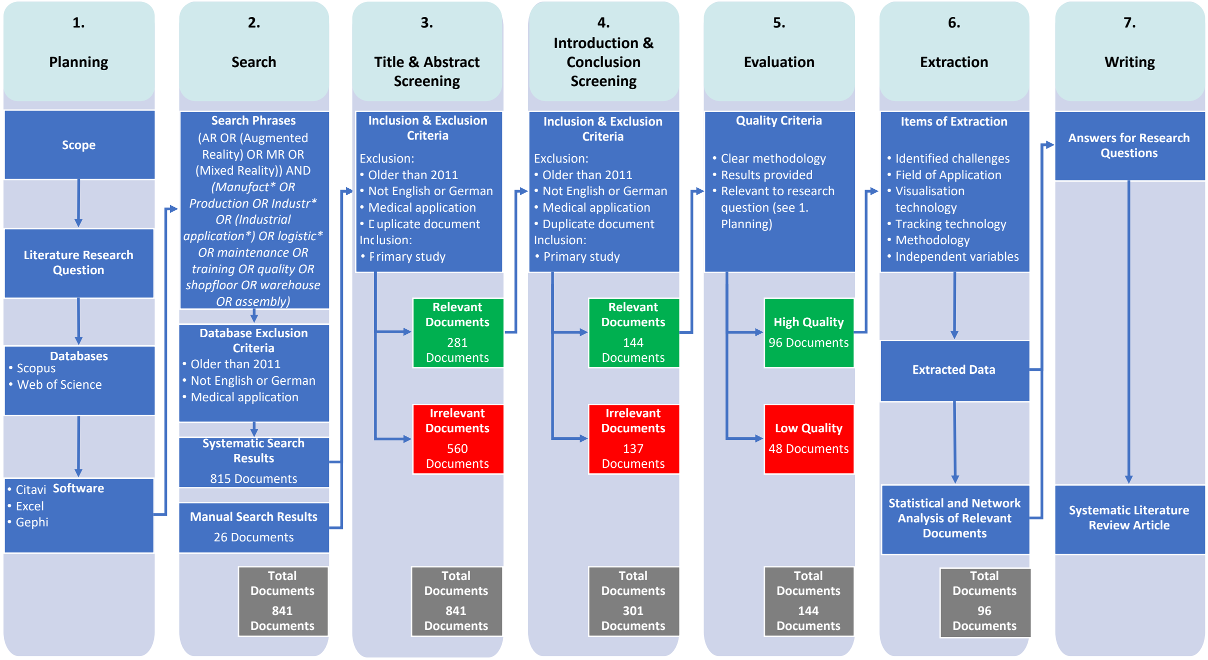


***Fig 4** Research methodology for the literature review which consists of seven steps. Within each of these steps, the results of the process are displayed. The arrows indicate the process flow. The numbers indicate how many documents were retrieved, discarded*

Step 1: Planning

The first step was to determine exactly which areas the research should cover, and which are excluded. This literature review was focussed on AR applications in manufacturing. Hence, the following research questions for the literature review were defined:

Q1: What is the current status of manufacturing related AR research?

The objective was to determine which AR systems were used, how they were tested and evaluated, what research focus areas within the different applications existed, and which authors and research clusters and institutions are involved in the research and connected with each other.

Q2: What are the current challenges that hinders the adoption of AR in manufacturing?

The objective was to uncover the current issues within a broad context. Not only technological limitations were taken into account but also challenges arising from industrial implementations in an organisational and user-focused context, as this can give indications concerning the maturity of the technology.

Q3: What are future directions of manufacturing related AR research?

Based on the reviewed documents and the results concerning Q1 and Q2, future research directions were identified and summarised. These research directions should give guidance for the next steps alleviating the limitations and challenges.

Then, the following databases were identified for search purposes:

- Scopus
- Web of Science

Those databases were chosen due to their broad coverage of journals. *Citavi* was used as a reference manager software. This program was selected due to its broad functionality, like auto-import, integrated pdf-viewer, word citation add-in, or internal cross-referencing to link documents. Microsoft Excel was used as data extraction and evaluation tool.

Step 2: Search

To perform the systematic search, a set of search strings was defined to search the databases identified in step 1. Through an assessment of previous literature reviews on AR (Nee and Ong 2013; Nee et al. 2012; Carmigniani et al. 2011), the areas of application and the search string were defined. The search string

(AR OR (Augmented Reality) OR MR OR (Mixed Reality))

AND

(Manufact OR Production OR Industr* OR (Industrial application*) OR logistic* OR maintenance OR training OR quality OR shopfloor OR warehouse OR assembly)*

incorporated different synonyms for the areas of application. In addition to 'Augmented reality', the key phrase 'Mixed reality' (MR) was also used. The reason is that not every author follows the same definition of AR and MR.

This step was also important for utilising the capabilities of the databases to limit the results to the relevant timeframe and the relevant area of interest. The exclusion criteria used within the database are:

- Not in English or German

As the authors of this literature review are fluent in both languages, this can be used to gain a broader view of the field. Due to the fact that AR is often used in the context of the German *'Industrie 4.0'* initiative (Funk, Kosch and Kettner et al. 2016; Paelke and Röcker 2015; Paelke 2014; Kagermann et al. 2013), several research groups in Germany do research around industrial AR. Some of this research has been published in German.

- Older than 2011

The starting point of this literature review was the last literature review on AR in manufacturing published in 2012 (Nee et al. 2012). Due to the time discrepancy between conducting the research and publications, we deemed it necessary to also include studies from the year 2011 in this literature review. In addition, older studies become less relevant due to technological leaps forward.

- Not manufacturing or software engineering related

AR has a broad field of applications outside of the manufacturing industry; for example, marketing or medical applications. Those are outside of the scope of this literature review.

Table 2 shows the number of results from each database, which includes journal articles, review articles and conference papers. The search was conducted on 28th of September 2018. In this step, neither the titles nor the abstracts of the papers retrieved were read. For both of the databases, the term augmented reality OR mixed reality was applied to the title, while the rest of the search phrase was applied to the title, abstract, and keywords.

Table 2 *The table shows the number of results for each of the two databases searched with the search phrase*

		Number of Documents
Scopus	Papers found	704
	Irrelevant Papers	468
WebOfScience	Papers found	111
	Irrelevant Papers	67
	Duplicates	25

As Greenhalgh and Peacock (2005) showed, it is not likely that all relevant documents are retrieved through a systematic database search. To counteract that issue, relevant literature found throughout the project through backward or forward citation screening was included as well. Table 2 shows the result of this process. Documents retrieved from the manual search entered the same process as the one from the systematic search continuing with step 3.

Step 3: Title & Abstract Screening

The contents of the papers were assessed through screening of titles and abstracts. To do so, a catalogue of exclusion and inclusion criteria was developed by extending criteria of the database exclusion. The previously used criteria to restrict the database results were applied again, as the results showed that not all of the irrelevant papers were discarded by applying filters to the field of AR research.

Additional exclusion criteria:

- Duplicate document

Inclusion criteria:

- The primary study focused on manufacturing-related AR applications

These criteria were drawn and adapted from a literature review (Palmarini et al. 2018) and literature giving guidance in that area (Buchanan and Bryman 2009; Saunders et al. 2009). Fig 4 shows the process of screening and evaluation and the number of papers not included due to the exclusion criteria in the respective step.

Step 4: Introduction & Conclusion Screening

Utilising the same exclusion and inclusion criteria as in step 3, step 4 determined the relevance of a paper based on the introduction and the conclusion/discussion of the respective paper. Compared to step 3, this step was a more in-depth selection of the documents. Otherwise, the process was the same. Fig 4 shows the process of screening and evaluation and the number of papers not included due to the exclusion criteria in the respective step. The result of the screening process was a list of 144 documents. These documents were imported into the reference manager *Citavi*. As the search was conducted within different databases, duplicates were removed in this step.

Step 5: Evaluation

At this stage, the articles were probed concerning their quality. Quality criteria were drawn and adapted from the same literature as for step 3. Fig 4 shows the process of screening and evaluation and the number of papers not included due to the quality exclusion criteria in the respective step. Three quality criteria were used:

Quality Criteria:

- The methodology is clearly explained.
- Results are provided.
- The document is relevant to the research questions of the literature review.

The documents were assessed through a binary decision of compliance with the criteria. In the end, a decision was made if the paper will be looked into in detail within this literature review. However, it was not necessary to fulfil all of the criteria. For example, it was possible that a

Table 3 *The table shows a representative part of the data extraction document with the data points gathered for each of the documents entering step 6. The original document includes several additional columns for the author to make remarks concerning the content of each paper.*

Authors	Year	Field	Technology	Aim	Methodology	Dependent Variables	Identified Issues
Uva A.E. et al.	2018	Assembly	Projection Marker tracking	Improve operator assembly performance compared to paper based system	Lab experiment	Time measurement Error rate User survey	Distraction Influence of experienced operators
Doshi A. et al.	2017	Quality	Projection	Improve accuracy of manual spot welding	Lab experiment Field experiment	Time measurement weld location	Information display
Stoltz M.-H. et al.	2017	Logistics	HMD Marker tracking	Improve warehouse operations using the example of sorting	Field experiment Lab experiment	Time measurement User survey	Hardware selection Information display Cost Social acceptance
Wang X. et al.	2016	Assembly	HMD Static screen Marker tracking	Compare bare-hand gesture recognition AR system to LCD based AR system and a paper based system	Lab experiment	Time measurement Error rate User attention	Feedback system towards user
Hou L. et al.	2015	Assembly	HMD Marker tracking	Test prototype AR system to show assembly steps compared to paper based solutions Define advantages in terms of task performance and cognitive workload	Lab experiment	User survey Time measurement Error rate	Tracking Portability Cost Social acceptance Tracking technology
Henderson S. and Feiner S.	2011	Maintenance	HMD Static screen Marker tracking	Increase maintenance efficiency	Lab experiment	Head movement Time measurement NASA-TLX	Data display User centred content Multi-modal information Multi-modal communication

document was included despite lacking methodology due to an interesting concept.

Step 6: Extraction

The first part of this section explains the methodology of the network analysis, then the extracted items are explained in detail.

From the extracted papers, a citation network analysis was conducted to determine research hubs and the interconnection between the papers selected. The method was based on similar analyses conducted (Wilding et al. 2012; Kajikawa et al. 2007), however, the goal was to classify research hubs around the world, and not the development over time. To do so, the relevant papers were imported into the network analysis tool *'Gephi'* (Version 0.9.2) as nodes. Afterwards, all backwards citations of the papers were imported as nodes as well and linked to the main document. This step created the edges between the nodes. Then, the digital object identifier (DOI) was used to merge all duplicates within the backward citations. As the edges were maintained when merging nodes, the network was created at this step. To manage the large network, nodes were filtered based on the following criteria:

- 'Giant Component'

All nodes not connected to the main network were filtered.

- 'Degree range'

In this setting, all nodes with less than two edges (less than 2x cited) were filtered from the citation network analysis, but not from the review.

Afterwards, an in-built modularity algorithm (Lambiotte et al. 2014) was used to determine communities within the network. In the end, the Yifan Hu algorithm (Hu 2006) was used to obtain the layout. This force-based algorithm was used to draw graphs and is an inbuilt function of gephi. Those communities are analysed qualitatively to determine tendencies of certain authors and research institutions contained within a community.

In order to systematically extract information from the relevant documents, a table was generated. Within this table, the articles were inserted in the first column as rows and different characteristics of the AR system and the study as columns. Table 3 shows a representative extract of this document. The selection of the characteristics is based on other successful literature reviews and on the aim of this literature review. The different data extraction points will be discussed in the following section.

Field of application

Here, it is defined for which application an AR system has been developed or tested. Depending on the category, different requirements need to be met by the AR system.

Initially, the following categories were defined within step 2 of the review:

- Maintenance
- Assembly
- Quality
- Logistics
- Others

Step 4 and 5 showed, that a low number of papers focused on the areas outside of the maintenance, assembly, quality, and logistics. Those papers were summarised in the category 'Others'. These include AR for Supervisory Control and Data Acquisition (SCADA) or machining/machine set-up applications.

Technology

There are different ways to visualise the AR content for the user. Those were classified in four different categories:

- HMD
- HHD
- Static Screen
- Projector

In order to superimpose digital content at the right place in and dynamic system where the visualisation device and/or the parts of the environment are physically moving, tracking is essential. The different approaches to do so are classified as follows:

- Marker tracking
- Marker-less tracking
- Natural marker tracking

Methodology

From the results (see Table 2) different methods to test AR applications were defined. They have been divided into the following categories:

- Laboratory experiment
- Field experiment
- Simulation
- Pilot project

Some papers presented work on prototypes at early stages without results of their performance (Jayaweera et al. 2017; Kocisko et al. 2017; Schlagowski et al. 2017; Wolfartsberger et al. 2017; Flatt et al. 2015; Rodriguez et al. 2015). As the developed prototypes had interesting features, those papers were added to the literature review despite them being not tested rigorously. They are classified under 'Pilot project'.

The classification between laboratory and field experiment was not clear in every case. For this literature review, studies that were conducted in a factory environment are classified as field experiments. In addition, studies that recruited technicians, workers, etc. as participants for simulations of shop-floor tasks in a laboratory were classified as field experiments. The reason for this classification was that these studies give insights into the real-life applications and problems when deploying AR in industrial environments. The study participants would be the users of the technology within an industrial setting and appreciate the challenges posed by such an environment compared to e.g. students who participate. Additionally, the real-life inspired tasks within the study needed to be taken from real-life manufacturing applications. Despite the fact that those experiments were conducted not in the field, the authors of this literature review saw the value of those experiments modelled close to real-life applications despite not being conducted within a factory. Thus, they were regarded closer to field experiments than laboratory experiments with students as participants and/or tasks not directly related to manufacturing applications.

Metrics

Different studies use different metrics to determine the capability of the prototype. The following metrics were used:

- Time (for example (Uva et al. 2018))
- Error rate (for example (Uva et al. 2018))
- NASA Task Load Index (TLX) (for example (Murauer et al. 2018))
- User surveys (for example (Uva et al. 2018))
- Marker decoding distance (for example (Koch et al. 2014))
- Marker decoding time (for example (Koch et al. 2014))
- Head movement (for example (Renner and Pfeiffer 2017))
- Weld location (for example (Doshi et al. 2017))

Challenges

In order to answer the second research question (Q2: What are the current challenges that hinders the adoption of AR in manufacturing?) posed, it was necessary to determine the current limitations and challenges when utilising AR technologies. To do so, a hierarchical structure is used to classify the challenges extracted from the documents in the review. The three-tiered structure classifies issues into a 'technology', an 'organisation', and an 'environment' part. Within those classifications, the issues are labelled.

Current Status

To answer the first research question posed (Q1: What is the current status of manufacturing related AR research?), this section first looks into the findings of the network analysis. Then, the overall status of the research concerning AR in manufacturing applications is described. To conclude this section, each of the fields is analysed in more detail to draw the recent history and developments within the last seven years.

Network Analysis

In this section, the network analysis conducted is discussed. The goal was to determine where the manufacturing related AR research hotspots are, if and how they are interconnected, and if different areas focus on different aspects of AR research. This can lead to a better understanding of the research landscape and, thus, a better understanding of the current research status.

Fig 5 shows the network generated. The size of a node indicates the number of citations. Every edge represents a backward citation. There is no weight of some sort applied to the edges. The node colours indicate the different clusters identified.

The modularity algorithm used in *gephi* (Lambiotte et al. 2014) uncovers communities, called classes, within networks based on the structural and statistical properties of the network. The colour coding in Fig 5 shows the three classes uncovered by the modularity algorithm. It was overserved that class 1 (red) is not as tightly packed by the modularity algorithm used compared to class 2 (blue). This means, that the documents in class 1 tend to have a lower number of citations within that network (backwards and forward). This can be explained by the fact that the density of authors with a high output and, thus, the number of citations within that network, was higher in class 2. In addition, no differentiation between articles and conference articles was made in this literature review, which possibly could explain the difference to some extent.

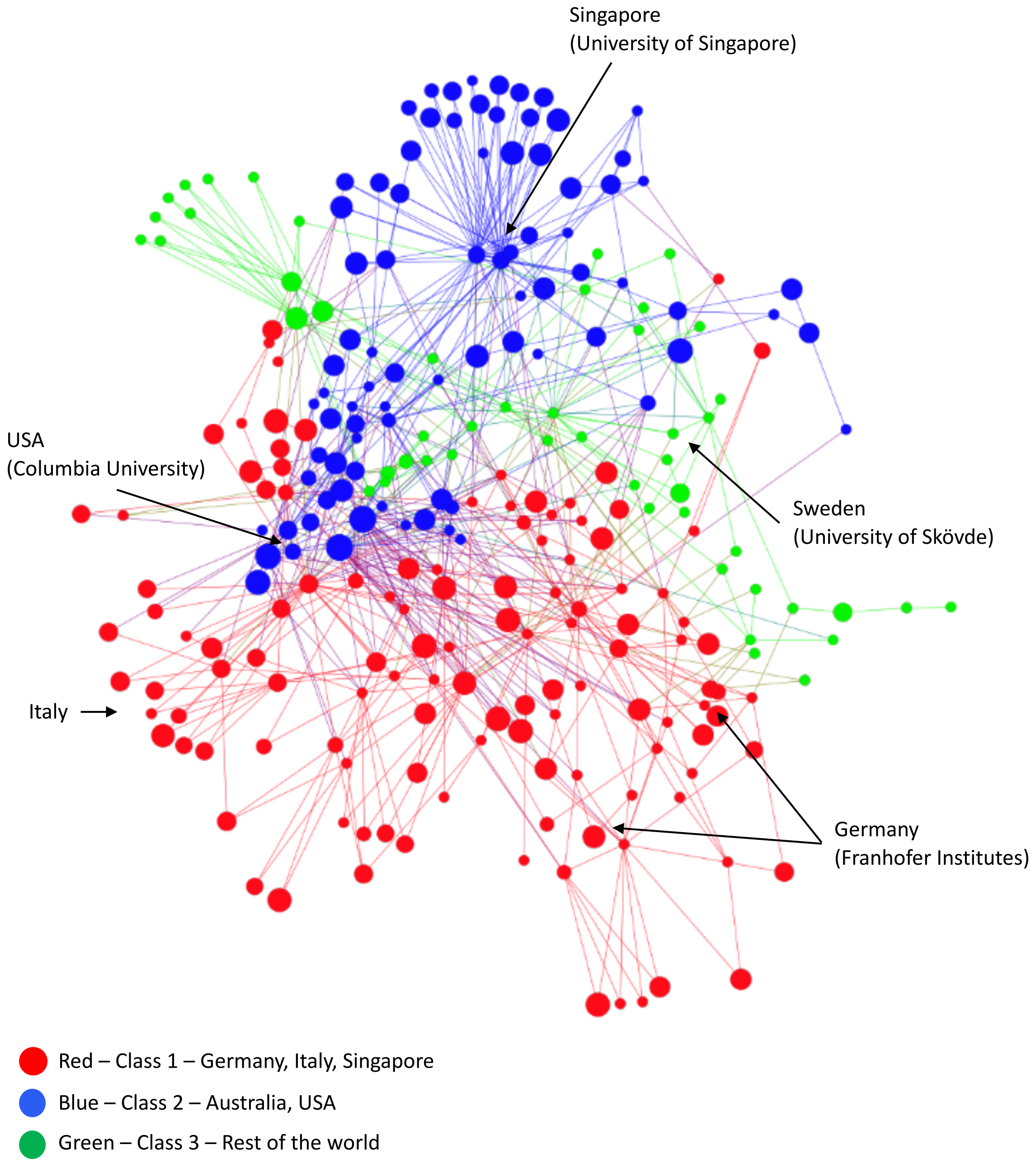


Fig 5 Citation network with colour coded classes and indication of research clusters within the classes. The size of the nodes indicates the number of citations.

Table 4 defines the geographical region, the most important research institutions, and influential authors within each class. Even within the classes, certain research institutes and/or countries have their distinct locations. The arrows and the description in Fig 6 indicate those areas. Germany was the country with the single most publications according to the initial search string (at step 2 of the methodology). When adding the documents of the Fraunhofer Institutes up, they did the most research in that area (at step 2 of the methodology). When looking at individual authors, Nee and Ong were the two authors with the most publications (at step 2 of the methodology).

Table 4 *Geographical region, important research institutions, and relevant authors for each of the classes identified.*

	Colour	Region	Institutions	Relevant Authors
Class 1	red	Germany	Fraunhofer Institutes	Funk, M.
			TU Munich	Reif, R.
		Italy	Politecnico di Bari	Uva, A.E.; Fiorentino, M.
Class 2	blue	Singapore	University of Singapore	Ong, S.K.; Nee, A.Y.C.
		Australia	University of South Australia	Lee, G.A.
			Curtin University	Wang, X.
		US	Columbia University	Henderson, S. J.; Feiner, S. K.
Class 3	green	Rest of the World	University of Skövde (Sweden)	Syberfeldt, A.; Holm, M.

The three classes identified were mainly differentiated by geographical region. There are some exceptions to this. A paper from researchers at the TU Chemnitz (Germany) (Kollatsch et al. 2014) was part of class 2 and a paper from researches based at the University of New South Wales (Australia) and Curtin University (Australia) (Hou et al. 2013) was classified in class 3. However, the general trend was clear. The research groups in certain geographical areas cite mainly research from that geographical region.

Yet, the different identified classes were far from being isolated. Fig 6 shows only the edges, thus the citations. The colour of an edge corresponds to the nodes it is connected with. If an edge is connected with two nodes from the same class, it has the colour of that class. If an edge is connected with two nodes from different classes, the colour is a mixture of the colours of each class. Especially the US researchers in class 2 had tight connections with the studies from Germany and Italy.

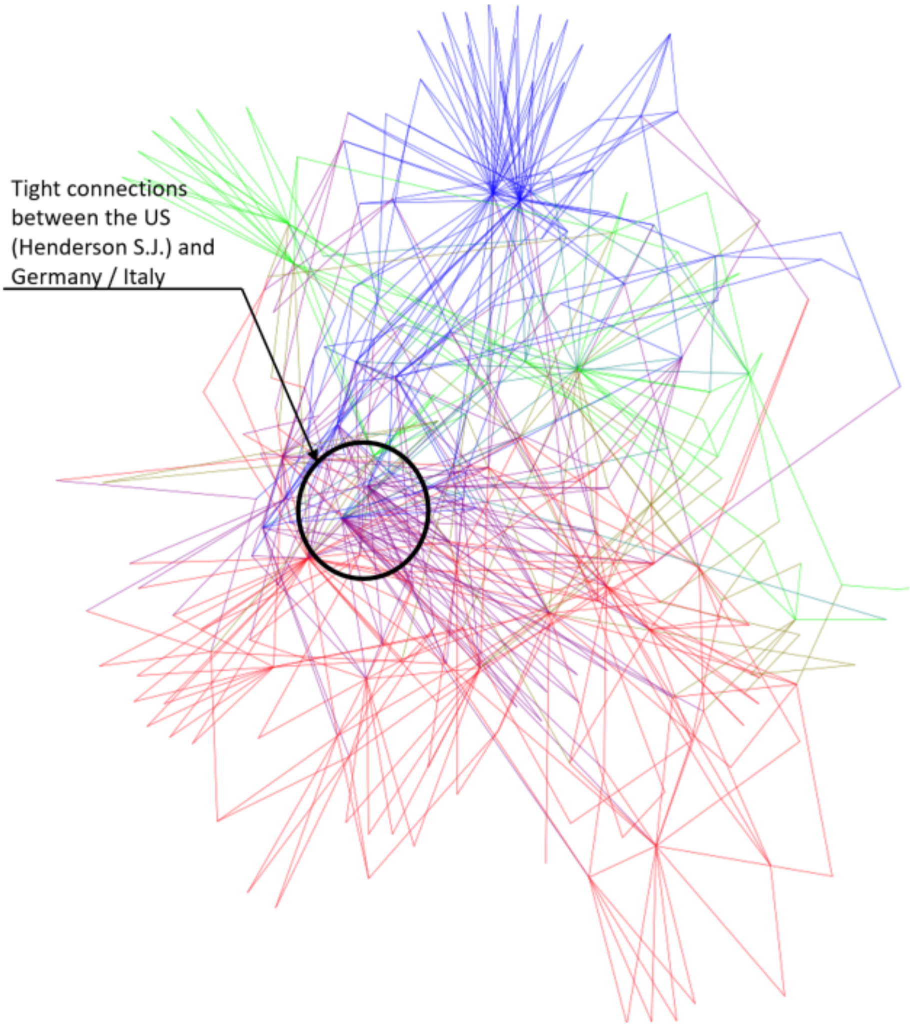


Fig 6 *Colour coded edges of the citation network. The circle indicates a close connection of class 1 and class 2; mainly through US authors*

Results of Data Extraction

In this section, the findings of the extracted data are analysed for all papers extracted.

Field of application

Compared to VR, AR can be used in environments, where the real world is relevant as well and additional information can benefit operators. AR can be used for assembly operations in intelligent manufacturing, either in training (Werrlich et al. 2017; Hahn et al. 2015) or as a live guidance system for operators (Blattgerste et al. 2017; Funk et al. 2017). In logistic, 'pick-by-vision' is a prominent concept utilising industrial AR to indicate picking locations and quantities (Hanson et al. 2017; Renner and Pfeiffer 2017; Guo et al. 2014; Reif et al. 2009). Another area of logistics where AR can be used are general warehouse operations (Stoltz et al. 2017). Additional prominent fields of applications include quality assurance (Antonelli and Astanin 2015; Segovia et al. 2015) and maintenance (Martinetti et al. 2017; Masoni et al. 2017; Mourtzis and Zogopoulos et al. 2017; Palmarini et al. 2017; Zhu et al. 2012). As soon as operators depend on or can profit from (real-time) information, AR can be used to intuitively display this information on site.

By providing flexible real-time information and the possibility of obtaining information hands-free AR can offer a substantial efficiency benefit (Guo et al. 2014; Hou and Wang 2013) by decreasing the error rate (Wang et al. 2016), like picking or assembly errors and it provides easy ways to communicate with experts in maintenance tasks (Mourtzis and Vlachou et al. 2017).

Fig 7 shows the percentage of the included documents focused on a certain field of application. Assembly and maintenance together account for nearly 75% of the relevant documents. 43 documents were classified in the 'assembly' field of application.

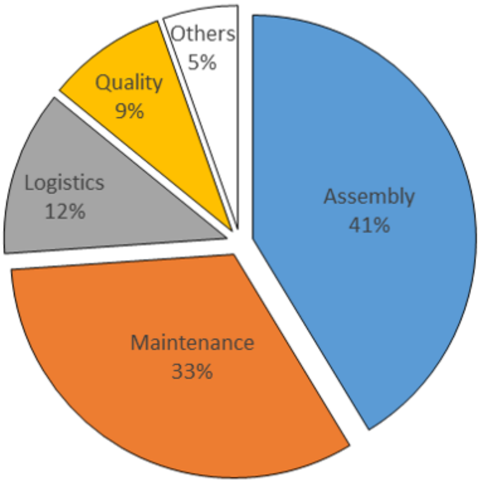


Fig 7 Distribution of the different fields of application for each of the documents reviewed

35% of the documents focused on maintenance, as the second part of the pie-chart shows (see Fig 7). One of the documents stated that the developed system is viable for both, assembly and maintenance. However, due to the focus of the paper on assembly, it was classified accordingly (Sanna et al. 2015).

The next slice (see Fig 7) focuses on logistics. While picking supported by AR (also called 'pick-by-vision') has already 'come of age' (Reif et al. 2009), the research now on tends to focus other applications within logistics, for example peripheral equipment (Murauer et al. 2018) and safety-related aspects (Sarupuri et al. 2016), or on very specific problems within picking, like peripheral equipment (Murauer et al. 2018).

Technology

A crucial part of an AR system is the visualisation technology used to display the digital content to augment the environment. Fig 8 shows the number of studies utilising a certain visualisation technology. The most dominant devices used were HMDs followed by HHDs. It should be noted that some studies used more than one visualisation technology. Their usual aim was to compare the performance of those technologies. Especially the price and the availability of HHDs make them attractive for use. Static screens are often used as the first proof of concept before further developing the system. The learnings of a first test-run were then used when porting the application onto HHDs or HMDs.

Another essential component is the tracking technology used to place the digital content correctly. The vast majority used marker tracking systems. Three studies developed (Wang et al. 2018; Crescenzio et al. 2011) or used marker-less tracking systems (Flatt et al. 2015). Here, the environment itself is used to anchor the digital content. Another approach is to use natural markers. Here, dominant physical pictograms or objects are used instead of dedicated markers (Koch et al. 2014). This system, however, does not seem to be promising, as to more recent research focuses on entirely marker-less systems.

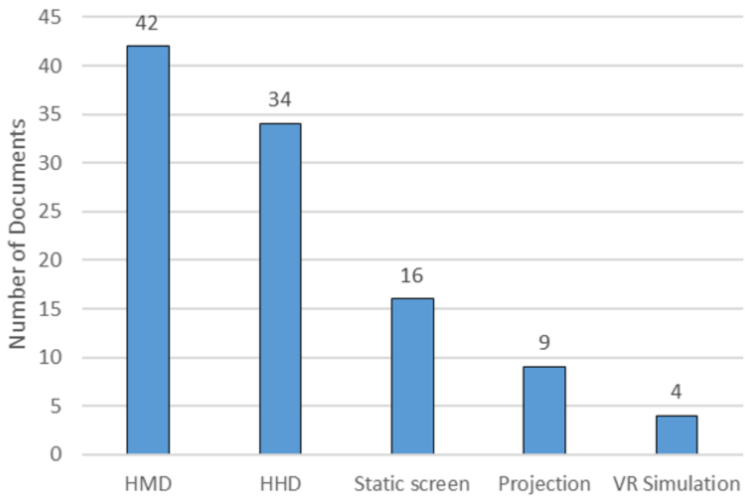
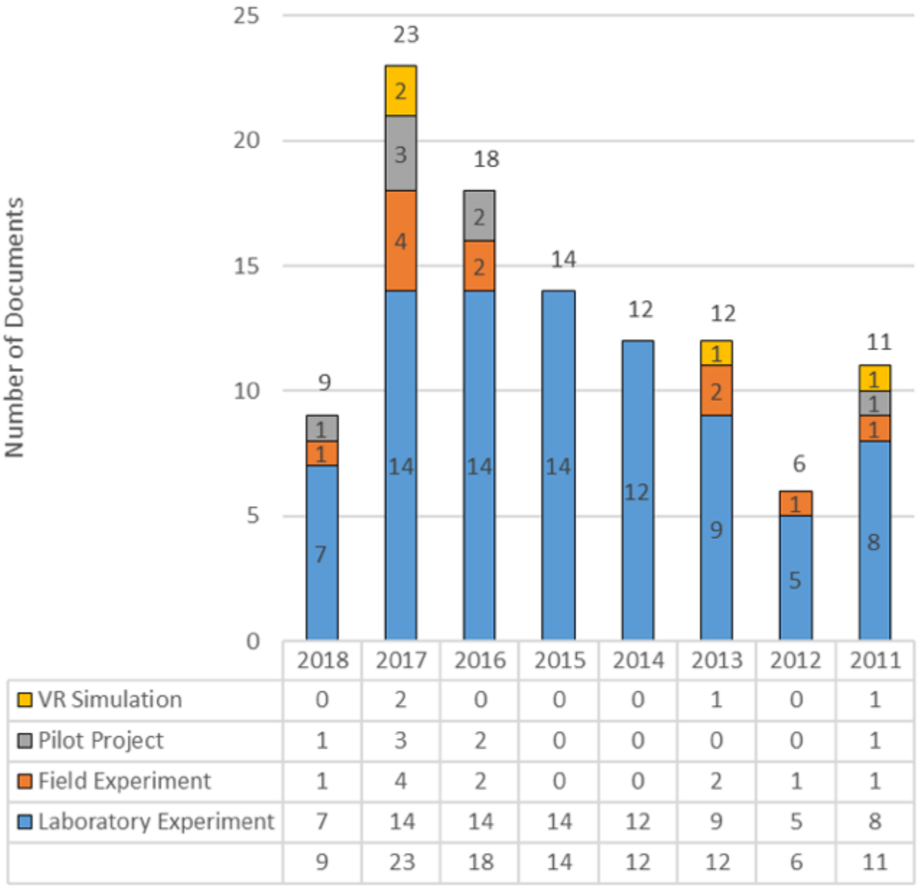


Fig 8 Number of documents that used a certain visualisation technology. It has to be noted that several studies utilise more than one technology

Methodology

Fig 9 shows the number of papers reviewed utilising a certain methodology throughout the years 2011 to 2018. The height of the bar and the number above each bar shows the total number of papers reviewed from that year. The stacked bars indicate the number of papers utilising a certain methodology.



	2018	2017	2016	2015	2014	2013	2012	2011
🟨 VR Simulation	0	2	0	0	0	1	0	1
⬜ Pilot Project	1	3	2	0	0	0	0	1
🟧 Field Experiment	1	4	2	0	0	2	1	1
🟦 Laboratory Experiment	7	14	14	14	12	9	5	8
	9	23	18	14	12	12	6	11

Fig 9 Number of studies that utilised a certain method to assess an AR system. It should be noted that some studies utilise more than one method.

The vast majority of experiments were conducted within a laboratory setting (see Fig 9). Some utilised laboratory and field experiments within one study. Interestingly seven out of the 11 field experiments were conducted within the 2015-2018 period, showing an immense interest from the AR research community. Only four of the documents retrieved that were published prior to 2015, a field study was reported. Another approach used to compare different methods of AR support and conventional methods is VR simulation. A task was modelled completely digitally using different methods of augmentation and even conventional paper-based information visualisation are simulated (Renner and Pfeiffer 2017; Renner and Pfeiffer 2017; Lee and Akin 2011).

Measures

Fig 10 shows the percentage of papers utilising a certain dependent variable. The most prominent measures to characterise the AR system were the time to task completion, the error rate, and the NASA TLX. Especially those three measures were often used within the same study.

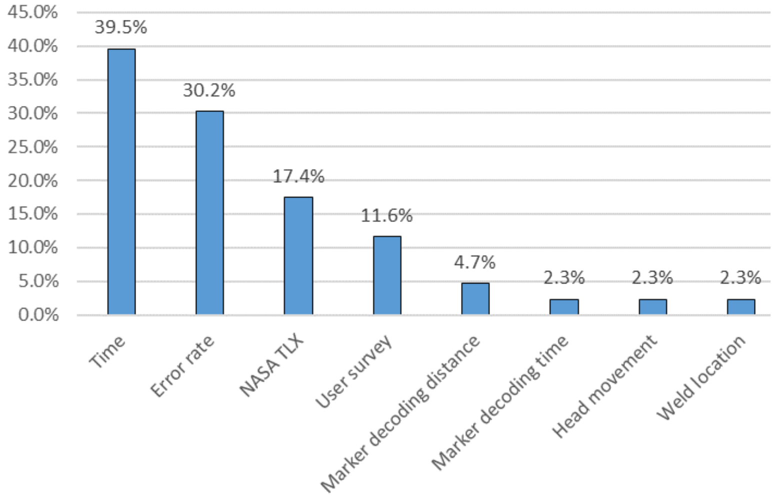


Fig 10 Percentage of studies that utilised a certain measure to assess an AR system. It should be noted that most of the studies utilise more than one measures

The different studies had different goals. Most of them focused on the possible improvements of a certain task through the AR system. Thus, the time to complete a task and the error rate were the most prominent measures used. Another focus was the usability of the system. For that reason, the NASA TLX (Hart and Staveland 1988), other user surveys, or the head movements were utilised as measures. However, some studies included in this literature review focused on the tracking technology itself (see Fig 10). It should be noted that most of the studies use more than one of those measures.

Assembly

Since the early beginnings of AR, it has been envisioned as a tool to support assembly workers (Azuma 1997) in intelligent manufacturing systems. Increasing product complexity and growing numbers of product variants have an impact on the assembly difficulty. Several authors state that AR can be used to counteract those difficulties (Funk et al. 2017; Holm et al. 2017; Wójcicki 2014). In addition, AR can decrease the learning curve (Hou et al. 2013) and supervise assembly steps by suggesting corrective measures once a mistake is detected (Mura et al. 2016).

Performance of AR in Assembly

The main focus of current research is determining the performance increase induced by AR guidance in different assembly scenarios. The most common measures used to quantify that efficiency increase are time and an error rate analysis. In addition, user surveys and surveys based on the NASA-TLX are commonly used to determine if the psychophysiological impact of the technology. Fig 10 shows what percentage of studies used those measurements.

A research at Curtin University in Australia focussed on the learning curve effects (Hou et al. 2013). In Hou et al. (2013), an AR static screen solution and paper-based instructions are compared for assembling a Lego model. They find that the error rate and the time necessary to complete the model is lower when using AR for assembly guidance. In addition, the cognitive workload of using AR in the static screen setup is lower. Another significant finding is the steeper learning curve when using AR as a training system for assembly novices. Hořejší (2015) confirmed a steeper learning in a rudimentary study of piping assembly training. In a follow-up study by Hou and Wang (2013), a difference of the learning effects between gender was analysed. They found that there is no significant difference when utilising AR as guidance.

A more complex assembly task was studied by Hou et al. (2015) as well. Again, an AR static screen solution and paper-based instructions were compared. In this instance, the task was to assemble a complex 3D piping system. Again, the AR solution proved to be superior in all categories of measurement. However, it has to be noted that the paper-based instructions were 2D isometric technical drawings. None of the test subjects had previous experience with such drawings but only received a brief introduction on how to read such isometric drawings prior to the assembly tasks.

Several other studies also confirm the superiority of AR guidance for assembly in laboratory experiments (Bosch et al. 2017; Chang and Jau 2016; Hahn et al. 2015; Sanna et al. 2015). Henderson and Feiner (2011) showed that AR is superior in completion time, but that the degree of performance increase depends on the nature of the physical manipulation itself. Especially complex assembly steps profit from AR in this study.

Most of the studies above utilised different assembly scenarios to determine the performance of AR systems. However, it is hard to compare those studies, as the task complexity, the setup, and the measurements differ. Funk et al. (2015) proposed a standardised experimental setup to evaluate AR solutions. This system is based on a Lego assembly task. Thus, it is easy and cheap to replicate. They utilise the set-up to compare HMDs, HHDs, projection, and paper-based instructions (Funk, Kosch and Schmidt 2016). In contrast to previous studies, only the projection solution was slightly superior to the paper-based guidance in every regard (time, error rate, subjective task load). A solution utilising an HMD was inferior to the paper-based solution in every regard.

Blattgerste et al. (2017) used by Funk et al. (2015) developed an experimental setup to replicate the study. They critiqued how the HMD was used in the previous study and showed that another approach using a Microsoft HoloLens HMD leads to performance improvement as compared to paper-based instructions. The main difficulty in this experiment is to find the correct colour of the Lego blocks. This is not representative of complex 3D assembly operations. However, this controversy confirms that there is no ‘one fits all’ solution for AR supported assembly. The selection of the hardware and the implementation from a software side needs to be tailored to the specific task.

Another issue with the aforementioned studies in this section are the users. All authors recruited test subjects for lab experiments from a university background. This can influence the findings, as indicated by Sanna et al. (2015). Another study of the research group at the Human-Computer-Interaction laboratory at the University of Stuttgart looked into that issue (Funk et al. 2017). In their long-term field experiment at a car manufacturer, they compared the performance of expert and untrained workers when using an AR projection system. The expert workers were already accustomed to the assembly task, as this part has been produced for years. The effects of in-situ projection AR for the manual assembly of engine starters for a total of eleven days at an automotive assembly plant was studied. Each participant assembled for three days using the projection-based AR system, which provided context-aware instructions. For both groups, the time to complete the task was surprisingly higher when using the AR projection system. In general, projection-based solutions are mainly used for assembly tasks, as they are stationary (Sand et al. 2016). Uva et al. (2018) used a similar setup but in a laboratory experiment, where all participants were students but no professional workers. The results showed AR superiority concerning completion time and error rate over a paper-based solution. The limitation of worker experience, however, is acknowledged.

The long-term results of the field study done by Funk et al. (2017) indicate that the expert workers get distracted by the system, but the difference between using the system and not using the system diminished over time. For novice workers, the benefit of the AR system was visible during the learning phase at the beginning of the experiment. After that, the AR system slowed them down. Holm et al. (2017) tried to tackle that problem of inflexible guidance by providing adaptive instruction through AR. Depending on the stored competence level of the user and the real-time completion time of a task, the visual guidance is adapted from basic text instructions to 3D animations. Another approach to show dynamic content based on the actions of the assembly worker is to detect assembly errors and show corrective measures (Mura et al. 2016).

Human-robot collaborative assembly

Another active research field of AR supporting assembly operations is improving the human-robot collaboration. In general, collaborative robots are designed to prevent health and safety issues for humans. Their maximum load and speed are limited. In addition, the physical design prevents any injuries from clamping or collisions. Two prominent examples are the *ABB YuMi* (ABB AG 2018) and the *KUKA LBR iiwa* (KUKA AG 2018). Those limitations prohibit using these robots in collaborative assembly tasks where heavy loads need to be manipulated. Usually, industrial robots need to be within physical or virtual safety areas preventing anyone from entering proximity while the robot is moving. Pai et al. (2014) developed an AR system allowing for safer online programming of industrial robots.

The results published by Michalos et al. (2016) and Makris et al. (2016) stem from the Laboratory for Manufacturing Systems and Automation at the University of Patras developing an AR system for human-robot collaboration. One of their main goals is to enhance safety when working with robots originally not designed for collaborative tasks. Their solutions consist of visualising safe working areas (volumes), using audio-visual cues to indicate danger, and a visual representation anticipating the movement of the robot.

Gesture Recognition

User interaction is a critical part of AR systems. Their usability has a profound impact on the performance of the system (Murauer et al. 2018). Saxen et al. (2017) state that user-friendliness is an important factor for the user acceptance. A focus of research concerning user interaction is hand gesture recognition. While this is applicable to all fields of applications, the relevant papers in this literature review address the issue of gesture recognition within the context of assembly tasks. Hence, it is covered in this section.

Earlier attempts to develop such a system by Wu and Wang (2011) and Radkowski and Stritzke (2012) focused on a digital task without guiding a physical assembly. Wang et al. (2016) developed a solution to navigate through digital AR manuals for assembly tasks. In addition, it can be used to manipulate digital objects. The comparison of an interactive system, an AR system navigated by mouse and keyboard, and a standard assembly manual displayed on a screen showed the advantages of the interactive AR system. The average completion time for a certain task dropped from approximately 32 seconds with the conventional manual to nearly 12 seconds while also decreasing the error rate. Additionally, the usability was superior. Despite not showing results for user performance, Saxen et al. (2017) demonstrated the reliability of such a system, classifying more than 99% of gesture correctly.

Maintenance

With the increasing complexity of machinery and industrial facilities, having information readily available can improve the economics of assets (Masood et al. 2018). Over the lifetime of machinery, the maintenance processes can account for a substantial part of the total cost of ownership. Lamberti et al. (2014) estimated a maintenance cost decrease of up to 30% for industrial machinery when utilising AR. Especially topics like improving the communication between an off-site expert and an on-site technician through augmented reality, conducting the maintenance operation itself, and the authoring of content are prominent in the current research.

AR-enabled maintenance can also harness the benefits of predictive maintenance. The move from a fixed maintenance schedule to an adaptive one based on real-time data can be supported by AR. The flexibility of maintenance workers can be increased by showing the right data at the right time for a certain maintenance task (Schlagowski et al. 2017; Flatt et al. 2015).

Tele-maintenance

The idea of improving maintenance operations through AR has been around for more than two decades (Azuma 1997). The main idea is to utilise off-site experts to improve maintenance operations. Usually, the communication is based on phone calls and electronic data exchange of pictures and descriptions. In order to improve the communication between the off-site expert and the on-site worker, AR can be used within the data exchange system (Leutert and Schilling 2015).

Masoni et al. (2017) describe such a system, where off-site experts utilise annotations, arrows, and other visual symbols which are then directly displayed by an AR application on the client side. The system uses natural markers; hence no artificial markers are necessary to determine the position of the visual clues. A similar system developed by Wang et al. (2014) is marker-based. According to Porcelli et al. (2013), using such AR telepresence systems can alter the whole service delivery system. The findings are based on a field experiment with several field operators using AR telepresence systems. The utilisation of highly skilled central operators can improve while optimising the education and the skill set of field workers. However, it is stated that this would call for significant organisational changes. Hence, the mindset within the organisation and the organisational structure itself can impede implementation of such a technology.

Lamberti and Pescador (2018) uses a prototype AR system for electronics maintenance, despite mentioning the airline industry as one of the industries with the highest percentage of maintenance of the total cost of ownership. However, future applications will be focused on industrial machine tools. A system is used that allows an operator providing assistance for technicians on site, but also allows the operator to author and alter content for maintenance operations.

Aschenbrenner et al. (2016) focus on the off-site expert side of telemaintenance and how to improve their situational awareness of the whole production process and peripheral machinery etc. Their *'ARTab'* concept uses AR on the other side of the telemaintenance collaboration than the studies above. While their system seems to improve situational awareness compared to VR or video solutions, it is not completely clear how the interaction between operator and field technician can be integrated into the system.

Maintenance Operation

A central part of AR in maintenance is the visualisation of maintenance procedures that are usually paper-based. Similar to displaying assembly steps, different maintenance tasks can be visualised step by step. Like other applications, using AR in laboratory experiments for maintenance tasks increases efficiency (Jayaweera et al. 2017; Mourtzis and Vlachou et al. 2017; Mourtzis and Zogopoulos et al. 2017; Fiorentino et al. 2014; Lamberti et al. 2014; Lee and Akin 2011). They provide evidence of AR superiority compared to paper-based maintenance instructions with regards to time to completion, error rate, and usability.

Two studies reporting on field experiments connected to maintenance were retrieved. A field experiment at a white goods manufacturer was conducted (Mourtzis and Vlachou et al. (2017). In this study, authors confirmed experimental results leading to a decrease in maintenance time of more than 50%. However, it has to be pointed out that the study not only focussed on the use of augmented reality but also looked into workflow improvement through software integration. Another exception is the study by Porcelli et al. (2013) as discussed above. However, no quantitative results have been used to validate the improvement due to AR.

At the Fraunhofer Institute for Casting, Composite and Processing Technology in Augsburg, Germany, a Microsoft HoloLense based system is used to develop a human-centred assistance system for maintenance tasks of a CNC lathe (Schlagowski et al. 2017). The currently published status of their research is a prototype test focusing on the assistant functions. However, one of their general research goals is to incorporate big data concepts into the architecture to advance the prediction of maintenance work. Mourtzis and Zogopoulos et al. (2017) also focussed on data integration and connecting different stakeholders. They utilised AR within the Product-Service System (PSS) between a machine tool manufacturer and the company operating the machine tool. The core of their proposed solution is a cloud-based platform automating the communication and integrating the data capturing within one system. Preliminary field experiments showed promising results.

The *CARMMI* (Portuguese acronym for '*CAx* models integrated to Mixed Reality and Intelligent Maintenance') ties together data from different sources (Espíndola and Fumagalli et al. 2013; Espíndola and Pereira et al. 2013). While the data extraction and visualisation include different sources of data, it is acknowledged that there are still data sources to consider, like product lifecycle management databases. Another issue anticipated in this study was the difficulty in technology adoption on the shop-floor level. Even though without having evidence on that topic, Espíndola and Fumagalli et al. (2013) argue that organisational processes need to be in place to fully utilise the new tool.

Authoring

Another active research area in AR maintenance applications is authoring for intelligent manufacturing systems. Creating content for AR maintenance systems can be challenging due to the complexity of the system and the tasks itself. In order to improve the efficiency of the authoring process and to give workers with no prior experience in computer science the ability to do so, easy authoring concepts are necessary. Havard et al. (2015) introduced a framework to create such content without programming skills. In addition, those systems should be context-aware.

In several papers included in this literature review, the content is created offline by developers. It can be beneficial to enable on-site technicians to adapt information within the system (Erkoyuncu et al. 2017). Then, it is possible to utilise their knowledge and their field experience. Zhu et al. (2012) proposed a bi-directional authoring tool where technicians are able to alter the maintenance contents on-site. Not only altering the content on-site but also creating the content in the first place is important (Espíndola and Fumagalli et al. 2013). Complex conventional manuals need to be translated into AR suitable content, which can be a time-consuming task. Engelke et al. (2015) developed a system by which technically skilled people are able to easily transform traditional content into AR content. In order to enable dynamic on-site information creation, Flatt et al. (2015) introduced a system where digital 'sticky notes' can be placed on machinery. They can contain dynamic information, like process parameters, or static information, like reminder messages.

Quality

The visualisation of quality data on site through AR can improve the reaction speed and failure investigation. Segovia et al. (2015) use a system to visualise quality data on each workstation through an HHD. However, the solution only shows rudimentary functionality and does not integrate quality data management systems.

Sampling is a crucial part of quality control. A subset of finished products is inspected. The product selection from a pallet or a batch is often determined by a (statistical or probabilistic) logic within an MRP system. In order to decrease human errors, Franceschini et al. (2016) developed a prototype to identify the products for inspection within a pallet. The focus of this study is the technical realisation of such a marker-based system. No trials have been conducted yet if such a system would decrease the error rate or increase efficiency in that task.

Despite automated robotic based spot welding being the state of the art for body-in-white car manufacturing, the inspection of these welding spots is still done manually to some extent. Zhou et al. (2011) tested a projector based AR system for operators to easily identify the spots to check. They improved their system to also be used to improve the spot-welding quality during the manufacturing welding process (Doshi et al. 2017). Field experiments at an automotive plant showed at least a 15% increase in precision. Thus, the distance between the real weld-spot and the optimum position decreased when using the AR system. Antonelli and Astanin (2015) used a similar technique to increase the accuracy and quality of manual spot welding in the process by indicating the correct position of the.

Logistics

The percentage of documents in the logistics field is with 13% relatively low compared to the other fields within the time-frame from 2011 to 2018 (see Fig 7). However, logistics is an important field that can contribute to the maturity of the AR technology. An indication of this notion is the involvement of companies already providing commercial AR solutions for logistics in the research process (Guo et al. 2014). The most labour-intensive task in warehousing and logistics is the picking process (Tompkins 2010). A broad variety of AR 'pick-by-vision' systems are already commercially available (e.g. the solutions used by Guo et al. (2014)). After a brief review of literature prior to the period in question (2011-2018) showed that the picking process had already extensively been researched, especially a research group at the Technical University Munich (TUM) was active in this field (Günthner et al. 2009; Reif et al; Reif and Günthner 2009; Reif and Walch 2008).

Despite the maturity, use of AR systems in warehousing and especially picking is still an active research area, especially as intralogistics can complex, as described in (Liu and Ma et al. 2017). In complex cases AR might be beneficial. A tendency can be observed towards more specialised research around the topic, e.g. focusing on the transparency of HMDs (Guo et al. 2015). Murauer et al. (2018) analysed at BMW different scan methods for AR picking solutions to confirm if the right item was picked. This pilot project close to real-life intelligent manufacturing applications showed that the scanning technology itself had a significant impact if the benefits of AR unfolded. Stoltz et al. (2017) also had a similar conclusion concerning the scanning speed. Hanson et al. (2017) looked into a special application of order picking, namely kit preparation for mixed-model assembly. While being similar to warehouse picking, the picks for kit preparation occur in shorter time intervals (Maurizio Faccio et al. 2015). Results show that AR systems can also be superior to paper-based systems for this application.

Other logistics operations can also benefit from AR. Sarupuri et al. (2016) used a forklift model to determine if AR enhanced imagery from the already built-in cameras could have helped the operators in performing tasks in high-racking storages. AR proved to be superior concerning completion time and the error rate. Similar to the majority of assembly related experiments, the participants were not trained operators. These results could change when testing the system in the field.

The Fraunhofer Institute for Material Flow and Logistics in Dortmund, Germany, looks into different areas of internal logistics where AR could be utilised as well. Notable examples are palletisation and packaging. Within the experimental setup of Kretschmer et al. (2018), palletisation efficiency does not profit significantly from the use of AR. For the process of packaging items, however, AR can significantly increase the packaging speed and also in the utilisation of packaging space (Mättig et al. 2016).

Others

The two main areas of application summarised in this section are SCADA tasks and machine set-up tasks supported by AR. Within a manufacturing environment, SCADA tasks can be enhanced through AR to, e.g. show real-time virtual copies and simulations (Lechevalier et al. 2017)of the physical system (Soete et al. 2015), or to preview the outcome of a machining operation during the process (Novak-Marcincin et al. 2014) and display relevant production data live on the factory floor (Rechowicz and Garcia 2016).

Liu and Cao et al. (2017) used AR to simulate and monitor the process by utilising real-time information from a milling machine. The AR framework developed by Ragni et al. (2018) supported the development of touching probes in manufacturing machines. They determine the exact position of a workpiece to prevent fatal collisions during machining. Their tool allowed for on-the-fly generation and simulation of probe trajectories with the aim of reducing set-up times.

Yew et al. (2016) went a step further and utilised AR as an intuitive online way to interact with a CPPS. Their solution not only showed process information, but allowed for interaction with a milling machine directly, replacing computer and paper-based tasks. The physical objects within their CPPS are completely replaceable with digital objects through AR.

Challenges

This section attempts to answer the second research question of this literature review (Q2: What are the current challenges that hinders the adoption of AR in manufacturing?). The challenges mentioned in the documents are classified according to a hierarchical structure. Fig 11 displays the structure and the results. The white rectangles show the number of papers that mentioned an issue that falls in a certain section of classification. It is obvious, that the technology and especially the software are still amongst the main current challenges.

Based on the data extraction from the survey, it was obvious that field experiments are not often conducted compared to laboratory experiments (see Fig 9). As discussed above, field experiments lead to new insights into the challenges faced when implementing AR solutions in the industry. From the conflicting results between laboratory and field experiments, it is obvious that those two scenarios are only comparable to a limited extent. Typically, new issues arose when AR systems were tested in industrial contexts. The current challenges ware rooted in that development. In order to analyse the field experiments in detail, a table has been compiled with detailed information on the experiment, the results, and identified challenges (see Table 5). The following sections show, where applicable, new challenges that were brought to light due to field experiments compared to the challenges encountered in laboratory experiments.

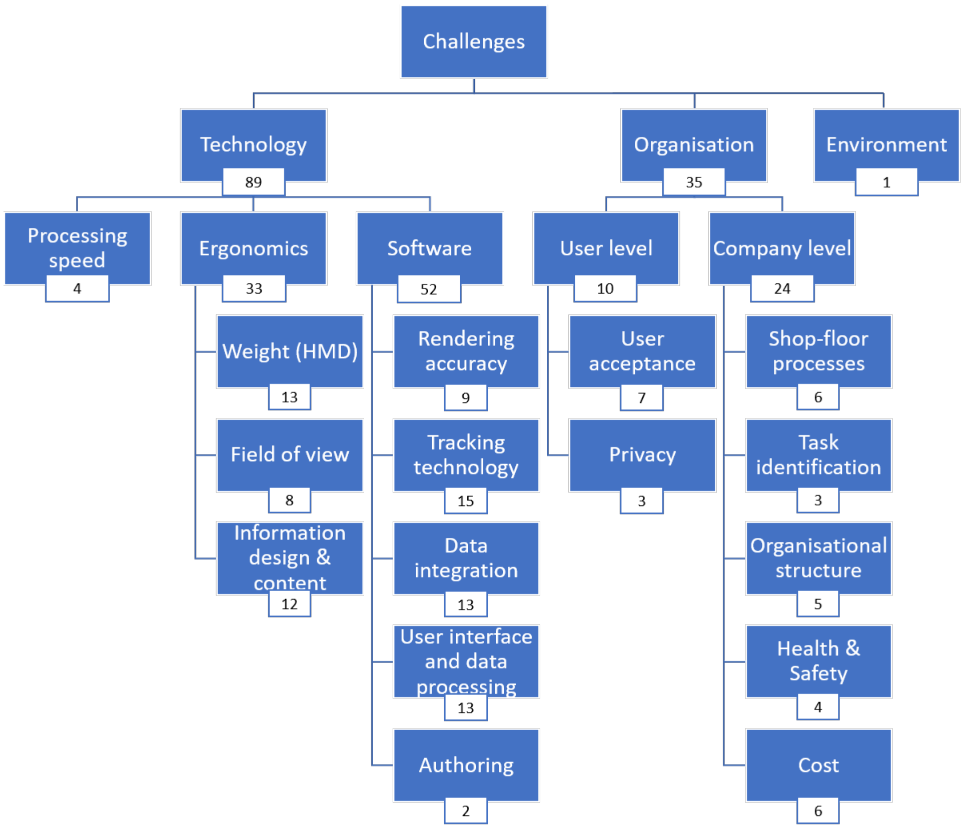


Fig 11 *The hierarchical classification structure of current challenges shows the number of documents that mention such an issue*

Technology

Despite the growing maturity of AR systems, most of the challenges were still classified as technological issues.

Processing speed

The processing speed of the hardware has improved over the years, as the processing power of microprocessors follows Moore's law (Moore 1965), which states that the density of transistors on integrated circuits doubles approximately every two years. This increase in processing power facilitates wearable and mobile solutions. A study done by Real and Marcelino (2011) still utilised laptops to provide the processing power for recognising markers and barcodes and for providing the digital content. The usability of that system prohibited adoption. Such a problem does not seem to be as pressing when using marker tracking technology. When using marker-less technology, the in-built processing power of HMDs was still an issue compared to HHDs. Marker-less tracking technology already was able to run in real-time on HHDs in certain applications (Wang et al. 2018).

Ergonomics

The usability of the systems was often a dependent variable of AR studies. The ergonomic design of an AR system is connected to user acceptance. It is still restricted by technological challenges. Before conducting (long-term) studies in industrial settings, the weight of HMDs and the field of view was often criticised (Holm et al. 2017; Schlagowski et al. 2017; Makris et al. 2016; Maly et al. 2016; Mura et al. 2016). Yet, ergonomics is not limited to the wear-ability of HMDs, but also on how ergonomic the user interface is. It has been shown that long-term usage of AR systems in industrial settings can lead to visual fatigue (especially when using HMD) and impact concentration performance levels (Murauer et al. 2018). Despite the fact that AR can reduce head and neck movements during operations, e.g. maintenance operations (Henderson and Feiner 2011), workers can be distracted or disoriented by the information displayed itself (Funk et al. 2017; Hou et al. 2013). Doshi et al. (2017) found that the design of visual cues itself could change the performance impact of the AR system. Also, how to use icons instead of textual information was one of the current challenges (Hahn et al. 2015).

Table 5 *Detailed analysis of the documents conducting field experiments. This table includes more detailed information compared to the data extraction table, as field experiments unveiled new issues and have not been that frequent yet. (continued on the next page) (Masood and Egger 2019)*

Author	Year	Application	Technology	Sample	Dependent variables	Results	Challenges
Real et al.	2011	Implementation of AR system to support warehouse inventorying.	HMD Marker tracking	2 IT specialists 2 workers	Decoding time Decoding distance User experience	Low user acceptance due to weight of system (laptop and HMD was necessary due to lack of in-built processing power of the HMD) Decoding time and distance of QR codes was not sufficient for the task	Weight and ergonomics Software decoding capabilities User acceptance can be limited due to disruption of existing processes
Servan et al.	2012	AR for assembly instructions of electrical harness routing in a frame part of the AIRBUS A400M Authoring and deployment of	HHD Marker tracking	Not disclosed	Task completion time	Authoring and content maintenance time decreased by 90%. Assembly time decreased by 50%. Working conditions and error rate reported to be improved (qualitative and subjective).	Need of data integration with product lifecycle management (PLM) suites Advances in AR devices and tracking systems necessary (not specified)
Porcelli et al.	2013	AR systems for maintenance of machinery in the industrial printing industry.	HMD	1 remote expert 2 field technicians	User experience (Interviews)	Increased need for expert guidance and collaboration in maintenance tasks can be supported by AR systems.	Weight and ergonomics Data transfer in remote areas Latency Automate content authoring Company openness towards innovation Cost Change of training focus and necessity
Gavish et al.	2013	Comparison of AR, VR, and instructional videos for training purposes on an electronic actuator assembly task.	HHD Marker tracking VR	40 expert technicians	Task completion time Error rate Training time Usability (9 Likert-scale questions)	Increased training time with AR and VR systems. Decreased error rate after training with the AR system. Improved cognitive understanding of the tasks through AR and VR. AR is favoured compared to VR by the technicians in terms of usability.	Cost Long training time due to unfamiliarity with AR and VR systems No clear performance difference between AR and VR
Hahn et al.	2016	AR assisted assembly for printed circuit boards (PCB) at the assembly line of an Electronics Manufacturing	HMD Marker tracking	30 workers	Error rate User experience	Error rate of 0. High acceptance among participants.	User interface visibility Content for user interface Marker tracking under different conditions
Syberfeldt et al.	2016	Evaluation of different AR solutions by representatives of different manufacturing firms in Sweden. Qualitative insights on industrial needs for AR adoption.	HMD HHD Projection Marker tracking	7 Swedish manufacturing companies	Usability (Interviews and Workshops)	Perceived efficiency improvement. Weight of HMDs is high. HMDs are preferred over tablets as both hands are free.	Level of complexity impacts efficiency gain through AR Adaptive instructions dynamically to improve user acceptance Data security and privacy policies to increase user acceptance
Stoltz et al.	2017	Identify potential benefits and barriers for AR adoption in warehouse operations. For the experiment, the process of sorting packaged orders was chosen.	HMD HHD Marker tracking	19 non-expert operators in laboratory experiment 5 expert operators in field experiment	Task completion time Error rate (qualitatively) Ease of use	User preference towards AR application due to high ease of use. AR application was slower due to processing power of HMD system used. Decreased error rate can justify slower speed through decreased re-work effort.	Hardware limitations Software limitations User acceptance Cost
Mourtzis et al.	2017	Real-life maintenance task (battery pack replacement) of an industrial robotics system at the facility where the system is installed. The use-case is provided by the	HMD HHD Marker tracking	Not disclosed	Task completion time Cost	No need of dispatching a technician to the site where the robot is installed. Cost reduction by nearly 20%. Time reduction from 9h to 2h.	Increase interoperability with existing systems. Automate content authoring.
Doshi et al.	2017	In-situ projection AR to support the precision of a manual spot welding process at a car manufacturer.	Projection	1 inexperienced worker (off-line) 4 shifts with 8 experienced workers (in-line)	Welding accuracy	Significantly smaller error distribution of the spot weld position. 15% to 52% improvements depending on the position of the weld.	Effect of visual cues on accuracy

Table 5 *(continued) Detailed analysis of the documents conducting field experiments. This table includes more detailed information compared to the data extraction table, as field experiments unveiled new issues and have not been that frequent yet. (Masood and Egger 2019)*

Author	Year	Application	Technology	Sample	Dependent variables	Results	Challenges
Funk et al.	2017	In-situ projection AR in manual assembly of engine starters for a total of eleven days at an automotive assembly plant. Each participant assembled for three days using the projection based AR system, which provides context-aware instructions.	Projection	3 expert workers 3 untrained workers (all employees of a car manufacturing company)	Task completion time Error rate TASA-TLX User experience (Interviews)	Expert workers: Significantly higher task completion time due to distraction by projection according to interviews. No indication of higher cognitive task load measured by NASA-TLX compared to conventional setting. Novice workers: Improved learning curve. Lower NASA-TLX compared to expert workers. Distraction by AR system after a while according to interviews.	AR slows workers down due to distractions Adaptive instructions based on the workers experience Diminishing reward curve for using AR in assembly training
Murauer et al.	2018	Simulated supermarket picking station within an automotive manufacturing plant. Compare AR with different scanning mechanisms to current monitor based system.	HMD Marker tracking	5 production workers	Task completion time Error rate NASA-TLX Visual fatigue questionnaire d2 test of attention Usability (system usability scale)	AR decreases error rate. Utilising a scan glove improves task completion time. Depending on the supporting scanning equipment, however, the task completion time can increase. AR can increase the cognitive work load, depending on the scanner system.	Visual fatigue and concentration performance levels.

Software

The most common issues were software related. Especially the tracking technology in different circumstances was still a research focus (Blanco-Novoa et al. 2018; Kretschmer et al. 2018; Tong et al. 2016). As the technology matures, it becomes inherently important to be able to integrate AR solutions with the current information technology systems, for example, to visualise shop floor management information (Qian et al. 2017). Several studies focussed on that problem (Flatt et al. 2015; Havard et al. 2015; Serván et al. 2012) or acknowledged it (Mourtzis and Vlachou et al. 2017; Soete et al. 2015; Espíndola and Pereira et al. 2013). However, this is part of a bigger issue. As industrial systems become digitally enabled, the standardisation of modelling, interfaces, and data structures needs to follow certain standards, like UML, or OPC UA (Flatt et al. 2015; Havard et al. 2015) in order to facilitate intelligent manufacturing systems. It is not clear yet which selection out of the vast number of standards (Trappey et al. 2017) will be the dominant one for a certain task. This challenge cannot be tackled within the AR research community but needs a broader approach.

The user feedback often used some kind of hardware. In AR user interfaces there is no common framework on how the user can give the system feedback intuitively. Different studies on gesture recognition use different hand-gestures for controlling the system (Saxen et al. 2017; Wang et al. 2016; Rodriguez et al. 2015; Radkowski and Stritzke 2012; Radkowski and Stritzke 2012). To improve the familiarity with such systems, a common way of using hand gestures to interact with the systems is imperative.

Organisation

Especially when thinking about implementing AR, long-term and organisational effects need to be considered as well. This section describes challenges from a user perspective and from an organisational perspective.

User level

While being discussed more detailed aspects of user acceptance in the ergonomics section, it was an overarching topic in the field, but also in laboratory experiments. A sensitive issue arising from surveys amongst trial users was privacy and its protection (Stoltz et al. 2017; Syberfeldt et al. 2016; Hou et al. 2015). The challenge is based on the fact that indoor localisation (Flatt et al. 2015) and task/error tracking (Wolfartsberger et al. 2017) are inherently important for the performance of such a system. That opens users up to increased surveillance from superiors. A workshop based study by Syberfeldt et al. (2016) identified solutions to such issues of significance to successfully gain user acceptance.

Company level

The identified challenges in this category originated nearly exclusively in field experiments, as it was hard to detect challenges connected to the company where the technology is deployed in a laboratory setting. It was already shown that the experience of workers and the human factor, in general, is important concerning the acceptance of the technology. The organisation itself needs to be looked into.

No study reviewed in this article has researched if and how shop-floor operations and processes need to be adapted to allow AR to employ its full potential. Yet, the possible disruption or incompatibility was mentioned in some instances where AR was tested in industrial settings (Funk et al. 2017; Espíndola and Fumagalli et al. 2013; Espíndola and Pereira et al. 2013; Garza et al. 2013; Gavish et al. 2013; Porcelli et al. 2013; Real and Marcelino 2011). Not every task is suitable for being supported by AR solutions. It was indicated that an increasing level of task complexity might correlate to the benefit provided by AR (Blattgerste et al. 2017; Syberfeldt et al. 2016; Gavish et al. 2013). It was not clear which kind of tasks could profit from AR solutions, as some of the field studies revealed a negative performance influence when utilising AR (Funk et al. 2017; Gavish et al. 2013). Yet, it has to be noted, that this effect could be attributed to other issues as well, like unfamiliarity (Gavish et al. 2013), non-adaptive instructions (Funk et al. 2017), or user acceptance in general (Stoltz et al. 2017). Additional challenges on a company level included the organisational structure in general, health and safety concerns (Murauer et al. 2018; Makris et al. 2016) e.g. due to distraction, and cost / profitability implications (Stoltz et al. 2017; Hou et al. 2015; Espíndola and Pereira et al. 2013; Gavish et al. 2013; Porcelli et al. 2013; Bondrea and Petruse 2012).

Environment

The environment of a company adopting and implementing AR might play a role in how the technology is used as well. Those challenges can include the information integration of third parties, the regulatory environment concerning employment protection, the industry-wide standardisation of AR solutions, or the necessity of external support. However, no research has been conducted into that area. Only the aspect of necessary external support was mentioned (Stoltz et al. 2017).

Future directions

In this section, the future directions of research are proposed to answer the second research question (Q3: What are future directions of manufacturing related AR research?). These directions are classified based on the challenges uncovered in the following areas:

1. Processing Speed
2. Ergonomics
3. Software
4. User level
5. Company level
6. Environment

Table 6 lists the uncovered future directions with more detailed suggestions for future research directions. It also highlights which of those research directions is summarised from the reviewed studies and which ones are identified by the authors of this study. Those points are common among the different areas of applications and are discussed in more detail in the following sections.

***Table 6** Suggestions of likely future research directions based on the current challenges and the reviewed studies*

Area of Challenge	Future Direction	Detailed Suggestions	Source
Processing Speed	Increase processing speed	-	Analysis of Q2/Q3 related articles
Ergonomics	Improve ergonomics	Improve wearability through weight decrease	Analysis of Q2/Q3 related articles
		Improve visibility of information through increased resolution and light intensity	Analysis of Q2/Q3 related articles
		Develop user interfaces to counteract visual fatigue	Analysis of Q2/Q3 related articles
Software	Improve softwar technology to support users and implementation	Improve marker recognition	Analysis of Q2/Q3 related articles
		Data exchange and software integration	Analysis of Q2/Q3 related articles
		Develop intuitive authoring solutions	Analysis of Q2/Q3 related articles
		Develop solutions for adaptive content based on the process or user experience	Analysis of Q2/Q3 related articles
End-User level	Improve end-user acceptance	Investigate factors influencing end-user acceptance	Newly identified
		Determine measures to ensure privacy	Analysis of Q2/Q3 related articles
Company level	Research into challenges of organisational implementation	Investigation of possible effects of AR systems on existing processes	Newly identified
		Investigation of possible effects of AR systems on the organisational strucutre	Newly identified
		Develop a framework to identify tasks suitable to be supported by AR systems	Newly identified
		Investigation of possible health and safety concerns	Analysis of Q2/Q3 related articles
Environment	Impact of the environment of the organisation on AR implementation	Determine factors attributed to the environment of the company that have an effect on AR adoption and implementation	Newly identified

Processing Speed

In the future, processing power will have to increase, as marker-less tracking solutions are starting to be used. Those solutions consume significantly more computing resources compared to marker-based systems. Especially stand-alone HMDs suffer from a lack of processing speed due to special and weight restrictions imposed by the wear-ability of such devices. Increasing miniaturisation is necessary to provide ergonomic wearability and the necessary processing speed.

Ergonomics

Fig 8 shows the most prominent visualisation technologies used within AR. HMDs are prominently used due to their characteristic of being ‘hands-free’. In general, the ergonomics have to be improved. The systems are still fairly heavy, and in several user surveys, the weight was a limiting factor for long-time usage of the device (Soete et al. 2015; Porcelli et al. 2013; Zhu et al. 2012). Those issues need to be resolved. In addition, the content visibility needs to be improved as well. The field of view is limited, prohibiting to extend the amount of information overlaid at a certain point.

When working with AR HMDs on a regular basis and throughout the day, visual fatigue is an identified issue (Murauer et al. 2018). Eye movement and the focus change between the user interface and the physical world can lead to visual fatigue. Currently, this effect is seldom measured. Measuring the extent of eye movement and visual fatigue after using HMDs for an extended period of time can provide information on how to improve the design of user interfaces (Aini and Arshad 2013).

Software

Even though marker-based tracking is the most widely used solution, improvements need to be made concerning its robustness and reliability (Kretschmer et al. 2018). While the number of markers necessary to reliably place objects has improved, the influence of the environment on the reliability is still an issue. The lighting conditions influence how well markers are recognised. In addition, in industrial environments dust or dirt can block the marker (Blanco-Novoa et al. 2018). Improved algorithms to detect and read markers can counteract those challenges in the future.

Natural markers within buildings have been proposed as a solution for such a problem but are not widespread in research. While marker-less tracking has the advantage that no markers need to be placed within the area the system is used, it was still in an early stage of (Radkowski and Stritzke 2012); (Real and Marcelino 2011); (Han and Zhao 2017; Wu and Wang 2011). Future research can focus on the new possibilities in manufacturing applications due to recent technological advancements.

As AR is moving towards real-life applications, the adaptability of the content is an important part and has two different perspectives to it. The first one is the adaptability towards the individual experience of the operator (Funk et al. 2017; Holm et al. 2017). Future research in that area could detect other parameters which indicate the experience of operators.

For widespread adoption, AR systems need to be integrated seamlessly into the existing IT infrastructure (Aini and Arshad 2013). To do so, standardised data exchange protocols need to be used (Zhou et al. 2017) and the solutions need to be flexible to be adapted for different needs (Kollatsch et al. 2014). Future research can focus on how to integrate AR systems solutions like predictive maintenance based on big data analysis (Schlagowski et al. 2017).

As laid out previously, implementing an AR solution in real-world environments brings new challenges. When looking into human-robot collaboration, the safety has to be improved. It has been pointed out that only visualising the safety areas around a robot might not be enough to ensure the safety of operators (Makris et al. 2016; Michalos et al. 2016). These systems need to integrate with detection systems and path planning algorithms to detect humans within the calculated path of the robot arm and to execute countermeasures.

The benefits provided by AR systems could be improved by developing easy content authoring systems that allow for content creation on both ends of the system. Operators need easy methods to author content while on the field. Currently, it is unclear to what extent such solutions are feasible using HMDs or when HHDs or stationary solutions should be preferred for content creation.

Another aspect that was not covered in the studies analysed is the adaptability concerning the operations itself. The experimental tasks were repetitive. However, several authors state that the number of product variants increases (Holm et al. 2017; Funk, Kosch and Schmidt 2016). This could that the number of different assembly operations a worker has to execute increases. The content displayed, especially for assembly tasks, needs to accommodate these changes. While this has been not dealt with yet, integrating AR systems in a broader data infrastructure is the goal of different research initiatives (Schlagowski et al. 2017; Porcelli et al. 2013). Future research can tackle this issue by developing systems that utilise real-time data from intelligent manufacturing information systems.

User level

User acceptance is crucial when implementing new technologies. Current research focuses on the cognitive workload when using AR, mainly utilising the NASA TLX for measuring. Yet, other models might be of use for a more holistic picture of user acceptance. The technology acceptance model (TAM) (Davis 1985) could help in answering those questions. It has been used to determine the user acceptance of AR in a consumer setting (Huang and Liao 2015). Yet, no research utilising this model has been conducted in an industrial environment. Another approach is to use experiments with workers determining the usability of AR solutions to discuss possible ways of involvement of the workforce to increase the user acceptance.

One issue that is highlighted in current research is the concern of privacy when using AR in the workplace. While the regulatory framework of each country obviously needs to be adhered to, it is unclear which measures would counteract the privacy concerns from a user perspective.

Company level

In general, the organisational challenges when adopting AR solutions need to be investigated. We propose that implementing such technologies within an industrial environment needs to be looked at from a broader perspective. AR does change work processes, the organisational hierarchy, and the whole information exchange process. This can have profound consequences for organisations, which have not been looked into yet in detail. Those changes affect the firm as a whole, but also operators on an individual level. Additionally, the company culture is affected. Stoltz et al. (2017) put it as follows: '… an important issue is a change in the existing mindset of both warehouse managers and operators who need to accept the new technology.' Future research can utilise technology adoption and implementation frameworks to explain the factors influencing the success of those implementation processes.AR was mainly applied in order to support existing processes by studies included in this review. However, it is possible that AR can only unfold its potential when altering the process and adapting it. For example, the work organisation process might become much more flexible through a significantly steeper learning curve of workers. This would also have implications for the organisational structure which need to be analysed.

The complexity of a task seems to correlate with the benefit AR can provide (Blattgerste et al. 2017; Syberfeldt et al. 2016; Gavish et al. 2013). Future research can focus on how to classify tasks based on their complexity and analyse the impact of AR systems on tasks with a different level of complexity. Some factors have already been used to determine where AR can provide a substantial benefit (Pantoja et al. 2014). However, it is not clear if those factors are representative and adequate. Thus, indicators, where AR would significantly improve performance, can be developed based on case studies in industry.

Industrial environments may be exposed to potential dangers. Using AR might have effects on the safety of the users. They could get distracted or plainly not see certain physical dangers. Research has to be conducted on how to ensure the safety of operators using AR.

Environment

The environment of the company has an effect on the adoption and implementation of technology (DePietro et al. 1990). Which factors attributed to the environment have an impact depends on the technology (Scupola 2014; Wang et al. 2010; Zhu et al. 2010; Kumar et al.) in the end and need to be taken into consideration. Currently, it is unclear what situation AR faces in that regard. Future research can build on previous research for other technologies and further develop it to also include AR systems.

Conclusion

The following main contributions of this paper are based on the literature review, which has answered the three questions within the context of AR in support of intelligent manufacturing.

Contribution 1: *First major contribution of this paper is the identification of the current status of manufacturing related AR research (in response to Q1).* Due to the systematic nature of the review we were able to provide a holistic view, not only focusing on an industry type or an application of the AR in manufacturing (see Table 1).

The citation network analysis highlighted active research areas and authors around the world. Three distinct geographical research clusters were identified in Europe and Asia. The technologies used and the current research focuses were outlined. From this current status, the industry can draw inspiration for industrial applications, as solutions applicable to industry as well as research in laboratories were reviewed.

While AR is not ready yet for industrial deployment in some areas, it is already used in others. Companies are testing and implementing AR solutions for different applications. The benefits shown for already implemented logistics solutions can also be (partially) applicable to other fields. The authors firmly believe that within a few years AR will be widespread among a broad variety of applications, especially as a growing proportion of research is conducted by or in cooperation with companies. Some of those experiments still showed mixed results concerning the performance. However, the potential benefits of AR shown through a broad variety of experiments incentivise to overcome those barriers.

Contribution 2*: Second major contribution of this paper is the identification of the current challenges that hinders the adoption of AR in manufacturing (in response to Q2). Compared to other reviews (see* Table 1*), the context of challenges was seen broader. Hence, not only technological challenges but organisational challenges are also included.*

The status of the AR research has advanced significantly in recent years. Field experiments highlighted new challenges and limitations, as the industrial implementation causes organisational and user acceptance issues. This is not only relevant for academia but also particularly for the industry. The analysis of the field experiments provides guidance concerning potentially problematic areas when implementing AR solutions. It can be used to determine which aspects need to be considered for such projects.

Academia and industry alike can obtain an overview of current challenges to determine if AR is usable for certain applications. While coming a long way, hardware and software still require improvements in certain areas. A classification of the challenges shows that most of them are still of technological nature. It has been identified, via the structured literature review presented in this paper, that hardware and software are still the main limitations of AR and require further research. Especially the user interfaces and the user interactions prove to be among major issues. It is not clear yet how the users can intuitively interact with the technology.

Tasks to be supported by AR vary. These variations influence the effectiveness of AR systems. Additionally, this new technology needs to be the starting point of re-engineering current processes to fit the technology.

Through analysis of these possible challenges, this structured literature review has highlighted stepping stones for further research, which can alleviate those challenges and promote the implementation of AR solutions in the industry of the future.

***Contribution 3**: Third major contribution of this paper is the identification of future directions of manufacturing related AR research (in response to Q3). Similar to contribution 2, the broad perspective of this literature review enabled identification of future research directions not only focused on the technological but also the organisational side.*

The future research needs to focus on intelligent manufacturing applications of AR based on the identified challenges and structured review of the recent research presented in this paper. Suggestions are made, that can inspire future AR research in support of intelligent manufacturing. It is obvious that hardware advances will alleviate some of the problems concerning data processing and wear-ability. However, our findings show that it is necessary to be user-centric in future application development. Otherwise, the user acceptance could suffer hindering the efficiency of the technology itself. Since a significant proportion of the literature has examined the technological aspects of AR, future research needs to focus on the implementation of AR in practice keeping in mind the intelligence requirements of the manufacturing industry of the future.

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